SCHOOL LAUNCH · EARTH SCIENCE K–8

Grade 6 Earth Science: The Dynamic Earth

A year of true stories about a restless planet, from Inge Lehmann listening to earthquake waves bend around the core and Alfred Wegener matching the coastlines of Africa and South America to Vesuvius, Krakatoa, the Lisbon earthquake, the island of Surtsey rising from the sea, Niagara Falls walking upstream and J Harlen Bretz reading the flood-scoured scablands of Washington, each one taken apart to see how it works and then measured, modeled and recorded at the kitchen table.

First edition

> *“In the beginning God created the heaven and the earth.” (Genesis 1:1, KJV)*

Course guide

This course follows eight strands of earth science through one school year: the inside of the earth, the moving plates, volcanoes, earthquakes, mountains, erosion and deposition, catastrophes, and the engineering that protects people from natural hazards. Each unit is built around real moments from history: Inge Lehmann in 1936 noticing earthquake waves that should not have arrived where they did, Antonio Snider-Pellegrini's 1858 map of the continents fitted together, the burial of Pompeii in A.D. 79, the explosion of Krakatoa in 1883 heard thousands of kilometers away, the earthquake that shook Lisbon on All Saints' Day in 1755, the birth of Surtsey off Iceland in 1963, the slow retreat of Niagara Falls, the canyon cut in days at Canyon Lake Gorge in Texas in 2002, and J Harlen Bretz standing alone for decades with his evidence that a great flood had carved the Channeled Scablands.

Every lesson follows the same path. First comes **the story**. Then **how they figured it out**: what was seen, what was measured, what was predicted and what surprised everyone. Then **the big idea** underneath, explained for a sixth grader and building toward high-school earth science: seismic waves and the layered earth, magnetism, plate boundaries, magma and lava, magnitude scales, folding and faulting, the rate of erosion, deposition and sorting, and the difference between slow and sudden processes. Then **the student measures**. Every lesson has worked examples and practice problems with rates, ratios, graphs and scale, and every experiment ends with a number written down in the field notebook: a wave timed across a tray of water, a slope measured in degrees, a layer of sand weighed in grams, a model fault offset in centimeters.

The thread of the year is a question: **how fast does the earth change, and how do we know?** Some changes are slow and steady and can be timed with a stopwatch and a ruler at the kitchen sink. Others are sudden and enormous, and they leave marks that can be read long afterward. The student learns to ask of every landform, "What process made this, how fast could it have happened, and what evidence would tell the difference?" That habit of observing, measuring and weighing evidence is the heart of science, and it serves a student whether the question is a volcano or a leaky faucet.

The course is written from a Christian view of the world: "In the beginning God created the heaven and the earth." (Genesis 1:1). The earth is a made thing, ordered and knowable, and studying it carefully is a way of honoring its Maker. The mountains that "skip like rams," the sea whose waves were given a bound, and the fountains of the great deep in Genesis 7 all appear in the lessons where they fit. Where the course meets the standard museum and textbook account of deep time, it teaches the words honestly so the student can read any sign, and then sets out plainly what we observe and how Christians have understood it.

WHO IT IS FOR

Written for students in grade 6 (about ages 11–12) who read well on their own, can multiply and divide with decimals, can read a simple graph and are ready to use ratios, rates and scale. A parent or teacher reads along, supervises every experiment, handles anything hot or

sharp, and takes part in the Field Lab outings. Metric units are used throughout. Nothing needs to be bought beyond ordinary household things: a kitchen scale, a ruler and meter stick, a protractor, a baking tray, sand and gravel, modeling clay, a bar magnet and a graph-paper notebook.

HOW TO USE THIS COURSE

The weekly rhythm. The year has 32 lessons, one a week, in eight units of four, plus an optional ninth unit, the Field Lab, with four outdoor lessons. Each lesson takes two sessions of about 45 minutes. Session 1 is the warm-up, the video when one is listed, the story and core ideas, the key terms and the picture study. Session 2 is the experiment, the worked examples, the practice problems and the field notebook. In the last week of each unit, add a third session for the unit test and the unit project.

The ★ quarter path. Ten lessons are marked with a star: 1.1, 2.1, 3.1, 3.2, 4.1, 5.1, 5.2, 6.1, 7.1 and 8.1. A family that wants a one-quarter course, or a student taking this alongside another science, can do the ten starred lessons in order, one a week, and still meet every major idea of the year. Lessons marked ⏳ carry a Thinking About Time box, explained below.

The field notebook. Use one graph-paper composition book for the whole year. Every experiment ends with something measured and written down: a data table, a graph, a labeled diagram, a sketch of a model with its scale, or a map. Date every page, label every column with its unit, and write one sentence about what the numbers show and one about what you would change. A clean record of a result that surprised you is worth more than a tidy record that matches the book.

Experiments and safety. Every experiment works with household things, and the instructions name what the student may handle and what the parent handles. The volcano and heat lessons use warm water, baking soda and vinegar, never open flame or anything that explodes. A parent stays in the room for every experiment, and the family cleans up sand, clay and water together. The Field Lab lessons go outdoors to a creek bank, a ditch, a road cut or a hillside; a parent chooses the site, checks the footing and the weather, and no one digs or climbs where there is traffic, loose rock or private property without permission.

Worked examples and practice. Each lesson has three worked examples, done step by step, that use real numbers: the speed of a seismic wave, the rate of retreat of a waterfall in centimeters per year, the ratio of a model to the real thing, a magnitude scale, or a graph of lava temperature against distance. Then come ten practice problems with answers. Two of them give the student a short table or graph to read and reason from, in the style of the science-reasoning items on the SAT and ACT, and one asks the student to design a fair test. Check the answers together and talk through any that went wrong.

Unit tests and unit projects. Each unit ends with a unit test of 60 points and ten to twelve problems: multiple choice, short answer and one diagram to label or draw. Each unit also ends with a unit project that pulls the unit together, such as a cut-away model of the earth with a scale, a plate map with the boundaries labeled, a volcano field guide, a seismograph

and a record of a staged earthquake, a folded-mountain model, a stream-table report, a scablands evidence poster or a family preparedness plan. Keep the project pages in one folder for the year.

A word about time. This course is written from a Christian view of creation (Genesis 1:1) and of the Flood (Genesis 6–9). Museum signs and most textbooks describe the earth with deep-time names such as “Jurassic,” “Ice Age” or “millions of years.” The course teaches those names as museum words, so that the student can read any sign, any park brochure and any textbook and know exactly what is being claimed. Wherever such a name comes up, a ⏳ Thinking About Time box sets out three things plainly: what the sign says, what we actually observe, and how Christians read it. The student learns to tell an observation from an interpretation, which is a skill every scientist needs, whatever his or her view of the earth’s age.

SCOPE AND SEQUENCE

Unit 1: Inside the Earth (1–4)

How Inge Lehmann used earthquake waves to find the inner core; the crust, mantle and core modeled to scale; the earth as a magnet and the compass; and measurements of the earth’s magnetic field over time.

Unit 2: Plates (5–8)

Antonio Snider-Pellegrini’s 1858 map and Alfred Wegener’s 1912 idea of drifting continents; matching coastlines, rocks and fossils; the three kinds of plate boundaries; and catastrophic plate tectonics as a creationist model.

Unit 3: Volcanoes (9–12)

Vesuvius and the burial of Pompeii in A.D. 79; Krakatoa in 1883 and the sound heard across the ocean; shield, cinder cone and stratovolcano; and Surtsey, new rock built in days off Iceland in 1963.

Unit 4: Earthquakes (13–16)

The Lisbon earthquake of 1755 and the questions it raised; how Richter and later moment magnitude measure shaking; building and reading a seismograph; and how a moving sea floor makes a tsunami.

Unit 5: Mountains (17–20)

How rock folds and faults; layers bent without cracking and what that tells about their condition when they bent; the Himalaya where India meets Asia; and fossil seashells on mountaintops read with Psalm 104.

Unit 6: Erosion and Deposition (21–24)

The measured retreat of Niagara Falls; deltas and how a river sorts and lays down its load; wind, dunes and desert rock; and canyons cut in days at Mount St. Helens and Canyon Lake Gorge, Texas, in 2002.

Unit 7: Catastrophes (25–28)

J Harlen Bretz and the Channeled Scablands; the fossil graveyard at Dinosaur National Monument; catastrophism and uniformitarianism as two ways to read the rocks; and Genesis 7–8 read as a catastrophe.

Unit 8: Hazards and Engineering (29–32)

Buildings that ride out an earthquake; how volcanoes are watched and warnings given; landslides and the slopes that fail; and a family plan and kit for the hazards of your own region.

Unit 9: Field Lab (optional) (Optional, any season)

Four outdoor lessons that take the year's skills to a real creek bank, yard, road cut or hillside: watching erosion over weeks, digging and recording a soil pit, mapping the hazards of your own area, and reading a rock outcrop.

MATERIALS

- **Field notebook (a graph-paper composition book)**: One for the whole year: data tables, graphs, labeled diagrams, model sketches with scale, and field maps.
- **Metric ruler, meter stick or tape measure, and a protractor**: For measuring models, slopes, offsets and distances. A 30 cm ruler and a 2 m tape are enough.
- **Kitchen scale that reads in grams, and a measuring cup in milliliters**: For weighing sand and gravel in the erosion and deposition experiments and measuring water.
- **A baking tray or shallow plastic bin, sand, fine gravel and a pitcher**: The stream table for the river, delta, erosion and tsunami lessons. Work outdoors or over a towel.
- **Modeling clay or play dough in several colors, and a few hard-boiled eggs**: For earth-layer models, folded and faulted rock layers, and plate-boundary models.
- **A bar magnet, a sewing needle, a cork or foam, iron filings or steel wool bits, and a compass if you have one**: For the magnetism lessons in Unit 1.
- **Baking soda, vinegar, dish soap, food coloring and an empty plastic bottle**: For the volcano models. No flame is used anywhere in the course.
- **A stopwatch or phone timer, string, a heavy washer or nut, a marker and a long strip of paper**: For timing waves and building a simple seismograph in Unit 4.
- **Cardboard, craft sticks, rubber bands, tape, a shoebox and a few books**: For the shake table and earthquake-proof building models in Unit 8.
- **Optional: a hand lens, a trowel, a local geologic or topographic map, and one of the books listed in a unit**: Never required. Useful for the Field Lab. See the list in each unit.

GRADING

Grades come from the unit tests, the field notebook, the experiments and the unit projects, because earth science is learned by observing, measuring, recording and then explaining. An experiment whose numbers did not come out as expected but are honestly recorded and explained earns full credit.

- Unit tests (eight tests, 60 points each): 35%
- Experiments (prediction, careful measurement, honest record and the improve-it step): 25%
- Field notebook (dated pages, labeled units, graphs and diagrams): 20%
- Unit projects: 20%

A 90–100, B 80–89, C 70–79, D 60–69. Below 60: review the unit with help and retake the test or redo the project.

- Each unit test has ten to twelve problems worth 60 points in all: multiple choice, short answer and one diagram item to label or draw. Give it in one sitting of about 45 minutes, closed book, with a ruler and calculator allowed.
- Grade experiments on the process: Did the student predict, measure in metric units, record the data honestly, draw the graph or diagram, explain what the numbers mean and suggest an improvement?
- A notebook page earns full marks when it has a date, a title, labeled columns with units, a graph or labeled diagram where one fits, and one sentence about what the result shows.
- The practice problems are for learning, not grading. Check them together and let the student correct his or her own work.
- A student who writes slowly may give short-answer test items orally while the parent writes the answers down. The diagram item should be drawn by the student.
- The Field Lab is optional and is not graded unless you choose to count it as extra credit in the experiments category.

A NOTE TO PARENTS

You do not need to be a geologist to teach this course. Read the story aloud together, do the experiment side by side, and ask three questions over and over: “What do you see?”, “What did you measure?” and “What process could make that, and how fast?” Those questions are most of what a good science teacher does. The worked examples show every step, and the practice problems come with answers, so you can check the work even if the mathematics is rusty.

The course is honest about where Christians and the standard textbook account differ, and it does not hide either one. Your student will learn what a museum sign means by “Jurassic” and what a park brochure means by “Ice Age,” and will learn to separate what was observed from what was interpreted. The ⏳ Thinking About Time boxes are written so that a family

can read them together and talk; they present what the sign says, what we observe, and how Christians read it, and they leave room for your own household’s conversation.

Keep the experiments safe and the outings sensible. Stay in the room for every experiment, handle the warm water yourself, and choose Field Lab sites where the footing is good and the bank is not undercut. Above all, the course hopes to raise a young person who looks closely at the world, measures carefully, speaks truthfully about what the evidence shows, and marvels at the One who made it. “The sea is his, and he made it: and his hands formed the dry land.” (Psalm 95:5)

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★ quarter path · ⏳ Thinking About Time box

UNIT 1

Inside the Earth

No one has ever been to the center of the earth. The deepest hole ever drilled reaches only about 12 km, a scratch on a planet 6,371 km in radius. Yet we know that beneath our feet lie a solid rocky mantle, an ocean of liquid iron and a solid iron ball at the center. In this unit you will learn how scientists found that out without going there: by weighing the world, by timing earthquake waves, and by watching compass needles.

You will meet Inge Lehmann, who sorted earthquake records into oatmeal boxes in Copenhagen and found the inner core in 1936; Henry Cavendish, who weighed the earth in 1798; William Gilbert, who carved a “little earth” out of lodestone; James Clark Ross, who stood at the north magnetic pole in 1831; and Carl Friedrich Gauss, who first measured the strength of Earth’s magnetic field. You will build a scale model of the layers, make a working compass, and graph the measured weakening of Earth’s magnetic field.

In the last lesson you will meet your first “Thinking About Time” box. You will learn exactly what textbooks say about the age of Earth’s magnetic field, what has actually been measured, and how many Christians read the evidence, so that you can read any textbook or museum sign carefully and fairly. “Where wast thou when I laid the foundations of the earth?” God asked Job (Job 38:4). We were not there, but we can measure what He made.

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and decimals, and find a percent
- Knows the difference between a solid, a liquid and a gas
- Can measure angles in degrees and read a compass rose
- Can read a simple data table and line graph

MASTERY CHECKLIST

- I can describe P waves and S waves and explain how the shadow zone reveals a liquid outer core and a solid inner core.
- I can calculate the time gap between P and S waves from their speeds and a distance.
- I can name Earth’s layers in order with their approximate depths and tell which are solid and which is liquid.
- I can explain how a compass works and correct a bearing for declination.
- I can read data showing that Earth’s magnetic field has weakened since the 1830s and calculate percent change and half-life steps.
- I can tell what the textbook says, what we observe, and how Christians read the history of Earth’s magnetic field.

OPTIONAL BOOKS AND RESOURCES

- **USGS Latest Earthquakes map** (https://earthquake.usgs.gov/earthquakes/map/): Free. A live world map of recent earthquakes from the U.S. Geological Survey. Use it in Lesson 1.1 to find an earthquake from the past day, see its depth and magnitude, and imagine its waves crossing the globe.
- **NOAA Magnetic Field Calculators** (https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml): Free. Enter your town or ZIP code to find your local declination and inclination and see how your declination has changed over the years (Lessons 1.3 and 1.4).
- **Jules Verne, *A Journey to the Centre of the Earth* (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/18857): Free. The 1864 adventure novel connected to the picture study in Lesson 1.1. Read a chapter aloud and compare Verne's imagined underworld with what seismic waves have revealed.

UNIT 1 · LESSON 1.1 · 2 SESSIONS OF 45 MINUTES

1.1 Seismic Waves Reveal the Core: Inge Lehmann, 1936

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OBJECTIVES

- Describe how P waves and S waves differ in their motion, their speed and the materials they can pass through.
- Explain how the S-wave and P-wave shadow zones show a liquid outer core, and how Inge Lehmann's 1936 study revealed a solid inner core.
- Use wave speeds to calculate travel times and the time gap between P-wave and S-wave arrivals.

Warm-up. Stretch a Slinky (or any long spring) along the floor with a partner holding the other end. First give your end one quick push forward and watch a bunched-up pulse race along the coils: that is like a P wave. Then flick your end sideways and watch a side-to-side wiggle travel: that is like an S wave. Which one seemed faster? No Slinky? Press your ear to one end of a wooden table while someone taps the far end gently with a spoon, then lift your head and listen again. Did the sound travel better through the wood or through the air?

Video. Coming soon. Inge Lehmann and the discovery of Earth's inner core; P waves, S waves and the seismic shadow zone (search USGS, EarthScope Consortium education animations, Smithsonian, SciShow, Science Max and university seismology channels).

KEY TERMS

seismic wave
A vibration that travels through the earth, usually sent out by an earthquake.

seismograph
An instrument that records ground shaking as a wiggly line marked with exact times.

P wave
Primary wave: the fastest seismic wave. It pushes and pulls rock in the direction it travels and can pass through solids, liquids and gases.

S wave
Secondary wave: a slower seismic wave that shakes rock from side to side. It can travel only through solids.

shadow zone
A region on Earth's surface, about 104° to 140° from an earthquake, where strong P waves do not arrive because the core bends them away.

inner core
The solid ball of iron and nickel at Earth's center, about 1,220 km in radius, discovered by Inge Lehmann in 1936.

CORE IDEAS

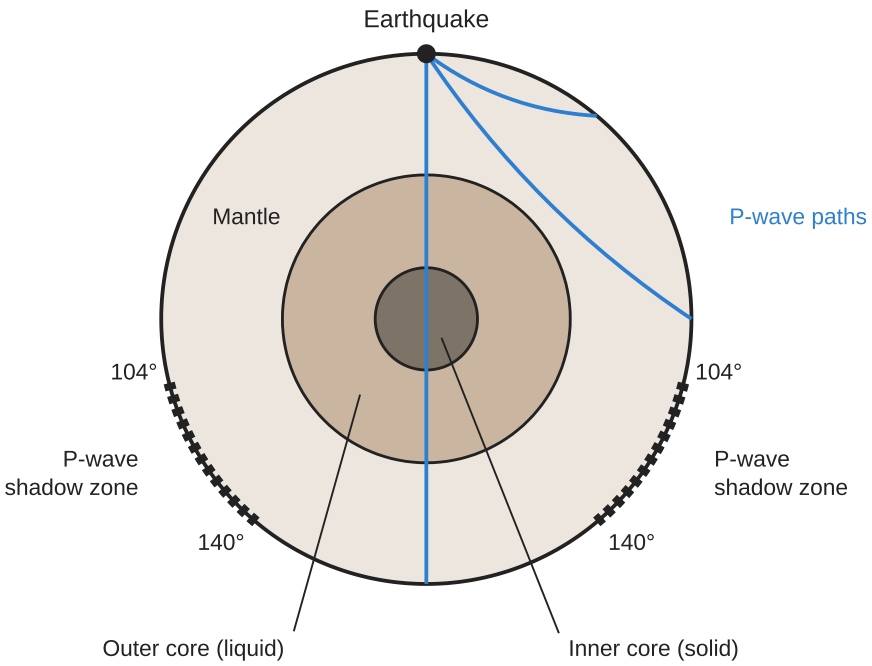
The story. In the early 1930s, in an office in Copenhagen, a Danish scientist named Inge Lehmann worked through stacks of paper records from earthquake stations around the world. Lehmann was head of the earthquake department of Denmark's Geodetic Institute, and one great earthquake puzzled her: a strong shock near Murchison, New Zealand, on June 17, 1929. New Zealand lies almost on the opposite side of the globe from Denmark. According to the best model of the day, some stations far from New Zealand should have recorded almost nothing from that earthquake. Yet faint waves had arrived there anyway. Lehmann copied the arrival times onto cards, which she famously kept in cardboard oatmeal boxes, and she checked them again and again. In 1936 she published a paper with one of the shortest titles in the history of science: just "P′" (say "P prime"). In it she proposed that Earth has a solid **inner core** hidden inside the liquid core.

How they figured it out. An earthquake shakes the ground and sends out **seismic waves**, vibrations that travel through the whole planet. A **seismograph** records the shaking as a wiggly line marked with the exact time. Two kinds of waves travel through Earth's inside. **P waves** (primary waves) push and pull the rock in the direction they travel, like a push passed along a Slinky. They are the fastest, and they can pass through solids, liquids and gases. **S waves** (secondary waves) shake the rock from side to side. They are slower, and they cannot travel through a liquid, because a liquid has no stiffness to spring back from a sideways shove. In 1914 the German scientist Beno Gutenberg calculated that a core begins about 2,900 km down. In 1926 the British scientist Harold Jeffreys argued that this core is liquid, because S waves never come through it to the far side of the world.

The big idea. Waves bend when they pass into material where their speed changes. This bending is called refraction, and light does it too when it passes into a glass of water. When P waves reach the liquid outer core, they slow down and bend sharply. That leaves a ring around the far side of Earth, from about 104° to about 140° away from the earthquake (measured as an angle at Earth's center), where strong P waves should not arrive. This ring is the **shadow zone**. Lehmann's faint waves landed right inside it. She saw that they made sense if a smaller, solid ball sat in the middle, where waves travel faster. Waves striking that inner ball would bounce and bend outward into the shadow zone. Today the inner core boundary is placed about 5,150 km deep, and the inner core is a ball of iron and nickel about 1,220 km in radius. In 1971, studies of how the whole earth rings like a bell after great earthquakes gave strong evidence that it really is solid.

In the world today. No one has ever drilled through even the crust; the deepest hole ever dug goes down only about 12 km. Nearly everything we know about the deep inside of the earth comes from careful timing like Lehmann's. Today the Global Seismographic Network, run by the U.S. Geological Survey and its partners, has about 150 stations around the world, and their records arrive within minutes. On the USGS earthquake map you can see dozens of earthquakes from the past day. Each one sends waves through the planet, and each one lets scientists look again at what lies beneath our feet.

God’s handiwork. When God asked Job, “Where wast thou when I laid the foundations of the earth?” (Job 38:4), Job had no answer. We were not there either. But God made a world that can be measured, and He gave people minds able to measure it. Lehmann never saw the inner core. She found it by patience: by timing faint wiggles on paper, sorting her cards, and refusing to ignore data that did not fit. That is how good science works, and it honors the Maker who set a ball of solid iron at the center of the world.



P waves bend at the liquid outer core, leaving a shadow zone from about 104° to 140° from the earthquake. S waves cannot cross the liquid outer core at all, so no S waves arrive beyond about 104°.

PICTURE STUDY

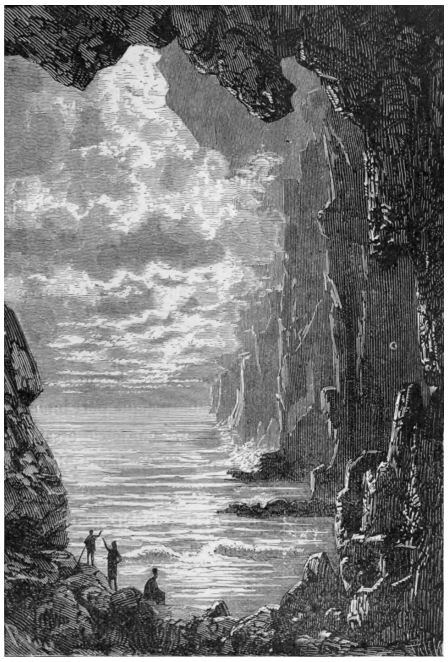


Illustration for Journey to the Center of the Earth, Édouard Riou, 1867 · Wood engraving (book illustration) · Published in Paris by Pierre-Jules Hetzel in the illustrated edition of Jules Verne’s novel; copies are held in many libraries

In 1864, seventy-two years before Lehmann’s paper, the French writer Jules Verne published *Journey to the Center of the Earth*. In the story, Professor Otto Lidenbrock, his nephew Axel and their Icelandic guide Hans climb down inside an extinct volcano in Iceland and find enormous caverns, an underground sea and strange creatures. The artist Édouard Riou made the engravings for the illustrated edition of 1867.

In the book, Axel worries that the inside of the earth must be terribly hot, and his uncle argues that it is not. Neither of them could measure it. Verne’s story is a wonderful adventure, but it is imagination. Lehmann and the seismologists found the real answer by listening to earthquake waves.

Look closely

- Find the people. How large do they look compared with the cavern around them?
- Look at the rock overhead. How does the artist make the cave feel deep and enormous?
- Where does the light in the picture seem to come from? What would really light a cave far underground?
- Find the lines the engraver used for water, rock and sky. How do the lines differ?

Talk about it

1. What did Verne imagine inside the earth? What did Lehmann actually find?
2. No explorer can climb down to the core. How do seismic waves let scientists “visit” it anyway?

3. Why is it important for scientists to test a good story against measurements?

> **Safety first.** Use a sturdy jar set on a towel, wipe up spills right away, and keep liquids away from outlets and electronics. Use an ordinary flashlight, never a laser pointer.

EXPERIMENT: BENDING LIGHT AROUND A MODEL CORE

Seismic waves bend when they enter rock or metal where their speed changes. Light does the same thing when it passes from air into water or oil. In this experiment a round jar of liquid stands in for Earth's core and a flashlight beam stands in for earthquake waves. You will test whether the kind of liquid changes how strongly the light bends.

Question: Does the kind of liquid in a round jar change how strongly light bends? **What we change:** the liquid (water or cooking oil). **What we keep the same:** the jar size, the flashlight, its distance, and the darkness of the room. **What we measure:** the distance from the back of the jar to the place where the light gathers into its narrowest, brightest stripe.

You will need

- Two identical round, straight-sided clear glasses or jars, about 6 to 8 cm across
- Water and cooking oil (vegetable or mineral oil), enough to fill one glass each
- A small flashlight (a phone light works)
- A stack of books to hold the flashlight level with the middle of the glass
- A white index card or sheet of paper folded so it stands up
- A metric ruler, a towel, and your lab notebook

Steps

1. Write the question in your notebook, then write your prediction: will oil or water bend the light more, or will they be the same?
2. In a dark room, set an empty glass on the towel. Place the flashlight on the books 30 cm in front of the glass, shining straight at its middle. Stand the white card just behind the glass.
3. Slowly slide the card away from the empty glass. Write down what the light on the card looks like.
4. Fill the first glass with water. Starting with the card touching the back of the glass, slide it away slowly until the light forms the narrowest, brightest vertical stripe. Measure the distance from the back of the glass to the card in centimeters.
5. Repeat the water measurement two more times and find the average.
6. Fill the second, identical glass with oil to the same height. Measure the distance to the brightest stripe three times and find the average.
7. Record your results in a table: Liquid, Trial 1, Trial 2, Trial 3, Average.
8. Look at the edges of the bright stripe. Notice the darker areas on each side, where little light lands. Compare them with the shadow zone in the diagram.

9. Write a conclusion of two or three sentences: Which liquid bent the light more? How do you know? How is this like P waves bending at the core?

Tips

- Light bends more when it slows down more. Light slows more in oil than in water, so oil should bring the stripe closer to the glass.
- If the stripe is hard to see, cover the flashlight with a card that has a thin slit cut in it.
- Keep the flashlight at exactly 30 cm each time; changing it would add a second variable.
- The analogy is not perfect: P waves *slow down* in the liquid outer core but *speed up* in the solid inner core. The lesson is that any change in speed bends a wave.

Check your work

- I can name what I changed, what I kept the same, and what I measured.
- I can explain why a round glass of liquid bends light.
- I can connect the bending of light to the bending of P waves at Earth's core.

FIELD NOTEBOOK

1. Draw two Slinkys. On one, show a P wave with bunched coils and an arrow along the spring. On the other, show an S wave with a side-to-side wiggle and an arrow across the spring. Label which is faster.
2. Draw a cross-section of Earth with an earthquake at the top. Shade the P-wave shadow zone on both sides and label 104° and 140°. Write one sentence explaining why S waves do not reach the far side.
3. Copy your light-bending data table into your lab notebook and add a bar graph of the average distance for water and for oil.

> **From history.** In 1971 Inge Lehmann received the William Bowie Medal, the highest honor of the American Geophysical Union, and she was the first woman to receive it. She kept studying earthquake waves long after she retired and lived to be 104, dying in 1993. Today the American Geophysical Union gives the Inge Lehmann Medal for important discoveries about the structure of Earth's mantle and core.

WORKED EXAMPLES

Example 1. An earthquake happens 210 km from a seismograph station. In the crust, P waves travel about 6 km/s and S waves about 3.5 km/s. How long after the earthquake does each wave arrive, and how many seconds apart are they?

1. Time = distance ÷ speed.
2. P wave: 210 km ÷ 6 km/s = 35 s.
3. S wave: 210 km ÷ 3.5 km/s = 60 s.
4. Gap: 60 s − 35 s = 25 s.

Answer: The P wave arrives after 35 s and the S wave after 60 s, so they are 25 s apart.

Example 2. A station records the S wave 10 s after the P wave. Using the same speeds (P 6 km/s, S 3.5 km/s), about how far away was the earthquake?

1. Each kilometer takes the P wave 1 ÷ 6 = 0.167 s and the S wave 1 ÷ 3.5 = 0.286 s.
2. So the S wave falls behind by 0.286 − 0.167 = 0.119 s for every kilometer.
3. Distance = 10 s ÷ 0.119 s per km ≈ 84 km.
4. Check: P takes 84 ÷ 6 = 14 s; S takes 84 ÷ 3.5 = 24 s; the gap is 10 s. ✓

Answer: About 84 km away. The longer the gap between P and S, the farther away the earthquake.

Example 3. The P-wave shadow zone runs from about 104° to about 140° from an earthquake. Earth's circumference is about 40,000 km. About how wide is the shadow zone, measured along the surface?

(Use the map or drawing "The shadow zone spans 36° of arc, about 4,000 km along the surface." shown earlier in this lesson.)

1. Width in degrees: 140° − 104° = 36°.
2. Kilometers per degree: 40,000 km ÷ 360° ≈ 111 km per degree.
3. Width: 36 × 111 km ≈ 4,000 km.

Answer: About 4,000 km wide, on each side of the globe, as a ring around the far side of the earth.

PRACTICE

1. EASY Which wave reaches a seismograph first, the P wave or the S wave? Why?
2. EASY Why can't S waves travel through Earth's outer core?
3. EASY Who discovered Earth's inner core, in what year, and what clue did she use?

4. MEDIUM A P wave travels through the crust at 6 km/s. How long does it take to travel 480 km?
5. MEDIUM A station is 420 km from an earthquake. P waves travel 6 km/s and S waves 3.5 km/s. How many seconds after the P wave does the S wave arrive?
6. MEDIUM Data reading. Five stations recorded the same large earthquake. Their distances (as angles from the earthquake) and what they recorded were:
   Station A, 40°: strong P, S recorded
   Station B, 90°: strong P, S recorded
   Station C, 115°: faint P only, no S
   Station D, 130°: faint P only, no S
   Station E, 155°: strong P, no S
   (a) Between which two stations do S waves stop arriving? (b) Which stations lie in the P-wave shadow zone? (c) What explains the faint P waves at those stations?
7. MEDIUM Data reading. A table gives travel times in the crust:
   100 km: P 17 s, S 29 s
   200 km: P 33 s, S 57 s
   300 km: P 50 s, S 86 s
   400 km: P 67 s, S 114 s
   (a) What is the S − P gap at 300 km? (b) Does the gap grow, shrink or stay the same with distance? (c) A station records a gap of 47 s. About how far away is the earthquake?
8. HARD Lehmann used records from many stations at different distances, not just one. Explain why one station would not have been enough to discover the inner core.
9. HARD Experiment design. A student wants to know whether a pulse travels faster along a Slinky when it is stretched more. Describe a fair test: the variable to change, two things to keep the same, what to measure, and how to make the result trustworthy.
10. CHALLENGE Earth’s radius is about 6,371 km and the inner core’s radius is about 1,220 km. (a) What fraction of Earth’s radius is the inner core? (b) Volume grows with the cube of the radius. About what fraction of Earth’s volume is the inner core?

COMMON MISTAKES

- Thinking the center of the earth is hollow or one big pool of lava. The outer core is liquid metal, but the inner core is solid iron and nickel, and the mantle is solid rock.
- Thinking seismic waves travel in straight lines. They bend whenever their speed changes, and that bending is what creates the shadow zone.
- Thinking scientists have drilled down to the mantle or core. The deepest hole is only about 12 km, a tiny scratch on a planet 6,371 km in radius. Our knowledge of the deep earth comes from waves.

Make it a game · Shadow Zone Call-Out. A parent calls out an angle from 0° to 180°. You answer which waves arrive at a station that far from the earthquake. From 0° to 104°: P and S. From 104° to 140°: no S and no strong P, only faint P waves from the inner

core. From 140° to 180°: P waves that passed through the core, but no S. Score a point for each correct answer and a bonus point if you explain why. Then switch roles.

Scripture. “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding.” (Job 38:4, KJV)

No person was there when God laid the earth’s foundations, and no person can travel to its center. Yet God made a world orderly enough to be measured, so careful, humble work like Lehmann’s can still uncover a little of what He made.

Practice answers

1. The P wave, because it is the fastest seismic wave.
2. The outer core is liquid. S waves shake material from side to side, and a liquid has no stiffness to spring back, so S waves cannot pass through it.
3. Inge Lehmann of Denmark, in 1936. She noticed faint P waves arriving inside the shadow zone, where none were expected, from earthquakes such as the 1929 New Zealand earthquake.
4. 480 km ÷ 6 km/s = 80 s.
5. P: 420 ÷ 6 = 70 s. S: 420 ÷ 3.5 = 120 s. The S wave arrives 50 s after the P wave.
6. (a) Between B (90°) and C (115°), which fits the S-wave limit of about 104°. (b) C and D, which lie between about 104° and 140°. (c) A solid inner core, where P waves speed up and are bent and reflected into the shadow zone, as Lehmann proposed.
7. (a) 86 − 50 = 36 s. (b) It grows with distance, by about 12 s for every 100 km. (c) The gap at 400 km is 114 − 67 = 47 s, so about 400 km.
8. One station only tells what arrives at one distance. To find a shadow zone and notice faint waves inside it, scientists must compare what arrives at many distances around the globe and see the pattern: strong waves here, almost none there, and faint waves where none were expected.
9. Change: how far the Slinky is stretched (for example 2 m and 3 m). Keep the same: the same Slinky, the same kind of push, the same smooth floor. Measure: the time for a pulse to travel the length (or several trips back and forth), then speed = distance ÷ time. Repeat each trial at least three times and average, or film it with a phone to time it more exactly.
10. (a) 1,220 ÷ 6,371 ≈ 0.19, about one-fifth of the radius. (b) 0.19 × 0.19 × 0.19 ≈ 0.007, less than 1 percent of Earth’s volume.

1.2 Crust, Mantle and Core: A Model of the Earth

OBJECTIVES

- Name Earth's four main layers in order, with their approximate depths, their state (solid or liquid) and what they are made of.
- Explain how Cavendish's measurement of Earth's density and the changing speeds of seismic waves led to the layered model, including Mohorovičić's discovery of 1909.
- Build and use a scale model of the earth and calculate layer thicknesses and ratios.

Warm-up. With an adult's help, cut a hard-boiled egg in half with the shell still on. Look closely at the shell, the white and the yolk. Try to measure the shell's thickness with a metric ruler. If the egg were the earth, which part would be the crust, the mantle and the core? Write down one thing the egg model gets right and one thing you think it gets wrong.

Video. Coming soon. Earth's layers (crust, mantle, outer core, inner core), the Moho, lithosphere and asthenosphere, and Cavendish's experiment to weigh the earth (search USGS, NASA, Smithsonian, EarthScope Consortium animations, SciShow, Homeschool Pop (Alternate) and Science Max).

KEY TERMS

crust
Earth's thin, rocky outer layer: about 5 to 10 km thick under the oceans and about 30 to 70 km thick under the continents.

Moho
Short for the Mohorovičić discontinuity: the boundary between the crust and the mantle, where seismic waves suddenly speed up.

mantle
The thick layer of hot, solid rock between the crust and the core, reaching down to about 2,900 km. It can flow very slowly.

outer core
The layer of liquid iron and nickel from about 2,900 km to 5,150 km deep.

lithosphere
The cold, rigid outer shell of the earth, made of the crust plus the top of the mantle, about 100 km thick and broken into plates.

asthenosphere
The hot, soft zone of the upper mantle just below the lithosphere. It is solid but can flow slowly, so the plates can move over it.

CORE IDEAS

The story. In the summer of 1798, in an outbuilding at his house on Clapham Common near London, the shy English scientist Henry Cavendish set out to weigh the world. His apparatus, first designed by his friend John Michell, was a wooden rod about 1.8 m long hung from a thin wire, with a small lead ball on each end. Two great lead balls, each weighing about 158 kg, were swung close to the small ones. Their gravity tugged the small balls ever so slightly, and the wire twisted. Cavendish watched from outside the room through a telescope so that the warmth of his own body would not stir the air. From that tiny twist he calculated that Earth, on average, is about 5.48 times as dense as water.

How they figured it out. That number was a clue. Ordinary surface rocks such as granite are only about 2.7 times as dense as water. If the whole earth were made of rock like that, its average would be near 2.7, not 5.5. So something much heavier must lie deep inside. Seismic waves later showed where. On October 8, 1909, an earthquake struck the Kupa Valley south of Zagreb, Croatia. The Croatian scientist Andrija Mohorovičić noticed that stations a few hundred kilometers away recorded two sets of P waves. He explained that some waves had dived into a deeper layer where they traveled faster, about 8 km/s instead of about 6 km/s, and came back up ahead of the others. The boundary he found at the bottom of the crust is still called the Mohorovičić discontinuity, or the **Moho**. Gutenberg located the top of the core in 1914, and Lehmann found the inner core in 1936. Every boundary showed up as a place where waves suddenly change speed.

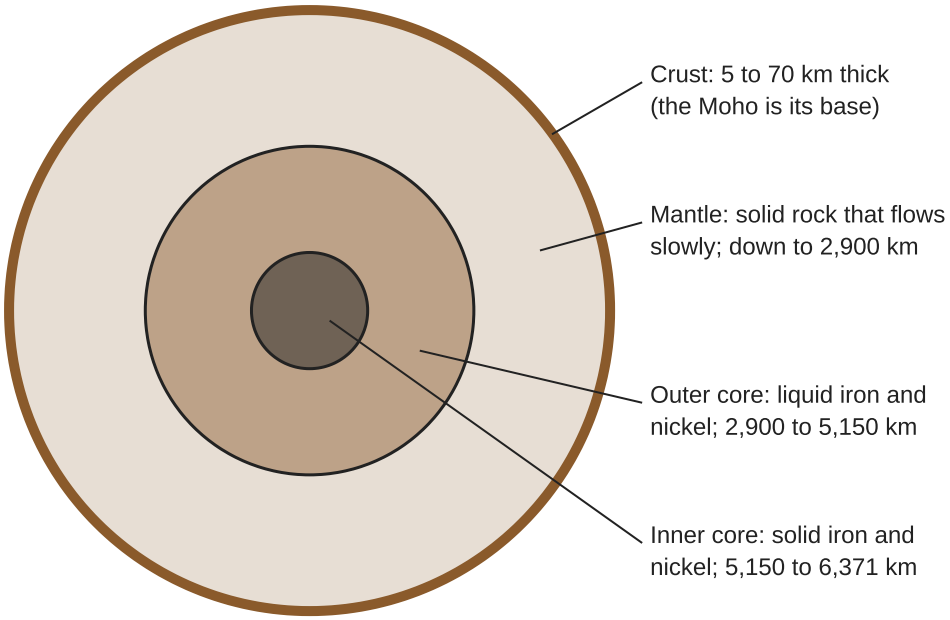
The big idea. Put together, the weighing and the waves give a model of Earth in layers, with the densest material at the center. The **crust** is the thin, rocky outer skin. Under the oceans it is dark basalt about 5 to 10 km thick; under the continents it is mostly lighter, granite-like rock about 30 to 50 km thick, and up to about 70 km thick under high mountains. The **mantle** reaches from the Moho down to about 2,900 km. It is hot rock rich in iron and magnesium, and it is solid, though it can creep and flow very slowly, like extremely stiff putty. The **outer core**, from about 2,900 to 5,150 km, is liquid iron mixed with nickel. The **inner core**, from 5,150 km to the center at about 6,371 km, is solid iron and nickel. It is hotter than 5,000 °C, close to the temperature of the sun’s surface, yet the crushing pressure of everything above squeezes it solid. Density climbs from about 3 g/cm³ in the crust to about 13 g/cm³ at the center.

In the world today. Geologists also sort the outer layers by how they behave. The crust and the very top of the mantle together make the **lithosphere**, a cool, rigid shell about 100 km thick that is broken into great plates (you will study them in Unit 2). Beneath it lies the **asthenosphere**, a hotter, softer zone of the upper mantle that can slowly flow, so the plates can move over it. People still try to reach deeper. The Kola Superdeep Borehole in far northern Russia, begun in 1970, reached 12,262 m in 1989. There the rock was about 180 °C, and the drill could go no farther. That is less than one five-hundredth of the way to the center.

Try it and see. A hard-boiled egg makes a handy model: the shell is the crust, the white is the mantle and the yolk is the core. But every model has limits. Compared with its size,

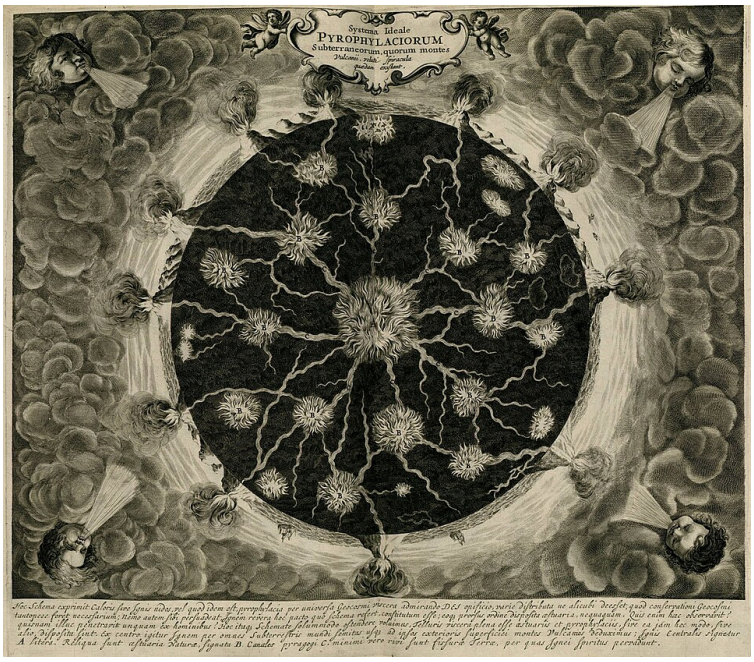
Earth’s crust is even thinner than an eggshell, and an egg has no liquid layer around a solid center. A good scientist uses a model and also says where it falls short.

God’s handiwork. “In his hand are the deep places of the earth” (Psalm 95:4). The layered earth is a well-ordered home: a thin crust to live and farm on, a solid mantle that bears the weight of the continents, and a core of moving liquid iron that, as the next lessons show, produces the magnetic field that guides compasses and helps shield the earth. The deep places are beyond our reach, but they are not beyond His.



Earth’s layers by composition and state. The crust is drawn much thicker than it really is so you can see it.

PICTURE STUDY



Ideal System of Underground Fire Chambers (Systema ideale pyrophylaciorum subterraneorum), Athanasius Kircher, 1664–1665 · Engraving, from the book *Mundus Subterraneus* (The Underground World) · Published in Amsterdam; copies are held in rare-book libraries

Athanasius Kircher was a German Jesuit priest and scholar who lived and taught in Rome. He wrote books on music, light, magnetism, languages and geology. In 1638 he traveled through southern Italy and Sicily and saw Etna and Vesuvius smoking, and he wrote that he had himself lowered into the crater of Vesuvius to look inside.

In *Mundus Subterraneus* he drew his model of the inside of the earth: a central fire joined by channels to fire chambers that feed the volcanoes. Another plate in the same book showed underground channels of water. Kircher built his model from what he could see at volcanoes and hot springs, but he had no way to test what lay deep below.

Look closely

- Find the fire at the center of the globe. Follow one channel of flame outward to a volcano on the surface.
- Is the inside of Kircher’s earth arranged in layers, or in branching channels?
- Compare this picture with the layers diagram in this lesson. What is at the center in each one?
- Find something Kircher got partly right.

Talk about it

1. Kircher was right that the inside of the earth is very hot. What did he get wrong?
2. Why could Kircher not test his model? What tool, invented much later, made testing possible?

3. What is the difference between a model drawn from guesses and a model built from measurements?

EXPERIMENT: HALLWAY EARTH AND THE SETTLING COLUMN

In Part A you will lay out the whole radius of the earth, from the surface to the center, along a hallway or driveway at a scale of 1 cm = 10 km. In Part B you will run a small experiment to see whether denser things settle below less dense things, the same sorting that put iron at Earth's center.

Part B question: Do denser materials settle lower in a column of liquids? **What we change:** the object dropped in. **What we keep the same:** the glass, the liquids and how gently we drop each object. **What we measure:** which layer each object comes to rest in.

You will need

- Part A: about 7 m of string, rope or adding-machine tape; a meter stick or tape measure; masking tape; colored markers or sidewalk chalk
- Part B: a tall clear glass; honey, dish soap, water (with a drop of food coloring) and vegetable oil, about 3 cm of each
- Small test objects: a steel nut or bolt, a grape, a plastic bottle cap, a piece of cork, a small piece of crayon
- Lab notebook and pencil

Steps

1. Part A. Tape one end of the string to the floor and label it SURFACE. At 1 cm = 10 km, mark these depths: ocean crust bottom, 7 km = 0.7 cm; continental crust bottom (the Moho), 35 km = 3.5 cm; deepest borehole, 12 km = 1.2 cm; base of the lithosphere, 100 km = 10 cm.
2. Keep going: base of the mantle, 2,900 km = 290 cm; base of the outer core, 5,150 km = 515 cm; the center, 6,371 km = 637 cm (6.37 m).
3. Color or label each section: crust, mantle, outer core (liquid), inner core (solid). Walk the whole length and notice how tiny the crust and the deepest hole look.
4. Part B. Write your prediction: where will each object come to rest?
5. Pour the liquids slowly into the glass in this order: honey, dish soap, colored water, oil. Pour each one down the side of the glass so the layers do not mix.
6. Gently drop in each object, one at a time. Wait one minute and record which layer it stopped in.
7. Make a table: Object, Predicted layer, Actual layer.
8. Write a conclusion: Did the densest objects settle lowest? How is this like Earth's iron core lying beneath a rocky mantle and crust?

Tips

- Drop objects gently and from the same height each time so that speed is not a second variable.
- If an object floats on the very top, it is less dense than oil.
- Your hallway model is a radius, from the surface to the center. The full earth would be twice as long, 12.74 m across.

Check your work

- I can name Earth’s four main layers in order with their approximate depths.
- I can place the Moho and the deepest borehole on a scale model.
- I can explain how density sorts materials, with the densest at the bottom or center.

FIELD NOTEBOOK

1. Draw a large cross-section of Earth and label the crust, Moho, mantle, outer core and inner core with their depths in kilometers. Color solid layers and the liquid layer differently.
2. Sketch Cavendish’s apparatus from the description: the hanging rod, the small balls, the large balls and the telescope outside the room. Label the force that made the wire twist.
3. Draw your settling column, label each liquid and object, and write one sentence about what it shows.

> **From history.** Before seismic waves could reveal the inside of the earth, people could only guess. In 1692 the English astronomer Edmond Halley, famous for his comet, suggested that the earth might be a set of hollow shells, one inside another, to explain why compass directions slowly shift over the years. His idea was a sincere attempt to fit the data he had, and it shows how models improve as new kinds of measurements arrive.

WORKED EXAMPLES

Example 1. You are making a poster cross-section at the scale 1 cm = 100 km. How far from the surface should you draw the bottom of the continental crust (35 km), the bottom of the mantle (2,900 km), the bottom of the outer core (5,150 km) and the center (6,371 km)?

(Use the map or drawing "The depths used in the scale model." shown earlier in this lesson.)

1. Divide each depth in kilometers by 100 to get centimeters.
2. Crust: 35 ÷ 100 = 0.35 cm (3.5 mm).
3. Mantle: 2,900 ÷ 100 = 29 cm.
4. Outer core: 5,150 ÷ 100 = 51.5 cm.
5. Center: 6,371 ÷ 100 = 63.7 cm.

Answer: Crust 0.35 cm, mantle bottom 29 cm, outer core bottom 51.5 cm, center 63.7 cm. The crust is only about the thickness of a pencil line.

Example 2. The Kola Superdeep Borehole reached 12,262 m (about 12.3 km). What fraction of the way to Earth's center (6,371 km) is that, as a percent? How long would the hole be on the 1 cm = 100 km poster?

1. Fraction: 12.3 km ÷ 6,371 km ≈ 0.0019.
2. As a percent: 0.0019 × 100 ≈ 0.19%, less than one-fifth of one percent.
3. On the poster: 12.3 ÷ 100 = 0.123 cm, about 1.2 mm.

Answer: About 0.19% of the way to the center; on the poster, a scratch only about 1 mm long.

Example 3. Cavendish found Earth's average density to be about 5.5 g/cm³. Granite, a common crust rock, is about 2.7 g/cm³. How many times denser is the average earth than granite, and what does that tell us?

1. Ratio: 5.5 ÷ 2.7 ≈ 2.0.
2. So the average earth is about twice as dense as granite.
3. Since the crust and most of the mantle are lighter than the average, then something deeper must be much heavier than 5.5 g/cm³ to bring the average up.
4. That fits an iron core with a density of about 10 to 13 g/cm³.

Answer: About 2 times denser. The inside of the earth must hold material much denser than surface rock, such as iron.

PRACTICE

1. EASY Name Earth’s four main layers in order from the surface to the center.
2. EASY Which layer of the earth is liquid? What is it made of?
3. EASY Which is thicker, ocean crust or continental crust? Give typical thicknesses.
4. MEDIUM The outer core runs from 2,900 km to 5,150 km deep. How thick is it? How thick is the inner core (from 5,150 km to the center at 6,371 km)?
5. MEDIUM Data reading. Approximate densities, in g/cm³:
   Crust: 2.7 to 3.0
   Mantle: 3.3 to 5.6
   Outer core: 9.9 to 12.2
   Inner core: 12.8 to 13.1
   (a) What pattern do you see from the crust to the center? (b) Between which two layers is the biggest jump in density? (c) About how many times denser is inner-core material than crust rock of 2.7 g/cm³?
6. MEDIUM Data reading. Approximate P-wave speeds at different depths:
   Lower crust, about 30 km: 6.5 km/s
   Just below the Moho, about 40 km: 8.1 km/s
   Bottom of the mantle, about 2,880 km: 13.7 km/s
   Top of the outer core, about 2,900 km: 8.1 km/s
   Top of the inner core, about 5,150 km: 11.0 km/s
   (a) At which boundary does the P-wave speed suddenly drop? (b) What does that drop tell us? (c) What does the jump at the Moho show?
7. MEDIUM Why is the inner core solid even though it is hotter than the liquid outer core?
8. HARD Many people think the mantle is a sea of liquid lava. Use evidence from seismic waves to explain why that is wrong.
9. HARD Experiment design. A student wants to test whether a heavier object always sinks lower in a settling column, or whether density matters more than weight. Describe an experiment with a variable to change, two things to keep the same, and what to measure.
10. CHALLENGE If the earth were shrunk to a ball with a radius of 12 cm (about the size of a basketball), how thick would a 35 km continental crust be? Compare it with a sheet of paper about 0.1 mm thick.

COMMON MISTAKES

- Thinking the mantle is liquid lava. The mantle is solid rock that can flow very slowly; only the outer core is liquid. Molten rock (magma) forms only in small pockets in the upper mantle and crust.
- Thinking the hottest layer must be liquid. The inner core is the hottest layer, yet it is solid because of the tremendous pressure.
- Thinking the crust is the same thickness everywhere, or that it is thick. It is thin, about 5 to 70 km, and thickest under mountains.

Make it a game · Layer Lineup. Write twelve fact cards, three for each layer, such as “liquid iron,” “where we live,” “5,150 km to 6,371 km,” “the Moho is its bottom,” or “solid but flows slowly.” Shuffle them. Race a timer to sort the cards into four piles: crust, mantle, outer core and inner core. Check your piles with the diagram. Then challenge a parent or sibling to beat your time.

Scripture. “In his hand are the deep places of the earth: the strength of the hills is his also.” (Psalm 95:4, KJV)

The deepest hole people have ever drilled barely scratches the crust, but the whole earth, down to its iron center, is in God’s hand.

Practice answers

1. Crust, mantle, outer core, inner core.
2. The outer core. It is liquid iron mixed with nickel.
3. Continental crust (about 30 to 50 km, up to 70 km under mountains) is thicker than ocean crust (about 5 to 10 km).
4. Outer core: 5,150 − 2,900 = 2,250 km. Inner core: 6,371 − 5,150 = 1,221 km, about 1,220 km.
5. (a) Density increases with depth. (b) Between the mantle (up to 5.6) and the outer core (from 9.9), a jump of about 4.3 g/cm³, because the material changes from rock to metal. (c) About 13 ÷ 2.7 ≈ 4.8, nearly 5 times denser.
6. (a) At the core-mantle boundary, about 2,900 km, from 13.7 to 8.1 km/s. (b) The waves have entered a very different material, the liquid outer core. (c) The waves enter denser, stiffer mantle rock below the crust, so they speed up. This is the boundary Mohorovičić found.
7. The pressure at the center is enormous because of the weight of everything above. That pressure squeezes the iron and nickel into a solid even at temperatures above 5,000 °C.
8. S waves, which cannot pass through liquids, travel through the whole mantle. So the mantle must be solid. It is hot and can flow very slowly like very stiff putty, but it is not liquid. Only the outer core stops S waves.
9. Change: use objects of the same weight but different densities (for example a small steel nut and a larger piece of wood or plastic of equal mass, checked on a kitchen scale). Keep the same: the same column of liquids and the same gentle drop from the same height. Measure: which layer each object stops in. If the equal-weight objects stop in different layers, density, not weight, decides where they settle.
10. Scale: 12 cm ÷ 6,371 km. Crust: 35 × 12 ÷ 6,371 ≈ 0.066 cm = 0.66 mm. That is only about 6 or 7 sheets of paper thick on a whole basketball.

1.3 Magnetism and the Compass

OBJECTIVES

- Describe magnetic poles, magnetic fields and how a compass works, including why the magnetic pole in the Arctic behaves like the south pole of a bar magnet.
- Tell how William Gilbert's terrella (1600) and James Clark Ross's visit to the north magnetic pole (1831) showed that the earth is a great magnet.
- Use declination to convert between a true (map) bearing and a compass bearing, and read simple data about magnetic strength.

Warm-up. Gather ten small things: a steel paper clip, an aluminum can, a copper-colored coin, a steel spoon, a wooden pencil, a key, a nail, a plastic button, a piece of foil and a staple. Predict which ones a refrigerator magnet will pick up or cling to, then test each one. Sort them into two piles. Were all the metal things attracted? What do the attracted ones have in common?

Video. Coming soon. How a compass works, Earth as a magnet, William Gilbert's terrella, magnetic declination and the north magnetic pole (search NOAA National Centers for Environmental Information, British Geological Survey, NASA, Smithsonian, SciShow Kids, Science Max and Moody Science classics).

KEY TERMS

magnet
An object that attracts iron, nickel and cobalt and has two poles: a north-seeking pole and a south-seeking pole.

magnetic field
The invisible region of magnetic force around a magnet, which can be mapped with iron filings or a small compass.

magnetic pole
A place where a magnet's force is strongest. On Earth, the magnetic poles are the places where a dip needle points straight down or straight up.

compass
A light, balanced magnetized needle that is free to turn and lines up with Earth's magnetic field.

declination
The angle between true (geographic) north and the direction a compass points. It differs from place to place and changes slowly over time.

inclination (dip)
The angle at which a freely hanging compass needle tilts below level: about 0° near the equator and about 90° at the magnetic poles.

CORE IDEAS

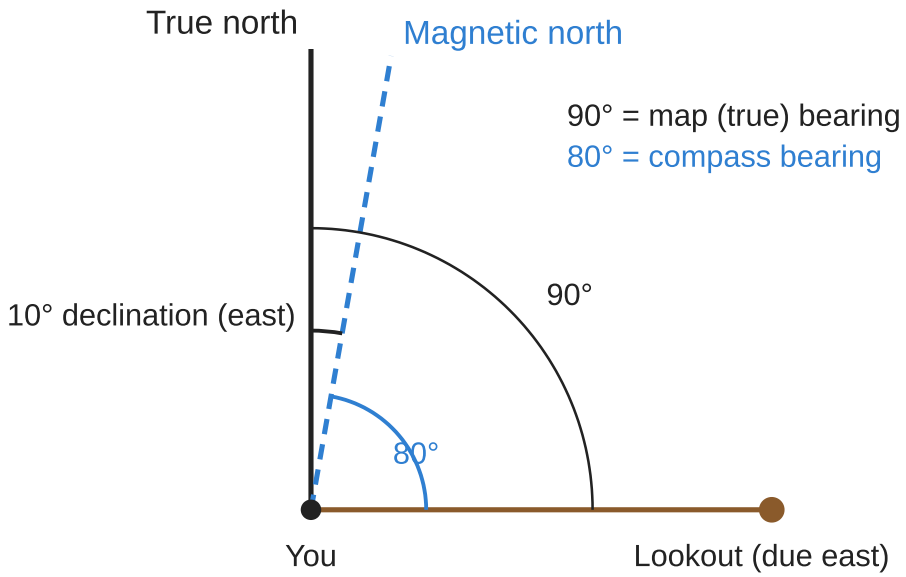
The story. On June 1, 1831, on the frozen Boothia Peninsula in the Canadian Arctic, a young British naval officer named James Clark Ross set up an instrument called a dip needle. A dip needle is a compass needle that can tilt up and down as well as turn. Ross's needle pointed almost straight down, within one-sixtieth of a degree of vertical. He had reached the **north magnetic pole**, the place where Earth's magnetism points straight into the ground. Ross and his uncle, Captain John Ross, had been trapped in the ice with their ship, the *Victory*, since the autumn of 1829, and they would not escape the Arctic until 1833. But the measurement they brought home helped confirm an idea that was more than two hundred years old.

How they figured it out. The idea came from William Gilbert, a physician to Queen Elizabeth I. People had used compasses for centuries: in 1088 the Chinese scholar Shen Kuo described a magnetized needle and noted that it did not point exactly north and south, and European sailors were steering by compass needles by about 1190. In 1581 Robert Norman, a London compass maker, found that a balanced needle tilts downward after it is magnetized. But no one knew why compasses behaved this way. Gilbert carved a ball out of lodestone, a natural magnetic rock, and called it a *terrella*, a "little earth." When he moved a tiny needle over it, the needle pointed toward the poles of the ball and tilted downward more and more as it neared a pole, just like Norman's needle. In 1600, in his book *De Magnete*, Gilbert concluded that the earth itself is a great magnet.

The big idea. Every **magnet** has two poles, a north-seeking pole and a south-seeking pole. Like poles push each other away, and unlike poles pull together. Around every magnet is a **magnetic field**, an invisible region of force that we can map with iron filings or a small compass. The field lines leave the magnet's north-seeking pole and loop around to enter its south-seeking pole. A **compass** is simply a light, balanced magnet that is free to turn, so it lines up with the field it sits in. Here is a surprise: because unlike poles attract, the magnetic pole in the Arctic, which pulls on the north-seeking end of every compass, behaves like the *south* pole of a bar magnet. Earth's field is weak, about 25 to 65 microteslas at the surface. A small refrigerator magnet, up close, is roughly a hundred times stronger. Yet Earth's field reaches around the whole planet and far out into space.

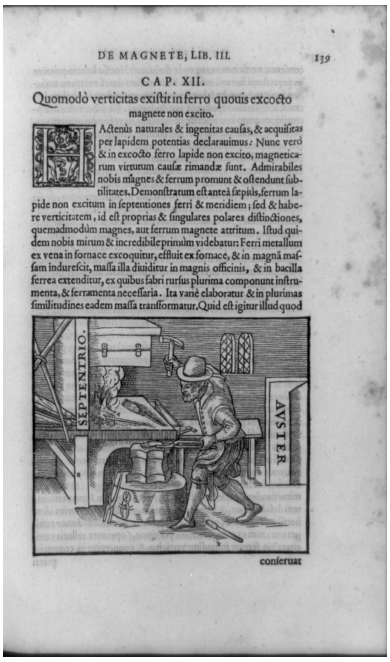
In the world today. The magnetic poles are not at the geographic poles, where Earth's axis comes out. So a compass usually does not point to true north. The angle between true north and the direction a compass points is called **declination**. In some places it is zero; in parts of the United States it is 15° or more, east or west, and everywhere it changes slowly over the years as the magnetic pole wanders. Hikers, sailors and pilots correct for it. NOAA and the British Geological Survey publish the World Magnetic Model, which phones, ships and aircraft use to make the correction automatically. A free-swinging needle also tilts toward the ground at an angle called **inclination**, or dip: about 0° near the equator and about 90° at the magnetic poles, just as Ross found. Even airports care: runway numbers come from their compass directions, so runways are sometimes renumbered when the declination shifts.

God's handiwork. Long before Gilbert, God had built compasses into living creatures. Scientists have found that sea turtles, many migrating birds and some fish can sense Earth's magnetic field and use it to find their way across oceans and continents. Job 26:7 says that God "stretcheth out the north over the empty place, and hangeth the earth upon nothing." The invisible field that turns the needle in your hand wraps around the whole earth, a quiet and faithful guide that He made.



Where magnetic north is 10° east of true north, a lookout at a map (true) bearing of 90° shows on the compass as 80°.

PICTURE STUDY



A Smith Forging Iron Along the North–South Line, from De Magnete, Unknown woodcut artist, for William Gilbert, 1600 · Woodcut, from the book *De Magnete* (On the Magnet) · Scanned from the copy of the 1600 London edition in the Library of Congress, Washington, D.C.; other copies are held in rare-book libraries

William Gilbert spent many years doing careful experiments with magnets before he published *De Magnete* in 1600. He insisted on testing ideas by experiment rather than repeating old stories, such as the tale that garlic could spoil a magnet. He tested that one and found it false.

This small woodcut shows one of his discoveries. A smith hammers a hot bar of iron that lies along the north–south line. Gilbert reported that iron worked this way becomes a weak magnet by itself. We now know why: Earth’s magnetic field lines up tiny regions inside the iron as it is hammered and cools.

Look closely

- Find the smith, the anvil and the bar of iron. Which way is the bar lying?
- Find the words that mark north and south. Why did the artist include them?
- Look at the smith’s hammer and arm. What moment did the artist choose to show?
- What tools in the smithy would a scientist today replace with modern instruments?

Talk about it

1. What did Gilbert discover about iron that is hammered while it points north and south?
2. Why is testing an idea better than repeating what people have always said?
3. How does this picture connect to the idea that the earth itself is a magnet?

> **Safety first.** Sewing needles are sharp: hold them by the middle and keep them in a labeled container. Keep strong magnets away from small children (swallowed magnets are very dangerous), away from pacemakers, and away from phones and bank cards. Wipe up spilled water.

EXPERIMENT: MAKE A FLOATING COMPASS AND TEST ITS STRENGTH

You will magnetize sewing needles, float one to make a working compass, and then test whether stroking a needle more times makes it a stronger magnet.

Question: Does stroking a needle with a magnet more times make it a stronger magnet? **What we change:** the number of strokes (10, 25 or 50). **What we keep the same:** identical needles, the same magnet, the same direction and speed of stroking. **What we measure:** the greatest distance, in centimeters, at which each needle makes a compass needle turn.

You will need

- Four identical steel sewing needles
- A strong refrigerator magnet or bar magnet
- A thin slice of cork, a plastic bottle cap or a small leaf
- A shallow bowl of water (not metal)
- A real compass for testing (or a phone compass app set to magnetic north)
- A metric ruler, masking tape, a marker and your lab notebook

Steps

1. Write the question and your prediction in your notebook.
2. Make the floating compass: stroke one needle 50 times along its length with one end of the magnet, always in the same direction, lifting the magnet away at the end of each stroke. Lay the needle on the cork and float it in the bowl, away from metal. Watch it turn. Compare it with the real compass. Which way does it settle?
3. Label the other three needles with tape flags: 10, 25 and 50. Stroke each one that many times, exactly as before.
4. Tape the ruler to the table so its 0 cm mark touches the side of the real compass, pointing east or west (across the needle).
5. Slide the 10-stroke needle slowly along the ruler toward the compass, point first. Record the distance at which the compass needle first moves.
6. Repeat for the 25-stroke and 50-stroke needles. Do three trials for each and find the average.
7. Record your data in a table: Strokes, Trial 1, Trial 2, Trial 3, Average distance (cm).
8. Make a bar graph of strokes versus average distance and write a conclusion: Did more strokes make a stronger magnet? Did the effect keep growing, or level off?

Tips

- Keep the magnet and the spare needles far from the compass during each test, or they will add a second variable.
- Many phone compasses show true north, not magnetic north. Check the setting before comparing.
- The floating needle points along Earth’s magnetic field, toward magnetic north and south, not exactly toward true north.

Check your work

- I can make a compass from a needle and explain why it turns.
- I can name the variable I changed, the ones I kept the same, and what I measured.
- I can describe my results with a table, a graph and a conclusion.

FIELD NOTEBOOK

1. Draw a bar magnet with its field lines, using arrows that leave the north-seeking pole and enter the south-seeking pole. Draw three small compasses around it, each pointing along a field line.
2. Draw the earth as a giant bar magnet tilted slightly from the spin axis. Label true north, magnetic north, and which pole of the inner “bar magnet” is near the Arctic.
3. Record your needle-strength data table and bar graph, and write a two-sentence conclusion.

> **From history.** Around 1190 an English scholar named Alexander Neckam wrote one of the earliest European descriptions of the compass. He explained that sailors touched a needle to a magnet, and when clouds hid the sun and the stars, the needle showed them which way the ship was heading. From that simple needle came the instruments that guided the great voyages of exploration.

WORKED EXAMPLES

Example 1. A map shows a fire lookout tower at a true bearing of 90° (due east) from you. The local declination is 10° east, meaning magnetic north is 10° east of true north. What bearing should you follow on your compass?

(Use the map or drawing “The 10° of declination is subtracted from the true bearing.” shown earlier in this lesson.)

1. A compass measures angles from magnetic north, not true north.
2. Magnetic north is already 10° around toward the east.
3. So the angle from magnetic north to the tower is 90° − 10° = 80°.
4. Rule: for east declination, compass bearing = true bearing − declination.

Answer: Follow a compass bearing of 80°.

Example 2. In another town the declination is 6° west. A trail leaves the parking lot at a true bearing of 45°. What compass bearing should you follow?

1. Here magnetic north is 6° west of true north.
2. Measured from magnetic north, the trail is 6° farther around: 45° + 6° = 51°.
3. Rule: for west declination, compass bearing = true bearing + declination.

Answer: Follow a compass bearing of 51°.

Example 3. Earth's magnetic field is about 60 microteslas (μT) near the magnetic poles and about 30 μT in parts of the tropics. A small refrigerator magnet produces about 5,000 μT right at its surface. (a) How many times stronger is Earth's field near the poles than in the tropics? (b) How many times stronger is the refrigerator magnet, up close, than an average Earth field of 50 μT?

1. (a) 60 μT ÷ 30 μT = 2.
2. (b) 5,000 μT ÷ 50 μT = 100.
3. The refrigerator magnet is far stronger up close, but its field fades within a few centimeters. Earth's field is weak but surrounds the whole planet.

Answer: (a) About 2 times stronger near the poles. (b) About 100 times stronger, but only very close to the magnet.

PRACTICE

1. EASY Fill in the blanks: Like magnetic poles _____ each other. Unlike poles _____ each other.
2. EASY What is declination?
3. EASY What did William Gilbert conclude in 1600, and what model did he use?
4. MEDIUM The declination is 12° east. A map bearing (true bearing) to a cabin is 180°. What compass bearing should you follow?
5. MEDIUM The declination is 8° west. Your compass shows a bearing of 100° to a hilltop. What is the true bearing you would draw on the map?
6. MEDIUM Data reading. A student moved a bar magnet toward a compass and recorded how far the compass needle turned from north:
   10 cm: 3°
   8 cm: 8°
   6 cm: 20°
   4 cm: 45°
   2 cm: 80°
   (a) Describe the pattern. (b) Predict the turn at 12 cm. (c) Why does the needle point north again when the magnet is far away?

7. MEDIUM Data reading. For a simple model of the earth as a bar magnet, the dip (inclination) of a compass needle at different magnetic latitudes is:
   0°: 0°
   20°: 36°
   40°: 59°
   60°: 74°
   80°: 85°
   (a) What happens to the dip as you move toward the magnetic pole? (b) What dip would you expect at 90°? (c) A sailor measures a dip of about 59°. About what magnetic latitude is the ship at?
8. MEDIUM In the early 2000s the north magnetic pole was moving about 50 km per year. At that rate, how far would it move in 15 years?
9. HARD Experiment design. A student thinks that objects near a compass can throw it off. Design an experiment to test which materials (a steel wrench, an aluminum pan, a wooden block, a glass jar) disturb a compass. Name what you change, what you keep the same and what you measure.
10. CHALLENGE A hiker's map shows a trail at a true bearing of 30°. The local declination is 14° west, but the hiker forgets to correct for it and simply walks on a compass bearing of 30° for 2 km. (a) What true direction did the hiker actually walk? (b) Pilots use the rule that 1° off course puts you about 1/60 of the distance off. About how far off the trail is the hiker?

COMMON MISTAKES

- Thinking a compass points to the geographic North Pole. It points along Earth's magnetic field, toward the magnetic pole, which is in a different place and slowly moves.
- Thinking the magnetic pole in the Arctic is the "north" end of Earth's magnet. Because it attracts the north-seeking end of a compass, it actually behaves like the south pole of a bar magnet.
- Thinking magnets attract all metals. Magnets attract iron, nickel, cobalt and steel, but not aluminum, copper, brass, gold or silver.

> **Make it a game · Compass Commands.** Stand in an open room or yard with a compass. A parent calls out a bearing such as 0°, 90°, 225° or 315°, and you turn to face it as quickly and accurately as you can. Score a point for being within 10°. Then play the declination round: the parent calls out a true bearing and a declination, such as "true 90°, declination 10° east," and you must work out and face the compass bearing (80°). Play to ten points.

> **Scripture.** "He stretcheth out the north over the empty place, and hangeth the earth upon nothing." (Job 26:7, KJV)

The earth hangs in space with nothing visible holding it, and an invisible magnetic field surrounds it. Both are reminders that God's ordering of creation goes far beyond what our

eyes can see.

Practice answers

1. Like poles repel (push away) each other. Unlike poles attract (pull toward) each other.
2. The angle between true (geographic) north and the direction a compass needle points (magnetic north).
3. He concluded that the earth itself is a great magnet. He used a terrella, a small ball carved from lodestone, and moved a tiny needle over it.
4. East declination: subtract. 180° − 12° = 168°.
5. For west declination, compass = true + 8°, so true = compass − 8° = 100° − 8° = 92°.
6. (a) The closer the magnet, the more the needle turns, and the effect grows very quickly at short distances. (b) Less than 3°, perhaps about 1°. (c) Far away, the bar magnet's field is weaker than Earth's field, so Earth's field controls the needle again.
7. (a) The dip increases. (b) 90°, straight down, as Ross found in 1831. (c) About 40°.
8. 50 km/year × 15 years = 750 km.
9. Change: the material placed near the compass. Keep the same: the same compass, on the same table, with each object at the same distance and on the same side, and no other metal nearby. Measure: how many degrees the needle turns from its starting direction. Repeat each test three times. (Expected: only the steel wrench turns the needle, because steel contains iron.)
10. (a) With west declination, true = compass − declination = 30° − 14° = 16°. (b) The hiker is 14° off: 14 ÷ 60 × 2 km ≈ 0.47 km, nearly half a kilometer off the trail.

1.4 Earth's Magnetic Field Is Getting Weaker

OBJECTIVES

- Describe how Earth's magnetic field has been measured since Gauss and read data showing that its main (dipole) part has grown weaker.
- Explain that the field is produced by electric currents in the liquid outer core, and compare the geodynamo explanation with the creationist model of rapid decay and rapid reversals.
- Calculate percent change, average rate of change and half-life steps, and explain why extending a trend into the past depends on assumptions.

Warm-up. Spin a top (or a coin on its edge) on a smooth table and time how long it spins. Do it three times and write down the times. Why does it slow down and stop? What would you have to do to keep it spinning forever? Write one sentence about anything else you know that runs down unless something keeps renewing it.

Video. Coming soon. Earth's magnetic field, its measured weakening, the South Atlantic Anomaly, magnetic reversals recorded in lava, and Gauss's first measurements (search the European Space Agency Swarm mission, NASA, NOAA National Centers for Environmental Information, British Geological Survey, Smithsonian and Moody Science classics).

KEY TERMS

dipole field
The main part of Earth's magnetic field, which acts like one giant bar magnet through the center of the earth. Its strength is called the dipole strength.

electric current
A flow of electric charge. Every electric current makes a magnetic field around it.

geodynamo
The mainstream explanation that churning liquid iron in the outer core acts like a natural generator, keeping Earth's electric currents and magnetic field going.

magnetic reversal
A change in which Earth's magnetic north and south swap places, so a compass would point the opposite way.

half-life
The time it takes for something that is decaying to fall to half its amount.

extrapolation
Extending a trend beyond the measured data, into the future or the past. It always assumes the trend keeps going the same way.

CORE IDEAS

The story. In 1832, in the university town of Göttingen, Germany, the great mathematician Carl Friedrich Gauss hung a magnetized steel bar from a fine thread and timed how fast it swung back and forth in Earth's field. Then he used the same bar to push a second needle aside and measured how far it turned. By combining the two experiments, Gauss found a way to measure the *strength* of Earth's magnetic field in absolute units, numbers that any scientist anywhere could check. With the physicist Wilhelm Weber he built a magnetic observatory, and in 1834 the two men began organizing observers in many cities to read their instruments at the same agreed moments. In 1839 Gauss used measurements from around the world to calculate the strength of the whole earth's magnet. With that, the long record of Earth's magnetic strength began.

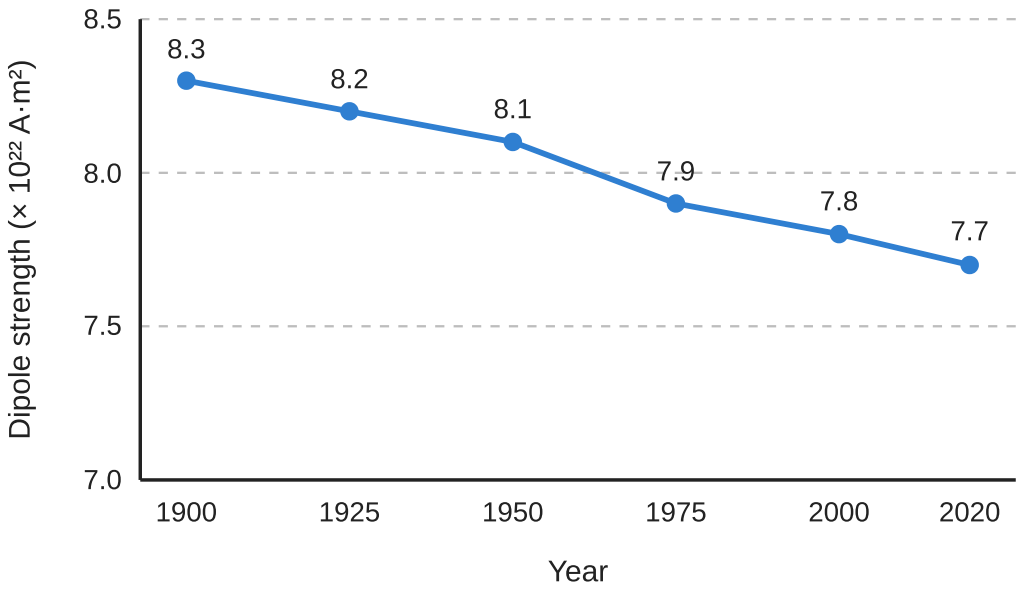
How they figured it out. Since Gauss, observatories, ships, airplanes and satellites have measured the field again and again. Scientists describe the main part of the field, the part that acts like one great bar magnet through Earth's center, by its **dipole strength**. That number has been going down. Rounded values from published models are about 8.3 units in 1900, 8.1 in 1950 and 7.7 in 2020 (the unit is 10^{22} ampere-square meters). The European Space Agency reports that the field has lost about 9 percent of its strength, on a global average, over the last 200 years. Over South America and the southern Atlantic Ocean lies an especially weak region called the South Atlantic Anomaly, where satellites passing overhead are hit by extra radiation.

The big idea. Earth's field does not come from a giant bar magnet; iron loses its magnetism above about 770 °C, and the core is far hotter than that. Instead the field is made by **electric currents** flowing in the liquid iron of the outer core. In 1820 the Danish scientist Hans Christian Ørsted found that an electric current turns a compass needle, and Michael Faraday later showed how moving conductors and magnetic fields produce currents. A current in a conductor meets resistance, and unless something keeps driving it, it dies away and turns its energy into heat, like a spinning top slowing down. Most geologists explain the field with a **geodynamo**: the churning liquid iron keeps regenerating the currents, so the field can rise and fall and even reverse, but it does not simply run down. Other scientists read the measurements differently. In 1973 the physicist Thomas Barnes of the University of Texas at El Paso argued that the field is simply running down, losing half its strength about every 1,400 years, so it could not have been running for an extremely long time. In 1984 the physicist D. Russell Humphreys proposed that God created the field strong, that it reversed rapidly during the Flood, and that it has decayed ever since. Using his model, he published predictions of the magnetic strengths of Uranus and Neptune, and when the Voyager 2 spacecraft measured them in 1986 and 1989, Humphreys pointed out that both fell within the broad ranges he had predicted.

In the world today. When lava cools, tiny grains of the mineral magnetite line up with Earth's field and lock in its direction, like frozen compass needles. Geologists have found many lava flows and seafloor rocks whose grains point the "wrong" way, showing that the field has **reversed** in the past. How fast can a reversal happen? At Steens Mountain in Oregon, the geologists Robert Coe and Michel Prévot studied lava that cooled while the field

was changing, and in 1989 and 1995 they reported that its direction seemed to swing by several degrees per day, astonishingly fast. Scientists still debate what that means. Meanwhile, the European Space Agency's three Swarm satellites, launched in 2013, map the field from orbit, and NOAA and the British Geological Survey update the World Magnetic Model every five years so that compasses, ships and phones stay accurate.

God's handiwork. Earth's magnetic field reaches tens of thousands of kilometers into space and turns aside much of the solar wind, the stream of charged particles that flows from the sun. Some of those particles are steered toward the poles, where they light up the glowing curtains of the aurora. The psalmist wrote that the earth and the heavens "shall wax old like a garment," but he said to God, "thou art the same, and thy years shall have no end" (Psalm 102:26–27). A field that is measurably weakening reminds us that creation does not run itself. God made it and God sustains it.



Earth's dipole strength, 1900 to 2020 (rounded values from published geomagnetic field models, in units of 10^{22} A·m²). The vertical axis starts at 7.0 to show the change clearly.

⏳ Thinking About Time

What the sign says. What the sign says: Textbooks say Earth's magnetic field has been produced by a geodynamo in the liquid outer core for more than 3 billion years, that it has reversed hundreds of times, and that the most recent full reversal happened about 780,000 years ago. They treat today's weakening as one of the field's normal ups and downs.

What we observe. What we observe: Since Gauss's first measurements in the 1830s, the main (dipole) part of the field has grown weaker, losing roughly 9 percent in about 200 years. Lava and seafloor rocks hold magnetic grains that point in reversed directions, and lava at Steens Mountain, Oregon, seems to record the field changing several degrees in a

day. No one measured the field directly before the 1830s; older values are worked out from rocks and pottery using assumptions.

How Christians read it. How Christians read it: Many creation scientists see the measured decline as a sign that the field is running down and cannot be extremely old. Following the physicists Thomas Barnes and D. Russell Humphreys, they propose that God created the field strong only thousands of years ago, that it reversed rapidly during the Flood year, when great amounts of lava and new seafloor formed quickly, and that it has been decaying ever since. Both sides agree on the measurements; they differ on what happened before anyone was measuring.

Try it. Graph the dipole strengths from this lesson, then extend two dotted lines into the past: a straight line, and a curve that doubles every 1,400 years. Notice how much the answer depends on which assumption you choose.

Psalm 102:25

PICTURE STUDY



Aurora Borealis, Frederic Edwin Church, 1865 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C.

Frederic Edwin Church was one of America’s great landscape painters. He painted *Aurora Borealis* using sketches and descriptions from his friend Isaac Israel Hayes, an Arctic explorer whose schooner spent the winter of 1860 to 1861 frozen in the ice off northwestern Greenland. Church himself had sailed among icebergs off Newfoundland and Labrador in 1859.

The aurora is one of the most beautiful signs of Earth's magnetic field. Charged particles from the sun are steered by the field toward the polar regions, where they strike the thin upper air and make it glow.

Look closely

- Find the ship. How does the painter show that it is trapped in the ice?
- Look at the shapes of light in the sky. Are they arches, curtains, rays or something else?
- Compare the dark cliffs and ice with the bright sky. Where does your eye go first?
- What colors did Church choose for the aurora?

Talk about it

1. Why do auroras usually appear near the poles and not at the equator?
2. How would it feel to spend a whole winter in the Arctic dark with only the stars and the aurora for light?
3. What does this painting suggest about the unseen magnetic field that surrounds the earth?

> **Safety first.** Nails are sharp: hold them by the middle. Drop the nail onto a hard floor away from feet and from anything breakable, and keep strong magnets away from small children, pacemakers, phones and bank cards.

EXPERIMENT: DOES A MAGNET RUN DOWN? THE DROPPED-NAIL TEST

A magnetized steel nail is a small magnet. Its magnetism comes from tiny regions in the metal that have been lined up. In this experiment you will see whether jolts can knock those regions out of line, so that the nail's magnetism fades, and you will graph the decline the way scientists graph Earth's field.

Question: Does dropping a magnetized nail make it a weaker magnet? **What we change:** the number of drops. **What we keep the same:** the same nail, the same drop height (1 m), the same hard floor, and the same staples. **What we measure:** how many staples the nail can lift.

You will need

- A large steel nail (about 8 to 10 cm long)
- A strong refrigerator magnet or bar magnet
- A small pile of loose staples (break a strip into single staples) or very small paper clips
- A meter stick, masking tape, graph paper and your lab notebook

Steps

1. Write the question and your prediction in your notebook.

2. Check that the nail is not already magnetized: dip it into the staples. It should pick up none.
3. Stroke the nail 50 times from head to point with one end of the magnet, always in the same direction, lifting the magnet away at the end of each stroke.
4. Dip the point of the nail into the staples, lift it slowly, and count how many staples it holds. Return them to the pile. Do this three times and record the average. This is the reading for 0 drops.
5. Hold the nail 1 m above a hard floor (use the meter stick) and drop it 5 times. Test it again three times and record the average.
6. Repeat until the nail has been dropped 10, 15, 20 and 25 times in all, testing after each set of 5.
7. Make a table: Total drops, Trial 1, Trial 2, Trial 3, Average staples. Then draw a line graph with drops on the horizontal axis and staples on the vertical axis.
8. Write a conclusion: Did the nail’s magnetism fade? Did it fade by the same amount each time, or by less as it got weaker? What would you have to do to restore it?

Tips

- Dip the nail to the same depth in the pile each time, so the test is fair.
- A nail is a permanent magnet that runs down when jolted. Earth’s field comes from electric currents instead, but both show the same lesson: stored magnetic energy fades unless something renews it.
- Compare the shape of your graph with the dipole graph in this lesson.

Check your work

- I can name the variable I changed, the ones I kept the same, and what I measured.
- I can draw and read a line graph of my results.
- I can explain why a magnet, or a magnetic field, can weaken unless something renews it.

FIELD NOTEBOOK

1. Copy the dipole strength values into a table and draw your own line graph of them. Label the axes with units and give the graph a title.
2. Draw a lava flow cooling, with small arrows for magnetite grains pointing along Earth’s field. Draw a second, older flow beneath it with arrows pointing the opposite way, and label it “reversed.”
3. Make a three-box chart titled “Thinking About Time” with the headings What the sign says, What we observe, and How Christians read it, and fill it in from memory.

> **From history.** In 1833 Gauss and Weber strung a wire about a kilometer long over the rooftops of Göttingen, from the observatory to Weber’s physics laboratory, and sent messages along it with electric currents and moving magnetic needles. It was one of the

first working electromagnetic telegraphs. A unit of magnetic field strength, the gauss, is named in Gauss's honor; Earth's field at the surface is about half a gauss.

WORKED EXAMPLES

Example 1. Earth's dipole strength was about 8.3 units in 1900 and about 7.7 units in 2020. Find the total drop, the percent drop and the average drop per year.

(Use the map or drawing "Read the 1900 and 2020 values from the graph." shown earlier in this lesson.)

1. Drop: 8.3 − 7.7 = 0.6 units.
2. Percent drop: 0.6 ÷ 8.3 = 0.072, which is about 7.2%.
3. Years: 2020 − 1900 = 120 years.
4. Average drop per year: 0.6 ÷ 120 = 0.005 units per year.

Answer: A drop of 0.6 units, about 7.2%, or 0.005 units per year on average.

Example 2. Thomas Barnes calculated in 1973 that the dipole strength was halving about every 1,400 years. If that rate is taken as constant, how much stronger would the field have been 1,400, 2,800 and 4,200 years ago, compared with today?

1. Going forward, each half-life cuts the strength in half. Going backward, each half-life doubles it.
2. 1,400 years ago: 1 half-life back, 2 times today.
3. 2,800 years ago: 2 half-lives back, 2 × 2 = 4 times today.
4. 4,200 years ago: 3 half-lives back, 2 × 2 × 2 = 8 times today.

Answer: 2 times, 4 times and 8 times as strong as today. This rests on the assumption that the decay rate stayed the same all that time.

Example 3. Suppose the dipole strength keeps falling at the average rate of 0.005 units per year found in Worked Example 1. Starting from 7.7 units in 2020, in about what year would it reach 7.2 units?

1. Drop needed: 7.7 − 7.2 = 0.5 units.
2. Years needed: 0.5 ÷ 0.005 per year = 100 years.
3. Year: 2020 + 100 = 2120.
4. This is an extrapolation. It is only as good as the assumption that the rate stays the same.

Answer: About the year 2120, if the rate does not change.

PRACTICE

1. EASY What produces Earth’s magnetic field?
2. EASY Who first measured the strength of Earth’s magnetic field in absolute units, and where and when?
3. EASY What is a magnetic reversal, and where do geologists find evidence of reversals?
4. MEDIUM If a field halves every 1,400 years, how many times stronger would it have been 5,600 years ago, assuming a constant rate?
5. MEDIUM Data reading. Earth’s dipole strength (rounded, in units of 10^{22} A·m²):
   1900: 8.3
   1925: 8.2
   1950: 8.1
   1975: 7.9
   2000: 7.8
   2020: 7.7
   (a) Which 25-year period had the largest drop? (b) What was the total drop from 1900 to 2020? (c) Did the strength go up in any period?
6. MEDIUM Data reading. A student ran the dropped-nail test and recorded these averages:
   0 drops: 12 staples
   5 drops: 9 staples
   10 drops: 7 staples
   15 drops: 6 staples
   20 drops: 5 staples
   (a) What percent of its lifting power did the nail lose after 10 drops? (b) Did it lose the same number of staples every 5 drops? (c) Predict the result after 25 drops.
7. MEDIUM Why can’t Earth’s magnetic field come from a giant permanent magnet in the core?
8. HARD One student extends the 1900 to 2020 trend backward as a straight line. Another extends it as halving steps (doubling each 1,400 years going back). Explain why their answers for the field strength long ago are different, and what this teaches about extrapolation.
9. HARD Experiment design. Design a safe experiment to test whether temperature affects how strong a refrigerator magnet is. Name what you change, what you keep the same, and what you measure.
10. CHALLENGE In four or five sentences, explain how mainstream geologists and creation scientists each explain the weakening of Earth’s magnetic field, and name one observation that both must account for.

COMMON MISTAKES

- Thinking Earth’s field comes from a giant permanent bar magnet. The core is far too hot for that; the field comes from electric currents in liquid iron.
- Thinking a magnetic reversal means the earth flips over or the North Pole moves to the south. Only the magnetic field reverses; the earth keeps spinning on the same axis.

- Thinking the weakening field is an emergency. It changes slowly over many years, compasses still work, and scientists update the World Magnetic Model every five years to keep navigation accurate.

Make it a game · Halving Ladder. Draw a ladder with eight rungs on a sheet of paper. The bottom rung is "today, strength 1." Each rung up is 1,400 years earlier and doubles the strength. Take turns rolling a die and climbing that many rungs; to stay on your rung you must say the years back and the strength correctly (for example, rung 3: 4,200 years, strength 8). Miss and you slide back down one rung. The first to the top rung must also name one assumption behind the ladder to win.

Scripture. "Of old hast thou laid the foundation of the earth: and the heavens are the work of thy hands. They shall perish, but thou shalt endure: yea, all of them shall wax old like a garment; as a vesture shalt thou change them, and they shall be changed: But thou art the same, and thy years shall have no end." (Psalm 102:25–27, KJV)

Things in creation wear out, like a garment. God does not. A slowly weakening magnetic field is one small example of a world that depends on its Maker.

Practice answers

1. Electric currents flowing in the liquid iron of the outer core.
2. Carl Friedrich Gauss, in Göttingen, Germany, in 1832.
3. A reversal is when Earth's magnetic north and south swap places. Evidence is found in lava flows and seafloor rocks whose magnetite grains point in the opposite direction from today's field.
4. 5,600 ÷ 1,400 = 4 half-lives. 2 × 2 × 2 × 2 = 16 times stronger.
5. (a) 1950 to 1975, a drop of 0.2 units. (b) 8.3 − 7.7 = 0.6 units. (c) No; it went down in every period shown.
6. (a) It went from 12 to 7, a loss of 5 staples: 5 ÷ 12 ≈ 42%. (b) No. It lost 3, then 2, then 1, then 1: the loss slowed as the nail got weaker. (c) About 4 or 5 staples.
7. Iron loses its permanent magnetism above about 770 °C, and the core is thousands of degrees hotter than that. So the field must come from electric currents instead.
8. A straight line adds the same amount for every year back, while halving steps multiply, so the doubling curve rises much faster the farther back you go. Both fit the short measured record, but they give very different answers outside it. Extrapolation depends on assumptions about how the rate behaved when no one was measuring.
9. Change: the magnet's temperature (for example, from the freezer, at room temperature, and after sitting in warm tap water in a sealed bag). Keep the same: the same magnet, the same staples or paper clips, the same way of testing, and testing right after removing it. Measure: how many staples or paper clips the magnet can hold, three trials each, then compare the averages.
10. Mainstream geologists say a geodynamo of churning liquid iron in the outer core keeps renewing the field, so the present weakening is a normal fluctuation in a field that has lasted billions of years and reversed many times. Creation scientists such as Barnes and Humphreys say the field is running down because its electric currents lose energy, so it began strong only thousands of years ago and reversed rapidly during the Flood. Both must account for the

measured loss of about 9 percent in 200 years and for reversed magnetism in lava rocks, including the rapid changes recorded at Steens Mountain. They agree on the measurements but differ on the assumptions about the unmeasured past.

Unit 1 review

Answer each question. Show your work for calculations and use complete sentences for explanations. For multiple choice, write the letter of the best answer. The test is worth 60 points.

1. (4 pts) Which seismic wave cannot travel through a liquid? (a) P wave (b) S wave (c) both P and S waves (d) neither
2. (5 pts) A seismograph station is 280 km from an earthquake. P waves travel 6 km/s and S waves 3.5 km/s. When does each wave arrive, and how far apart are they?
3. (5 pts) Explain how Inge Lehmann discovered the inner core in 1936. Use the words shadow zone and P waves.
4. (4 pts) Which layer of the earth is liquid? (a) crust (b) mantle (c) outer core (d) inner core
5. (8 pts) Diagram. Draw a circle as a cross-section of the earth and label the crust, the Moho, the mantle, the outer core and the inner core. Write the depth of each lower boundary (bottom of the mantle, bottom of the outer core, the center) in kilometers, and mark each layer “solid” or “liquid.”
6. (5 pts) In 1798 Henry Cavendish found that the earth’s average density is about 5.5 g/cm³. Surface rock such as granite is about 2.7 g/cm³. What does this tell us about the inside of the earth? Show a calculation.
7. (4 pts) The north-seeking end of a compass needle points toward (a) the geographic North Pole exactly (b) the magnetic pole in the Arctic, which behaves like the south pole of a bar magnet (c) the sun (d) the North Star
8. (5 pts) The local declination is 15° east. Your map shows a campsite at a true bearing of 270° (due west). What compass bearing should you follow? Explain.
9. (5 pts) What did William Gilbert’s terrella (1600) and James Clark Ross’s dip needle (1831) each show about the earth?
10. (6 pts) Earth’s dipole strength was about 8.1 units in 1950 and about 7.7 units in 2020. Find (a) the drop, (b) the percent drop and (c) the average drop per year.
11. (5 pts) If Earth’s field halved every 1,400 years, how many times stronger would it have been 7,000 years ago? Name the assumption your answer depends on.
12. (4 pts) Fill in a “Thinking About Time” box for Earth’s magnetic field: one sentence each for What the sign says, What we observe, and How Christians read it.

Unit project: inside the earth: scale model and lab notebook

Make a large poster cross-section of the earth at a scale you choose and state (for example, 1 cm = 100 km). Show the crust, the Moho, the mantle, the outer core and the inner core at their correct scaled depths, mark the P-wave shadow zone, and draw Earth’s magnetic field lines around the outside. Beside the poster, include your floating compass, your lab notebook pages from the three experiments (light bending, needle strength, and the dropped nail), your graph of Earth’s dipole strength, and a one-paragraph “Thinking About Time” box on the magnetic field.

- **Accuracy**: Layers, boundaries, depths, the shadow zone and field lines are correct and drawn to the stated scale.
- **Experiments and data**: Each experiment states its question, variables and measurements, with complete data tables, averages and labeled graphs.
- **Explanation**: Written explanations correctly use P and S waves, density, magnetism and declination, and the Thinking About Time box is fair to both readings.
- **Care**: The poster and notebook are neat, labeled in metric units, and easy to read.

Answer key

1. (b) S wave.
2. P: 280 ÷ 6 ≈ 46.7 s. S: 280 ÷ 3.5 = 80 s. The S wave arrives about 33.3 s after the P wave.
3. The liquid outer core bends P waves so that a shadow zone, about 104° to 140° from an earthquake, should receive no strong P waves. Studying records such as those of the 1929 New Zealand earthquake, Lehmann found faint P waves arriving inside the shadow zone. She explained them by a solid inner core, where P waves speed up and are bent and reflected into the shadow zone.
4. (c) outer core.
5. Thin crust on the outside with the Moho at its base (about 5 to 70 km); solid mantle down to about 2,900 km; liquid outer core from 2,900 to 5,150 km; solid inner core from 5,150 km to the center at about 6,371 km. Award 1 point for each of the five labels in the right order and 1 point each for the three depths.
6. 5.5 ÷ 2.7 ≈ 2, so the average earth is about twice as dense as surface rock. Since the crust and most of the mantle are lighter than 5.5 g/cm^3, the deep interior must be much denser, which fits a core of iron and nickel (about 10 to 13 g/cm^3).
7. (b).
8. With east declination, magnetic north is 15° east of true north, so subtract: 270° − 15° = 255°.
9. Gilbert’s terrella, a lodestone ball, made a small needle point to its poles and dip more steeply near them, just as compasses behave on the earth, so he concluded the earth is a great magnet. Ross’s dip needle pointed almost straight down on the Boothia Peninsula, showing he had reached the north magnetic pole, where the field points straight into the ground.
10. (a) 8.1 − 7.7 = 0.4 units. (b) 0.4 ÷ 8.1 ≈ 0.049, about 4.9%. (c) 0.4 ÷ 70 years ≈ 0.0057 units per year.
11. 7,000 ÷ 1,400 = 5 half-lives; 2 × 2 × 2 × 2 × 2 = 32 times stronger. It assumes the decay rate stayed the same the whole time.
12. Sign: textbooks say a geodynamo has kept the field going for billions of years, with many reversals, the last about 780,000 years ago. Observe: the dipole field has weakened about 9% in 200 years, and lava rocks record reversals, some apparently very rapid. Reading: many creation scientists say the field was created strong thousands of years ago, reversed rapidly during the Flood, and has been decaying since.

UNIT 2

Plates

Look at a world map and the coasts of South America and Africa seem to call to each other across the Atlantic. In 1858 a French geographer drew them together and then apart and said the Flood had split them. In 1912 a German weather scientist named Alfred Wegener gathered fossils, rock belts and ice scratches to argue that all the continents had once been one land, and he was laughed at for fifty years. In this unit you will follow that idea from a mapmaker's guess to a measured fact, and you will measure it yourself: today GPS shows the Atlantic widening by about 2.5 centimeters a year, roughly as fast as your fingernails grow.

You will cut out the continents and measure how well they fit, model all three kinds of plate boundary with crackers and frosting, and learn where ridges, trenches, volcanoes and faults form and why. You will stand, in a painting, on the floor of the rift valley at Þingvellir where Icelanders have met for a thousand years, and you will trace the earthquakes that mark a plate sinking into the mantle.

Finally you will meet a geophysicist who asked what the Flood of Genesis would have done to the plates, and you will learn to read a museum sign with care: to spot the measurement, spot the assumption behind the long age, and state both the mainstream reading and the young-earth reading fairly. "In the beginning God created the heaven and the earth" (Genesis 1:1), and He laid its foundations so firmly that we can measure them.

BEFORE YOU BEGIN

- Knows the crust, mantle and core model of the earth from Unit 1
- Can multiply and divide decimals and convert between millimeters, centimeters, meters and kilometers
- Can read a world map, find the continents and use a map scale
- Can find the average of a short list of measurements

MASTERY CHECKLIST

- I can tell how Snider-Pellegrini (1858) and Wegener (1912) argued that the continents were once joined, and why most geologists rejected the idea until the ocean floor was mapped.
- I can name four kinds of evidence that the continents fit together and explain why several independent clues are stronger than one.
- I can name the three types of plate boundary, give a real example of each, and describe what forms there.
- I can use a plate speed in centimeters per year to calculate a distance or a time, and compare two rates as a ratio.
- I can describe the catastrophic plate tectonics model in order and explain the assumption that turns a measured rate into an age.

- I can state what a museum sign says, what is actually observed, and how Christians read it, fairly and without mocking either side.

OPTIONAL BOOKS AND RESOURCES

- ***This Dynamic Earth: The Story of Plate Tectonics*** **(USGS online book)** (https://pubs.usgs.gov/gip/dynamic/dynamic.html): Free. A clear, well-illustrated government booklet on Wegener, the ocean floor and the three boundary types. Parents should note that it gives mainstream ages; use it alongside Lesson 2.4 to practice spotting the assumption behind them.
- **USGS Latest Earthquakes map** (https://earthquake.usgs.gov/earthquakes/map/): Free. Turn on the plate boundaries layer in the settings and watch the dots of recent earthquakes outline the plates, just as they did for scientists in the 1960s.
- **Smithsonian Global Volcanism Program** (https://volcano.si.edu/): Free. A world map and database of volcanoes. Compare the volcano map with the earthquake map and find the Ring of Fire.

2.1 Snider-Pellegrini's Map (1858) and Wegener's Idea (1912) ★

OBJECTIVES

- Tell how Antonio Snider-Pellegrini (1858) and Alfred Wegener (1912) each argued that the continents were once joined, and name the evidence each one used.
- Explain why most geologists rejected continental drift for about fifty years and what ocean-floor discoveries changed their minds.
- Use a rate in centimeters per year to calculate how far a plate moves in a given time, and convert between centimeters, meters and millimeters.

Warm-up. Open an atlas or pull up a world map and lay a sheet of tracing paper (or thin printer paper) over it. Trace the east coast of South America. Move the paper and trace the west coast of Africa beside it. Now slide the two tracings toward each other until they nearly touch. Write one sentence: do they fit like puzzle pieces, roughly, or not at all? Keep the tracing for Lesson 2.2.

Video. Coming soon. Alfred Wegener and the history of the continental drift idea, Pangaea and its evidence; search USGS, Smithsonian, SciShow, Homeschool Pop (Alternate), Crash Course Kids style explainers and documentary footage of Wegener's Greenland expeditions.

KEY TERMS

continental drift
Wegener's hypothesis that the continents were once joined in one landmass and have since moved apart.

Pangaea
The name Wegener gave the supercontinent, from Greek words meaning "all land."

supercontinent
A single huge landmass made of most or all of the earth's continents pressed together.

hypothesis
A careful explanation of something observed that can be tested by further observations or experiments.

evidence
Observations and measurements that support or go against a hypothesis.

rate
An amount of change per unit of time, such as centimeters per year or millimeters per day.

CORE IDEAS

The story. In 1858 a French geographer named **Antonio Snider-Pellegrini** published a book in Paris whose title in English is *Creation and Its Mysteries Unveiled*. Inside were two small maps printed side by side. In the first, the Americas are pressed snugly against Europe and Africa, with no Atlantic Ocean between them. In the second, the continents have pulled apart and the ocean lies open. Snider-Pellegrini had noticed two things. The coastlines fit, and the fossil plants in the coal beds of Europe matched the fossil plants in the coal beds of North America. He concluded that the continents had once been one piece of land and had been torn apart suddenly during the Flood of Noah's day. Hardly anyone paid attention. He was not even the first to wonder about the fit. Back in 1596 the Flemish mapmaker Abraham Ortelius had written that the Americas looked as if they had been torn away from Europe and Africa by earthquakes and floods.

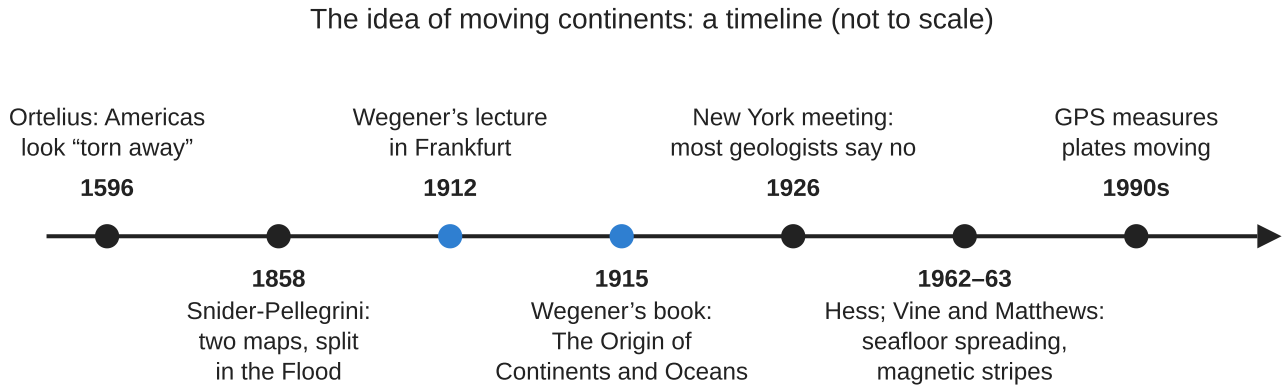
How they figured it out. The idea came back with force in Germany. **Alfred Wegener** (VAY-guh-ner), born in Berlin in 1880, was a meteorologist, a scientist of weather. He and his brother Kurt once stayed aloft in a balloon for more than 52 hours to study the air, a record at the time, and he had spent two years in Greenland on a Danish expedition. In 1910, looking at a world atlas, he was struck by how neatly the east coast of South America fits the west coast of Africa. The next year he read a report listing the same fossil animals and plants on both sides of the Atlantic. Geologists explained the match with land bridges that had supposedly sunk beneath the sea. Wegener thought a simpler answer was that the lands themselves had been joined. On January 6, 1912, he presented his hypothesis of **continental drift** to the Geological Association in Frankfurt, and in 1915 he published a book, *The Origin of Continents and Oceans*. He pictured all the continents gathered into one **supercontinent**, which he named **Pangaea**, from Greek words meaning "all land."

The big idea. A **hypothesis** is a careful explanation that can be tested, and **evidence** is what you can observe and measure to test it. Wegener gathered four kinds of evidence: the fit of the coasts, matching fossils, matching belts of rock that end at one shore and begin again across the ocean, and clues about past climate such as scratches left by glaciers in lands that are warm today. What he could not supply was a cause. He suggested that the continents plowed through the ocean floor like ships, pushed by the tides and by a force that made them flee the poles. Physicists calculated those forces and found them millions of times too weak. At a meeting in New York in 1926, most American geologists rejected drift. Wegener died in 1930 on the Greenland ice, carrying supplies to a weather station, and his idea went into the shadows for thirty years.

In the world today. The evidence that finally turned the tide came from the ocean floor. In the 1950s, ship soundings mapped a great mountain chain running down the middle of the Atlantic, with a deep valley along its crest. In 1962 Harry Hess proposed that new ocean floor forms at that ridge and spreads away on both sides, and in 1963 the pattern of magnetic stripes in the seafloor rock matched that idea. By the late 1960s geologists had put the pieces together as **plate tectonics**. Wegener had the right conclusion but the wrong picture. Continents do not plow through the ocean floor. Instead, whole plates of rock, carrying continents and ocean floor together, move as one. Today the Global Positioning

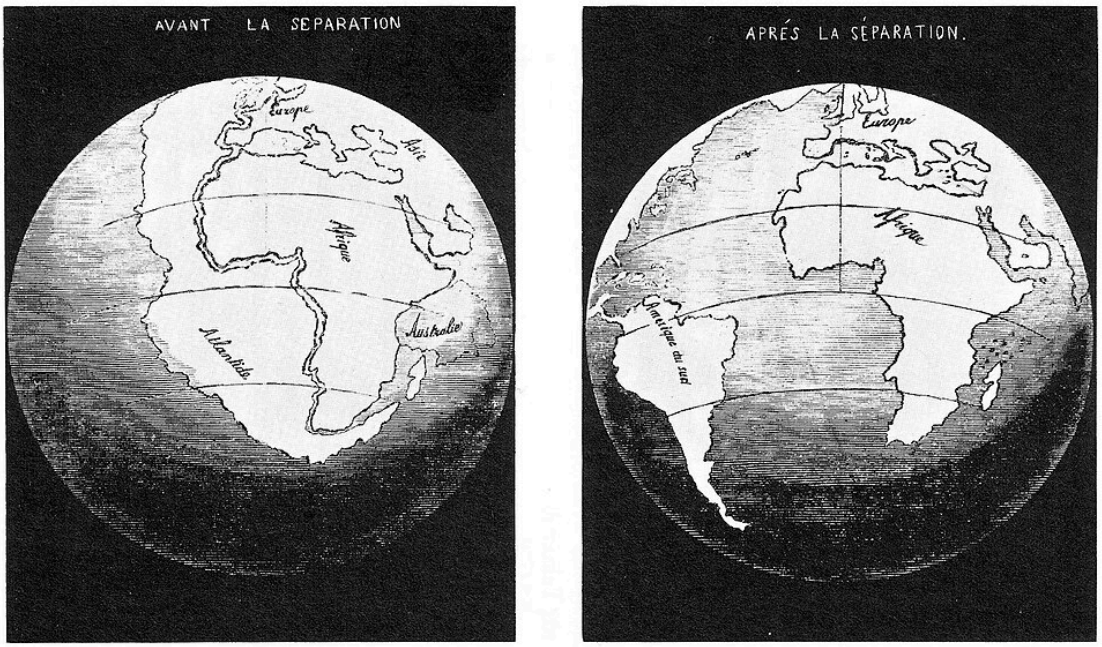
System (GPS) measures that motion directly. The Atlantic is widening by about 2.5 centimeters per year, a **rate** the U.S. Geological Survey compares to the speed your fingernails grow.

God's handiwork. Snider-Pellegrini read Genesis as well as maps, and he was right that the shapes of the continents tell a story about the earth's past. Wegener was right that the story was written in fossils and rock. Both men were laughed at or ignored, and both kept careful records anyway. The Bible says of God, "Who laid the foundations of the earth, that it should not be removed for ever" (Psalm 104:5). The earth is firm enough to build on and ordered enough to measure, yet its plates are moving beneath our feet. A patient observer who writes down what he sees, even when others disagree, is doing what a scientist and a Christian should both do: telling the truth about what God has made.



The idea of moving continents took almost four hundred years to go from a mapmaker's guess to a measured fact. The spacing is not to scale.

PICTURE STUDY



The Opening of the Atlantic (two maps from Creation and Its Mysteries Unveiled), Antonio Snider-Pellegrini, 1858 · Engraved book plate · Printed in Paris in 1858; copies survive in libraries and the plate is reproduced in many geology textbooks

This is the picture that started our unit. Snider-Pellegrini drew the Atlantic shut and then drew it open. He was a geographer, not a famous geologist, and his book was little read. Yet the two globes he engraved say in one glance what Wegener would spend a lifetime arguing with words.

Look at it as a scientist would. A drawing like this is a hypothesis, not proof. It asks a question: do these shapes really fit, and if they do, what else should we expect to find on both sides?

Look closely

- Find South America and Africa in the left globe. Where exactly do they touch?
- Compare the two globes. Which continents moved the farthest between the “before” and “after” pictures?
- Look at the shapes of the coastlines. Are they drawn carefully or roughly? Would a rough drawing make the fit look better than it really is?
- Notice how small the pictures are. Why might a scientist publish an idea as a picture instead of a long argument?

Talk about it

1. What two observations did Snider-Pellegrini use to support his maps?
2. What cause did he give for the separation, and how was that different from Wegener’s suggested cause?

3. If the maps are right, name one thing you would expect to find matching on both sides of the ocean.

EXPERIMENT: HOW FAST IS 2.5 CENTIMETERS A YEAR? MEASURING FINGERNAIL GROWTH

The U.S. Geological Survey says the Atlantic widens about as fast as your fingernails grow. Is that true? For two weeks you will measure your own fingernails and compare their growth rate with the plate rate of 2.5 centimeters per year. Along the way you will learn how scientists measure a change far too slow to see.

Question: Do my fingernails grow faster or slower than the Atlantic widens, and does every finger grow at the same rate? Prediction: write your guess in millimeters per week for your thumb and your middle finger before you begin.

You will need

- A fine-tip permanent marker (ask a parent first)
- A ruler marked in millimeters, or a small plastic ruler and a magnifying glass
- Your science notebook and a pencil
- A calendar to mark measuring days

Steps

1. On day 1, with a parent’s help, make one tiny marker dot on the nail of your thumb and one on your middle finger, right where the nail meets the skin at its base (the cuticle line). The dot will ride outward as the nail grows.
2. Measure the distance from the cuticle line to the dot in millimeters. It should be about 0 mm on day 1. Record the date, the finger and the measurement in a table.
3. What we change: the finger (thumb or middle finger). What we keep the same: the same hand, the same ruler, the same way of measuring, the same time of day. What we measure: millimeters the dot has moved from the cuticle line.
4. Measure again on day 4, day 7, day 11 and day 14. If the dot fades, measure first, then put a new dot exactly on the old one.
5. Find the growth rate for each finger: total millimeters moved divided by 2 weeks gives millimeters per week.
6. Convert to centimeters per year: multiply millimeters per week by 52 weeks, then divide by 10 to change millimeters to centimeters.
7. Compare with the Atlantic rate of 2.5 cm per year. Which is faster? Was your prediction right? Did both fingers grow at the same rate?

Tips

- Most people’s fingernails grow roughly 3 to 4 cm per year, and the middle finger usually grows a little faster than the thumb. If your numbers are a little different, that is real data, not a mistake.

- Hold the ruler flat against the nail and read it at eye level. Small measurements are easy to misread by a millimeter.

Check your work

- I can measure a slow change by marking a starting point and measuring from it later.
- I can convert a rate in millimeters per week to centimeters per year.
- I can say whether fingernails grow faster or slower than the Atlantic widens, using my own numbers.

FIELD NOTEBOOK

1. Copy Snider-Pellegrini’s two globes as small sketches, labeled “Before” and “After.” Under them write the year and the cause he proposed.
2. Draw a timeline from 1596 to 1990 and place at least five events from this lesson on it. Mark Wegener’s two dates in a second color.
3. Rule a measurement table for the fingernail project with columns for date, day number, thumb (mm) and middle finger (mm). Fill in day 1.

> **From history.** Wegener never saw his idea accepted. In 1930 he led a German expedition to Greenland that set up a weather station called Eismitte in the middle of the ice cap. When supplies ran short, Wegener and a Greenlander named Rasmus Villumsen drove dog sleds through the autumn cold to deliver food and fuel. Wegener turned fifty at the station on November 1 and set out for the coast that same day. He died on the ice, and the following spring searchers found his body carefully buried by his companion, who was never found. Thirty years later, maps of the ocean floor proved that the continents really do move.

WORKED EXAMPLES

Example 1. GPS stations show the Atlantic Ocean widening at about 2.5 cm per year. How much wider will it be after 80 years, about one human lifetime? Give the answer in centimeters and in meters.

1. Distance = rate × time. Rate is 2.5 cm per year and time is 80 years.
2. 2.5 cm/yr × 80 yr = 200 cm.
3. There are 100 cm in a meter, so 200 cm ÷ 100 = 2 m.

Answer: About 200 cm, which is 2 m. In a whole lifetime the ocean widens by about the height of a tall door.

Example 2. On a classroom world map, 1 cm stands for 500 km. The narrowest gap across the Atlantic, from Brazil to West Africa, is about 2,900 km. How many centimeters apart are those coasts on the map?

1. Set up the scale as a ratio: 1 cm on the map = 500 km on the earth.
2. Divide the real distance by the distance one centimeter stands for: 2,900 km ÷ 500 km per cm = 5.8 cm.
3. Check: 5.8 cm × 500 km/cm = 2,900 km. It matches.

Answer: About 5.8 cm on the map.

Example 3. Convert the Atlantic's widening rate of 2.5 cm per year into millimeters per day. Compare it with the thickness of a sheet of paper, about 0.1 mm.

1. Change centimeters to millimeters: 2.5 cm = 25 mm per year.
2. Divide by the days in a year: 25 mm ÷ 365 days = 0.068 mm per day, about 0.07 mm.
3. Compare: 0.07 mm is less than the thickness of one sheet of paper (0.1 mm).

Answer: About 0.07 mm per day, thinner than a single sheet of paper. That is why no one can see a plate move, and why it took GPS to measure it.

PRACTICE

1. EASY In what year did Snider-Pellegrini publish his two maps, and what event did he say pulled the continents apart?
2. EASY What was Alfred Wegener's main field of science, and in what year did he first present his hypothesis of continental drift?
3. EASY What does the name Pangaea mean, and what does it name?
4. MEDIUM At 2.5 cm per year, how much wider does the Atlantic become in 200 years? Answer in centimeters and in meters.
5. MEDIUM Two GPS stations, one in North America and one in Europe, record how much the distance between them has grown since the year 2000. Year 2000: 0 cm. Year 2004: 10 cm. Year 2008: 20 cm. Year 2012: 30 cm. Year 2016: 40 cm. (a) What is the rate of separation in centimeters per year? (b) Predict the extra distance in 2024. (c) Which statement is best supported by the data? A. The stations move apart faster every year. B. The stations move apart at a steady rate. C. The stations are moving closer together.
6. MEDIUM Give two reasons most geologists rejected Wegener's hypothesis in the 1920s.
7. HARD The table lists four fossils Wegener and later scientists used and the continents where each is found. Glossopteris (a seed plant): South America, Africa, India, Australia, Antarctica. Mesosaurus (a small reptile): South America, Africa. Lystrosaurus (a reptile): Africa, India, Antarctica. Cynognathus (a reptile): South America, Africa. (a)

Which fossil is found on the most continents? (b) Which continent appears in every row? (c) Based only on this table, which two continents must have been joined if these animals walked between them?

8. HARD In two or three sentences, explain the difference between a hypothesis and evidence, using Wegener's work as your example.
9. HARD Design an experiment to test this question: Can a person reassemble a torn page as quickly using only the torn edges as when the page also has printing across the tear? Name the independent variable, the dependent variable, two things you would keep the same, and how many trials you would run.
10. CHALLENGE Convert 2.5 cm per year to meters per century and to meters per 1,000 years. Then explain in two sentences why measuring today's rate alone cannot tell you how long the Atlantic has been opening.

COMMON MISTAKES

- Thinking Wegener invented the idea of moving continents. Ortelius wondered about it in 1596 and Snider-Pellegrini published maps in 1858. Wegener's contribution was gathering several kinds of evidence and arguing the case fully.
- Picturing continents plowing through the ocean floor like ships. That was Wegener's picture and it was wrong. Whole plates move, carrying continents and ocean floor together.
- Believing a good idea is accepted as soon as it is published. Continental drift waited about fifty years for the ocean-floor evidence that convinced most geologists.

Make it a game · Evidence or Hypothesis?. Your parent reads statements from this lesson and you call out "evidence" or "hypothesis" before they count to three. Examples: "The coasts of Africa and South America fit together" (evidence). "The continents were once one piece of land" (hypothesis). "The same fossil reptile is found in Brazil and South Africa" (evidence). "Tides pushed the continents apart" (hypothesis). Score a point for each right answer and a bonus point if you can say what observation would test a hypothesis. Play to ten.

Scripture. "Who laid the foundations of the earth, that it should not be removed for ever." (Psalm 104:5, KJV)

The psalm praises God for an earth firm enough to live on. The plates move, but only by a fingernail's width each year, and the ground stays steady enough for every house, field and city. Order and motion together are God's design.

Practice answers

1. 1858. He said the continents were torn apart suddenly during the Flood of Noah's day.
2. He was a meteorologist (a scientist of weather). He first presented continental drift on January 6, 1912, in Frankfurt.

3. It comes from Greek words meaning “all land.” It names the supercontinent Wegener believed once held all the continents together.
4. 2.5 cm/yr × 200 yr = 500 cm = 5 m.
5. (a) 10 cm every 4 years = 2.5 cm per year. (b) 24 years × 2.5 cm/yr = 60 cm. (c) B. The distance grows by the same 10 cm in each 4-year span, so the rate is steady.
6. Any two: he could not give a convincing cause, since the tidal and pole-fleeing forces he suggested were far too weak; the idea of continents plowing through solid ocean floor seemed impossible; some of his evidence could also be explained by sunken land bridges; and he was a meteorologist, an outsider to geology.
7. (a) Glossopteris, found on five continents. (b) Africa. (c) South America and Africa, since Mesosaurus and Cynognathus are found on both and nowhere else in the table.
8. A hypothesis is a testable explanation; Wegener’s hypothesis was that the continents were once joined and drifted apart. Evidence is what can be observed and measured to test the hypothesis; Wegener’s evidence included the fit of the coasts, matching fossils, matching rock belts and glacial scratches. The evidence supported his hypothesis, but without a cause many scientists were not convinced.
9. Independent variable: whether the page is blank or printed. Dependent variable: time to reassemble the pieces (or the number of correct joins). Keep the same: paper size, number of pieces, tearing pattern, the same person doing the reassembling, same lighting. Run at least three trials of each kind and average the times. Prediction: printed pages are reassembled faster because the print gives a second line of evidence.
10. 2.5 cm/yr × 100 yr = 250 cm = 2.5 m per century. 2.5 cm/yr × 1,000 yr = 2,500 cm = 25 m per 1,000 years. Today’s rate tells you only how fast the plates move now. To turn a rate into an age you must assume the rate never changed, and no one has measured the rate in the distant past.

2.2 Puzzle Continents: Fitting the Pieces and Reading the Clues

OBJECTIVES

- Fit cut-out continents into a supercontinent and explain why the fit along the edge of the continental shelf is better than the fit along today's shoreline.
- List four kinds of matching evidence across the oceans (coastline fit, fossils, rock belts and glacial scratches) and explain why several independent clues together are stronger than one clue alone.
- Read a data table of fossil locations and use a map scale to turn centimeters on a map into kilometers on the earth.

Warm-up. Take a page of old newspaper with large print and tear it in half along a wobbly line. Hand the two pieces to a brother, sister or parent and ask them to fit the halves back together. Then ask: did you use the torn edge, the printed words, or both? Write one sentence. Tonight's lesson is about continents that fit along their edges and also have "print" running across the tear.

Video. Coming soon. Evidence for Pangaea: fitting the continents, Glossopteris and Mesosaurus fossils, matching mountain belts and glacial scratches; search USGS, Smithsonian, SciShow Kids, Homeschool Pop (Alternate), Science Max and museum paleontology channels.

KEY TERMS

continental shelf
The gently sloping, shallow sea floor around a continent, covered by seawater but really part of the continent. Its outer edge drops steeply to the deep ocean floor.

Glossopteris
A fossil seed plant with tongue-shaped leaves found in South America, Africa, India, Australia and Antarctica.

Mesosaurus
A small fossil reptile about one meter long that lived in fresh water. Its fossils are found only in southern Africa and eastern South America.

glacial striations
Long parallel scratches cut into bedrock by stones dragged along under a moving glacier. They show which way the ice moved.

mountain belt
A long chain of folded and faulted rock, such as the Appalachians. Some belts end at a coast and seem to continue on another continent.

scale

The ratio between a distance on a map or model and the real distance it stands for, such as 1 cm = 500 km.

CORE IDEAS

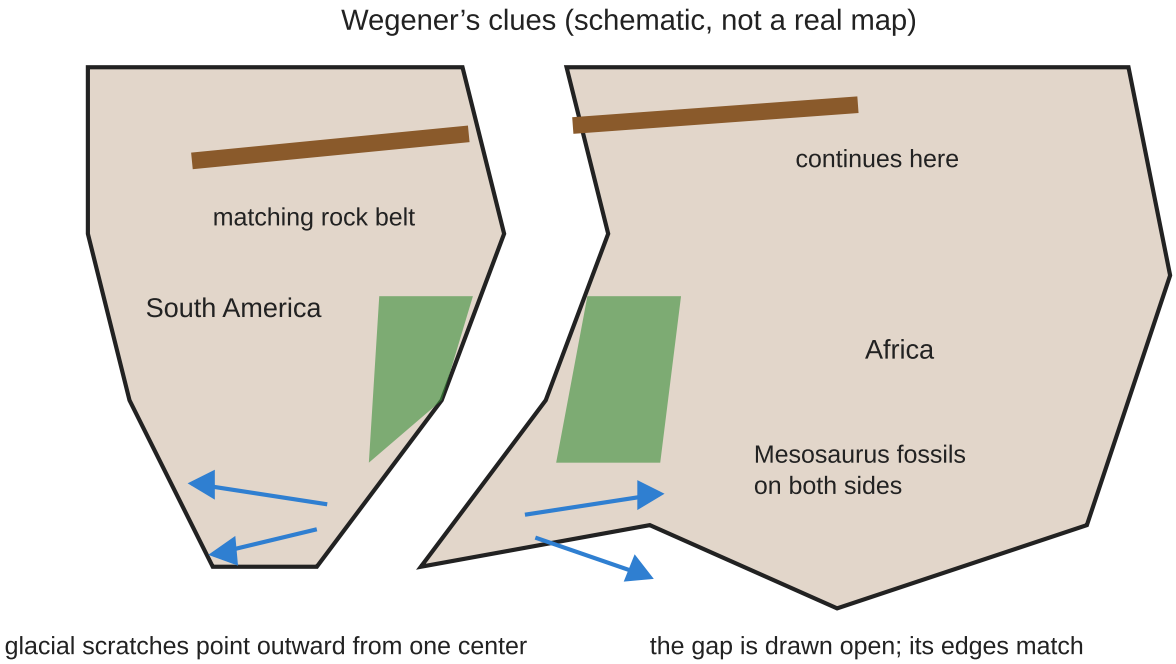
The story. In February 1912, on the Beardmore Glacier in Antarctica, five men hauling a heavy sled stopped to collect rocks. They were Captain Robert Falcon Scott's party, returning from the South Pole, and their doctor and naturalist, Edward Wilson, chipped specimens from a cliff where coal seams showed in the sandstone. Among the stones were slabs printed with the tongue-shaped leaves of **Glossopteris**, a fossil plant already known from India, Australia and Africa. The men did not survive the journey home, but they refused to leave their rocks behind, and the search party that found their tent in November 1912 found about 16 kilograms of geological specimens beside it. Those fossils became part of the strongest puzzle in Earth science. The same plant lay buried in Antarctica, where no trees grow today, and in lands now separated by thousands of kilometers of ocean.

How they figured it out. Fitting the continents together is more than tracing shorelines. The shoreline is wherever the sea happens to lap today. Around every continent lies a **continental shelf**, a shallow, drowned apron of continental rock that ends at a steep drop to the deep ocean floor. In 1965 the British geophysicist Edward Bullard and two colleagues used a computer to fit the continents along the shelf edge, about 900 meters below sea level. The fit between South America and Africa was remarkably tight, far better than the fit at the beaches. Then came the fossils. **Mesosaurus**, a reptile about a meter long, lived in fresh water, yet its bones lie in Brazil and in South Africa and nowhere else. Glossopteris seeds were too large to blow across an ocean. Two more fossil reptiles, Lystrosaurus and Cynognathus, repeat the pattern on both sides of the sea.

The big idea. The rocks match too. The Appalachian Mountains of eastern North America run northeast to the coast, stop, and rock of the same kind and structure appears again in the highlands of Scotland and Norway. Ancient rock belts of Brazil line up with belts in West Africa when the continents are closed together. In southern Africa, India, Australia and southern South America, the bedrock carries **glacial striations**, scratches left by ice, in lands that are hot today, and when the continents are fitted together the scratches point outward from a single center as if one ice sheet had spread over them all. Here is the heart of the matter. One clue could be a coincidence. Coastlines can happen to look alike. But when the edges fit, the fossils match, the **mountain belts** continue and the ice scratches line up, four independent clues point the same way, exactly as a torn page is proven whole by its edge *and* its print.

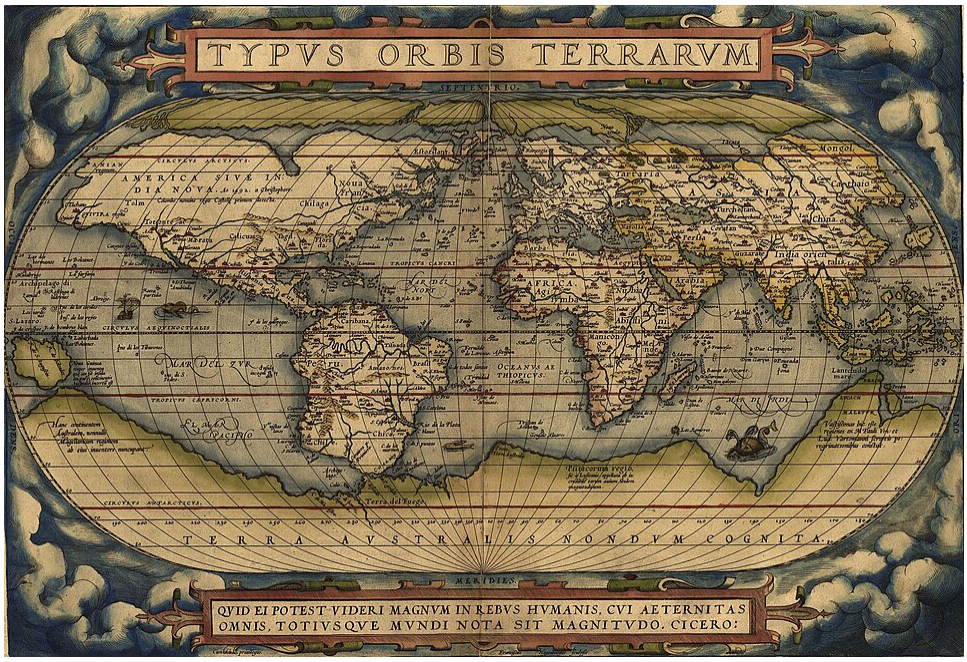
Try it and see. You can test the fit yourself with a map, scissors and a ruler, and you will do just that in today's project. Cut out the continents, slide South America against Africa and measure the gaps. Then mark the fossil locations from a table and see whether the Glossopteris and Mesosaurus zones line up across the join. Every map has a **scale**, a ratio such as 1 cm = 500 km, and with it you can turn each millimeter of gap into real kilometers. Scientists do the same thing with better maps and computers, but the reasoning is identical: measure, compare and ask whether the match is closer than chance would give.

God’s handiwork. God asked Job, “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding” (Job 38:4). None of us watched the continents take their places. What we can do is read the record left in stone: leaves pressed in Antarctic sandstone, a meter-long reptile on two shores, scratches in the bedrock. Those are real, and they fit together. How fast the pieces moved and when is a harder question that this unit will take up in Lesson 2.4. For now, notice the wonder: the earth keeps a record that a careful child with scissors and a ruler can begin to read.



Four clues that line up when the gap is closed: matching edges, the same fossil zone, a rock belt that continues, and ice scratches pointing away from one center. Schematic, not a real map.

PICTURE STUDY



Typus Orbis Terrarum (Map of the Whole World), Abraham Ortelius, 1570 · Hand-colored copperplate engraving, from the atlas Theatrum Orbis Terrarum · Printed in Antwerp; copies in many libraries, including the Library of Congress

Abraham Ortelius of Antwerp made the first modern atlas, a book of maps all the same size, in 1570. This is its world map. Twenty-six years later, in a geographical dictionary, Ortelius wrote that the Americas looked as if they had been torn away from Europe and Africa by earthquakes and floods, and that the torn edges still showed if you looked closely at a map.

His map is full of guesses. The great southern land at the bottom was imagined, not seen. Yet the coasts of South America and Africa are already drawn well enough that a thoughtful man could notice their fit.

Look closely

- Find South America and Africa. Follow the bulge of Brazil and the bend of West Africa with your finger. Do they look like they could fit?
- Find the huge southern continent along the bottom. Mapmakers imagined it must be there to balance the lands of the north. Nobody had seen it.
- Look at the shapes of North America and Asia. Which parts of the map look well known, and which look like guesses?
- Notice the clouds and the Latin writing in the frame. What does the decoration tell you about who bought atlases in 1570?

Talk about it

1. What did Ortelius suggest about the Americas in 1596, and what evidence did he have?
2. Why is a map a kind of evidence that must be checked, not simply trusted?

3. If Ortelius had owned a map showing the continental shelves, how might his argument have been stronger?

EXPERIMENT: THE CONTINENT PUZZLE: MEASURING THE FIT

You will cut out the continents, fit South America against Africa and measure how well they match, first along the shoreline and then along the edge of the continental shelf. Then you will add the fossil clues and see whether they line up.

Question: Does the fit between South America and Africa improve when we use the edge of the continental shelf instead of the shoreline? Prediction: write down the average gap in millimeters you expect for each.

You will need

- Two printed copies of a world map that shows the shallow continental shelves in a lighter blue (many atlases and free printable physical maps do), or one map and tracing paper
- Scissors, a ruler marked in millimeters, a pencil
- Colored pencils (green, red, blue, orange) for fossil zones
- The fossil table from Practice item 5
- Glue stick and a large sheet of paper for the finished puzzle

Steps

1. On the first map, cut out South America and Africa along the shoreline. On the second map (or a tracing), cut them out along the outer edge of the light-blue continental shelf.
2. Find the map scale and write it in your notebook, for example 1 cm = 500 km.
3. What we change: where we cut (shoreline or shelf edge). What we keep the same: the same map, the same two continents, the same way of sliding them together until the first point of contact. What we measure: the gap in millimeters at five places along the join.
4. Slide the shoreline pieces together until they first touch. Measure the gap at five evenly spaced points from north to south and record each in a table. Find the average.
5. Repeat with the shelf-edge pieces. Record and average.
6. Convert each average gap to kilometers using the scale. Which fit is tighter? Was your prediction right?
7. Now the “print across the tear.” Using the fossil table, color small zones on your shelf-edge pieces: green for Glossopteris, red for Mesosaurus, blue for Lystrosaurus, orange for Cynognathus. Place the pieces together. Do the colored zones meet across the join?
8. Glue the fitted shelf-edge pieces to the large sheet. Add Antarctica, India and Australia as best you can, fitted around the southern tip of Africa. Label the fossil zones and write two sentences about which clues lined up.

Tips

- Cut slowly around the small bays and capes. A rough cut can make a fit look better or worse than it really is.
- Maps flatten a round earth, so even a perfect fit will show some gaps and overlaps on paper. Scientists use a globe or a computer to avoid this.

Check your work

- I can measure gaps in millimeters and convert them to kilometers with a map scale.
- I can explain why the shelf-edge fit is a better test than the shoreline fit.
- I can show at least two fossil zones that meet across the join and say why that matters.

FIELD NOTEBOOK

1. Draw a Glossopteris leaf: tongue-shaped, with a strong central vein and a fine net of smaller veins. Label it and list the five continents where it is found.
2. Draw Mesosaurus as a slender reptile with a long tail and a long, narrow jaw beside a 1-meter scale bar. Note: freshwater, found in Brazil and South Africa.
3. Make a two-column table titled “Clue” and “What it shows,” with four rows: coastline fit, fossils, rock belts, glacial scratches.

> **From history.** In 1965 Sir Edward Bullard, James Everett and Alan Smith at Cambridge fed the outlines of the continents into a computer and asked it to find the best fit along the 500-fathom line (about 900 meters deep), the edge of the continental shelf. The machine closed the Atlantic with only small gaps and overlaps, and the picture it produced, printed in a report of the Royal Society, became one of the most reprinted diagrams in geology. It showed that Wegener’s puzzle fit was not wishful thinking but a measurable fact.

WORKED EXAMPLES

Example 1. A classroom globe is 30 cm across. The earth’s circumference is about 40,000 km. What is the globe’s scale in kilometers per centimeter, and how far apart on the globe are two coasts that are 2,900 km apart on the earth?

1. Find the globe’s circumference: circumference = π × diameter = 3.14 × 30 cm ≈ 94 cm.
2. Scale = real distance ÷ model distance = 40,000 km ÷ 94 cm ≈ 425 km per cm.
3. Distance on globe = 2,900 km ÷ 425 km per cm ≈ 6.8 cm.

Answer: About 425 km per centimeter. The 2,900 km gap between Brazil and West Africa is about 6.8 cm on the globe.

Example 2. Mesosaurus was about 1 m long and lived in fresh water. The narrowest part of the South Atlantic today is about 2,900 km. How many body lengths would a Mesosaurus have had to swim to cross? What does this suggest?

1. Convert the ocean width to meters: 2,900 km × 1,000 m/km = 2,900,000 m.
2. Divide by the animal's length: 2,900,000 m ÷ 1 m = 2,900,000 body lengths.
3. Add the other facts: the Atlantic is salt water, and Mesosaurus lived in fresh water.

Answer: About 2.9 million body lengths through salt water. It is far more reasonable that the two places were once joined than that a small freshwater reptile swam across an ocean.

Example 3. Glossopteris fossils are found on 5 of the earth's 7 continents. Mesosaurus is found on 2. Express each as a fraction and a percent of the continents.

1. Glossopteris: 5 ÷ 7 = 0.714, so about 71% of the continents.
2. Mesosaurus: 2 ÷ 7 = 0.286, so about 29% of the continents.
3. Notice that a plant spread more widely than an animal, which fits a plant that grew across a wide connected land.

Answer: Glossopteris: 5/7, about 71%. Mesosaurus: 2/7, about 29%.

PRACTICE

1. EASY Name the fossil plant with tongue-shaped leaves that is found on five continents, including Antarctica.
2. EASY Why do the continents fit together better along the edge of the continental shelf than along today's shoreline?
3. EASY List the four kinds of evidence that the continents were once joined.
4. MEDIUM On a map with the scale 1 cm = 400 km, the gap between the Brazilian coast and the West African coast measures 7.25 cm. How many kilometers is that?
5. MEDIUM Read the fossil table. Glossopteris: South America, Africa, India, Australia, Antarctica. Mesosaurus: South America, Africa. Lystrosaurus: Africa, India, Antarctica. Cynognathus: South America, Africa. (a) Which continent has all four fossils? (b) Which fossils are found on both South America and Africa? (c) Is Mesosaurus found in Australia? (d) Which continent in the table has only Glossopteris?
6. MEDIUM Explain in two sentences why the Mesosaurus fossils are hard to explain unless South America and Africa were once joined.
7. HARD A student measured the gap between cut-out South America and Africa at five points. Shoreline cut: 12, 8, 15, 10, 20 mm. Shelf-edge cut: 4, 3, 6, 5, 2 mm. The map scale is 1 cm = 400 km. (a) Find the average gap for each cut. (b) Convert each

average to kilometers. (c) Which statement do the data support? A. The shoreline fit is tighter. B. The shelf-edge fit is tighter. C. The two fits are equally good.

8. HARD The Appalachian Mountains run northeast to the Atlantic coast and stop. If North America and Europe were once joined, what would you predict to find in Scotland and Norway, and why is this prediction a good test?
9. HARD Design an experiment to decide whether a shoreline cut or a shelf-edge cut gives a better fit between two continents. State the question, the independent variable, the dependent variable, two controls and how you would reduce measurement error.
10. CHALLENGE Some geologists before Wegener explained matching fossils with land bridges that later sank into the ocean. In three or four sentences, compare the land-bridge explanation with the joined-continents explanation. Which one makes more predictions that can be checked, and what would you look for on the ocean floor to test for sunken bridges?

COMMON MISTAKES

- Thinking the coastline fit alone proves the continents were joined. Coastlines can resemble each other by chance. The case is strong because several independent clues all line up.
- Assuming matching fossils mean the animals swam or floated across. Mesosaurus was a small freshwater reptile and Glossopteris seeds were too large for the wind. The simplest explanation is that the lands were connected.
- Picturing the continental shelf as ocean floor. It is drowned continental rock. The real edge of a continent is the steep slope at the outer edge of the shelf, not the beach.

> **Make it a game · Clue Stack.** Your parent names an observation and you say which of the four clue types it belongs to: fit, fossils, rocks or ice. Examples: “Tongue-shaped leaves in Antarctica” (fossils). “Scratches in Indian bedrock pointing north” (ice). “Brazil’s bulge nests into the Gulf of Guinea” (fit). “The Appalachians continue in Scotland” (rocks). Each right answer stacks one block or coin on your tower. Build a tower of eight without it falling and you win.

> **Scripture.** “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding.” (Job 38:4, KJV)

None of us saw the continents take their places. God’s question to Job teaches humility: we read the record He left in the rocks carefully and honestly, and we admit what we did not see.

Practice answers

1. Glossopteris.
2. The shelf is really part of the continent, just covered by shallow sea. The shoreline is only where the sea happens to reach today and changes with sea level and erosion, so the true edge of the continent is the steep outer edge of the shelf.

3. The fit of the coastlines (best at the shelf edge), matching fossils, matching rock and mountain belts, and glacial scratches and deposits that line up when the continents are closed together.
4. 7.25 cm × 400 km/cm = 2,900 km.
5. (a) Africa. (b) Glossopteris, Mesosaurus and Cynognathus. (c) No. (d) Australia.
6. Mesosaurus was a small reptile about 1 m long that lived in fresh water, so it could not have swum nearly 3,000 km of salt ocean. Finding it only in Brazil and South Africa makes most sense if those two places were once connected land.
7. (a) Shoreline: (12+8+15+10+20) ÷ 5 = 65 ÷ 5 = 13 mm. Shelf edge: (4+3+6+5+2) ÷ 5 = 20 ÷ 5 = 4 mm. (b) 13 mm = 1.3 cm × 400 = 520 km; 4 mm = 0.4 cm × 400 = 160 km. (c) B. The average gap is about three times smaller for the shelf-edge cut.
8. You would predict rock of the same kind, age sequence and folded structure continuing in Scotland and Norway, and that is what geologists find. It is a good test because the prediction was made from the hypothesis and could have failed. If the rocks had not matched, the idea would have been weakened.
9. Question: Which cut gives the smaller average gap? Independent variable: where the pieces are cut (shoreline or shelf edge). Dependent variable: average gap in millimeters at set points along the join. Controls: the same map and scale, the same two continents, the same rule for sliding until first contact, the same ruler. Reduce error by measuring at five or more points, repeating the measurement twice, and having a second person measure without knowing which cut it is.
10. Land bridges could explain the fossils but not the fit of the coasts, the matching rock belts or the glacial scratches that point from one center. The joined-continents explanation accounts for all four clues at once and predicts that the shelf edges will fit and that rock belts will continue across the join, which can be checked. To test for sunken bridges you would look for drowned continental rock between Brazil and Africa on the ocean floor, but the deep Atlantic floor is made of basalt, not continental rock. The joined-continents explanation makes more checkable predictions and passes them.

2.3 Plate Boundaries: Where the Earth Moves

OBJECTIVES

- Name the three types of plate boundaries, give a real example of each, and describe what forms there (ridges, rifts, trenches, volcanoes, mountains and faults).
- Explain the difference between a plate and a continent, and describe how the rigid lithosphere rides on the hot, slowly flowing asthenosphere.
- Use measured plate speeds in centimeters per year to calculate distances over time and compare rates with ratios.

Warm-up. Lay two hardcover books flat on the table so their edges touch. Now do three things and watch the edge: pull them slowly apart, push them slowly together so one slides up over the other, and slide them past each other sideways. Each motion is a kind of plate boundary. Write one word for what you noticed at the edge each time (gap, pile-up, scrape).

Video. Coming soon. The three types of plate boundaries with real examples (Mid-Atlantic Ridge and Iceland, subduction at the Mariana Trench and the Andes, the San Andreas Fault); search USGS, Smithsonian, NOAA Ocean Exploration, SciShow, Homeschool Pop (Alternate) and Science Max demonstrations with crackers or clay.

KEY TERMS

lithosphere
The rigid outer shell of the earth, made of the crust and the cool top of the mantle, about 100 km thick. The plates are pieces of lithosphere.

asthenosphere
The hot, soft part of the upper mantle below the lithosphere. It is solid rock, but over long times it flows slowly, like very thick tar, so the plates above can move.

divergent boundary
A boundary where two plates move apart. Hot rock rises to fill the gap, making mid-ocean ridges and rift valleys.

convergent boundary
A boundary where two plates move toward each other, making trenches, volcanoes and mountain ranges.

subduction
The sinking of one plate beneath another at a convergent boundary. The sinking plate bends down into the mantle, forming a deep ocean trench.

transform boundary
A boundary where two plates slide past each other sideways along a fault, as at the San Andreas Fault in California.

CORE IDEAS

The story. In the summer of A.D. 930, the chieftains of Iceland rode to a grassy plain in the southwest of their island to hold the Althing, an open-air assembly that is counted among the oldest parliaments in the world. The place is called **Þingvellir**, "Assembly Plains." It is a long valley walled by cliffs of black lava, and the ground between the cliffs is split by deep cracks filled with water so clear that divers can see for a hundred meters. For a thousand years Icelanders met there to make laws. They did not know that they were standing on the floor of a **rift**, a place where the earth is pulling itself apart. The cliff on the west side of the valley is the edge of the North American plate. Across the valley lies the edge of the Eurasian plate. Measurements show the two sides are moving apart by about 2 centimeters per year, and the valley floor is slowly sinking between them.

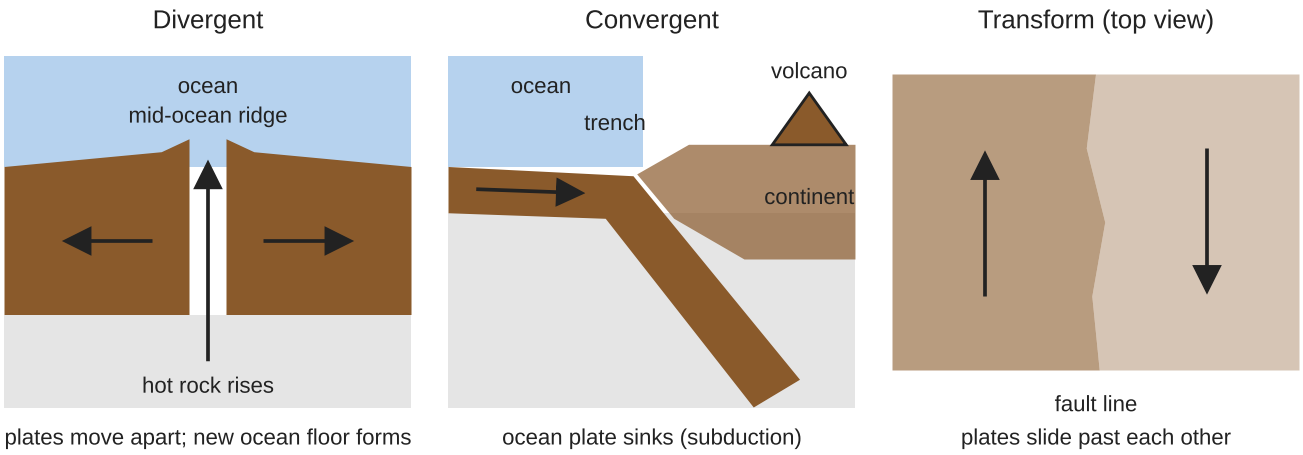
How they figured it out. In Unit 1 you learned that the earth has a thin crust, a thick mantle and a core. Plates are not the same as continents. A plate is a slab of **lithosphere**, the crust plus the cool, rigid top of the mantle, about 100 kilometers thick, and most plates carry both ocean floor and dry land. Beneath the lithosphere lies the **asthenosphere**, mantle rock so hot that, though solid, it flows slowly, and the plates ride on it. Scientists found the plate edges by plotting earthquakes. When seismographs were set up around the world in the 1960s, the dots of earthquake locations traced narrow belts that outlined the plates like the seams of a baseball. Along the deep ocean trenches, the Japanese scientist Kiyoo Wadati and the American Hugo Benioff had already noticed that earthquakes get deeper the farther inland you go from the trench, as if marking a slab sinking at a slant into the mantle. Today geologists count seven major plates: the Pacific, North American, South American, Eurasian, African, Indo-Australian and Antarctic plates, plus a number of smaller ones.

The big idea. Plates meet in three ways. At a **divergent boundary** they move apart, hot rock rises to fill the gap and hardens into new ocean floor, and the result is a mid-ocean ridge, such as the Mid-Atlantic Ridge that Iceland sits on, or a rift on land, such as the East African Rift. At a **convergent boundary** they move toward each other. When ocean floor meets a continent, the denser ocean plate bends down beneath it in **subduction**, making a deep trench offshore and a line of volcanoes inland, as along the Peru–Chile Trench and the Andes. When two ocean plates meet, one sinks beneath the other and makes a trench and a curved chain of volcanic islands; the Mariana Trench, where the Pacific plate sinks, holds the deepest known spot in the ocean at nearly 11,000 meters. When two continents collide, neither sinks easily, and the crust crumples into mountains such as the Himalaya, which Unit 5 will visit. At a **transform boundary**, plates slide past each other sideways along a fault. The San Andreas Fault in California is the famous example. In the earthquake of April 18, 1906, fences and roads crossing the fault near San Francisco were offset by as much as 6 meters in a few seconds.

In the world today. GPS now measures each plate's speed. The Atlantic widens about 2.5 centimeters per year. The East Pacific Rise, in the eastern Pacific, spreads much faster, up to about 15 centimeters per year. The Pacific plate slides northwest past the North American plate along the San Andreas at about 5 centimeters per year. Most of the world's earthquakes and volcanoes lie along plate boundaries, and the ring of trenches and

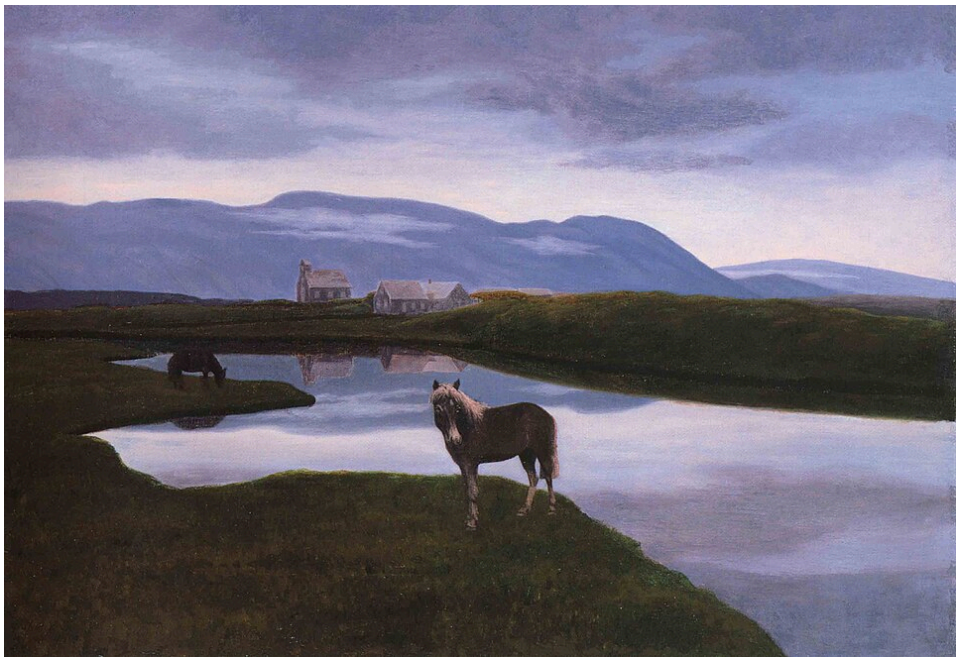
volcanoes around the Pacific is called the **Ring of Fire**. Not every volcano sits on a boundary, though. The Hawaiian Islands rise from the middle of the Pacific plate above a hot spot in the mantle, a reminder that the earth is always more varied than the first simple rule.

God's handiwork. The psalmist wrote, "Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea" (Psalm 46:2). He knew that the ground can shake and the mountains can move, and he knew where to put his trust. The plates are a picture of an earth that is powerful but not wild. Their edges are where the earth's heat escapes, where new rock is made, where ores are gathered and where islands like Iceland are born. The same boundaries that bring earthquakes also lift the land that people live on. Learning to read them is part of the dominion God gave us: to know the earth well enough to build wisely upon it.



The three kinds of plate boundary. Divergent: plates part and new rock forms. Convergent: one plate sinks (subduction) and volcanoes rise above it. Transform: plates grind past each other along a fault.

PICTURE STUDY



Þingvellir, Þórarinn B. Þorláksson, 1900 · Oil on canvas · National Gallery of Iceland, Reykjavík

Þórarinn B. Þorláksson was the first Icelander to make a career as a painter. He trained in Copenhagen and came home to paint the land he loved. In 1900 he set up his easel at Þingvellir, where the Althing had met for nearly a thousand years, and painted the plain in the long, soft light of a northern summer evening.

The painting shows no drama. Two horses graze, the lake is still, the cliff of Almannagjá is dark on the left. Yet that cliff is the edge of the North American plate, and the whole peaceful plain is a rift valley slowly widening and sinking. Þorláksson painted the quiet surface of a very active place.

Look closely

- Find the cliff on the left. It is a wall of lava rock. Which way would the land have to move to open a valley beside it?
- Look at the flat plain and the lake. Why would a sinking valley floor tend to collect water?
- Notice the light and the colors. What time of day does it seem to be, and why does a summer evening in Iceland last so long?
- Find the horses. How do they help you judge the size of the cliff and the plain?

Talk about it

1. Þingvellir is a divergent boundary. What two plates meet there, and about how fast are they moving apart?
2. Why did a thousand years of Icelanders not notice that their meeting place was splitting?

3. Can a place be both calm and dangerous? How does this painting show one and hide the other?

EXPERIMENT: GRAHAM-CRACKER PLATES

You will model all three boundaries with graham crackers (lithosphere) floating on a layer of frosting (asthenosphere). Then you will run a small experiment on the continent-to-continent collision.

Question: Does soaking the cracker edges longer make a taller mountain ridge when two “continents” collide? Prediction: write the ridge height in millimeters you expect for dry edges, 2-second soaked edges and 5-second soaked edges.

You will need

- A box of graham crackers (or firm crisp crackers)
- A tub of thick frosting, or thick peanut butter if no one at home is allergic
- Wax paper or a plastic tray, a butter knife
- A cup of water, a kitchen timer or phone, a ruler marked in millimeters
- Science notebook and pencil

Steps

1. Spread frosting about 1 cm thick over a sheet of wax paper. This is the asthenosphere: soft, able to flow, but not liquid.
2. Divergent boundary: lay two crackers side by side touching in the middle of the frosting. Press down gently and slowly pull them apart about 1 cm. Watch the frosting rise into the gap. That rising material is like the new rock at a mid-ocean ridge. Sketch it.
3. Ocean-to-continent convergent boundary: push one cracker slowly under the edge of another. The cracker that dives is the ocean plate. Notice how the top edge bends up and frosting piles against it. Sketch and label the trench.
4. Transform boundary: lay two crackers edge to edge and slide them past each other sideways. Feel the catch and jump. That sudden jump is what an earthquake is.
5. Continent-to-continent experiment, trial 1 (dry): place two fresh crackers end to end on fresh frosting and push them together exactly 2 cm. Measure the height of the ridge where they meet, in millimeters, above the flat cracker surface. Record it.
6. Trial 2: dip the meeting ends of two fresh crackers in water for 2 seconds, then push together 2 cm and measure the ridge height. Trial 3: soak for 5 seconds. What we change: soaking time. What we keep the same: push distance (2 cm), frosting thickness, type of cracker. What we measure: ridge height in millimeters.
7. Repeat each trial once more and average the two heights. Make a small bar graph of average ridge height against soaking time.
8. Write two sentences: did soaking change the result as you predicted, and which real mountain range does the wet collision remind you of?

Tips

- Push very slowly. Real plates move a few centimeters a year, and slow pushing shows the folding better.
- Soaked crackers bend and fold like warm, deep crust. Dry crackers crack and break like cold, shallow crust. Both happen in real mountains.

Check your work

- I can show all three boundary types with crackers and name a real example of each.
- I can run a fair test by changing only the soaking time and keeping the push distance the same.
- I can measure ridge height in millimeters and show my results in a bar graph.

FIELD NOTEBOOK

1. Draw cross-sections of the three boundary types, one above the other, with arrows for plate motion and labels for ridge, trench, volcano and fault.
2. Trace a world map and sketch the seven major plates with their boundaries. Color the Ring of Fire with red dots for volcanoes.
3. Record your cracker-collision data in a table and draw the bar graph of ridge height against soaking time.

> **From history.** The first detailed maps of the ocean floor were drawn by hand. In the early 1950s, Marie Tharp at Columbia University plotted depth soundings sent back by ships crossing the Atlantic while her colleague Bruce Heezen went to sea to collect them. As she drew profile after profile, Tharp noticed a deep notch running down the crest of the Mid-Atlantic Ridge, a rift valley thousands of kilometers long. Heezen at first dismissed it, but when earthquake locations were plotted on the same map they fell right along her valley. Their 1977 World Ocean Floor map, painted by the Austrian artist Heinrich Berann, showed the ridges and trenches of every ocean and let ordinary people see the plate boundaries for the first time.

WORKED EXAMPLES

Example 1. In the 1906 earthquake, a fence crossing the San Andreas Fault was offset by about 6 m in a few seconds. GPS shows the Pacific plate sliding past the North American plate at about 5 cm per year. How many years of steady plate motion were stored up and released in that one jump?

1. Convert the offset to centimeters: 6 m × 100 cm/m = 600 cm.
2. Time = distance ÷ rate = 600 cm ÷ 5 cm per year = 120 years.
3. The rock on either side of the fault was bent and stretched for about 120 years, then snapped back to catch up all at once.

Answer: About 120 years. Faults often stay locked for many years and then release all the stored motion in seconds.

Example 2. The Mid-Atlantic Ridge spreads at about 2.5 cm per year and the East Pacific Rise at about 15 cm per year. How many times faster is the East Pacific Rise? How far would each spread in 1,000 years, in meters?

1. Ratio: 15 cm/yr ÷ 2.5 cm/yr = 6. The East Pacific Rise spreads 6 times faster.
2. Mid-Atlantic: 2.5 cm/yr × 1,000 yr = 2,500 cm = 25 m.
3. East Pacific Rise: 15 cm/yr × 1,000 yr = 15,000 cm = 150 m.

Answer: The East Pacific Rise spreads 6 times as fast: 150 m in 1,000 years compared with 25 m for the Mid-Atlantic Ridge.

Example 3. A simplified table of earthquakes recorded beneath an ocean trench gives distance inland from the trench and the depth of the earthquakes. Distance 0 km: depth 10 km. Distance 100 km: depth 60 km. Distance 200 km: depth 110 km. Distance 300 km: depth 160 km. How fast does depth increase with distance, and what does this pattern show?

1. Find the change: from 0 to 100 km inland, depth goes from 10 to 60 km, an increase of 50 km.
2. Rate = 50 km of depth per 100 km of distance = 0.5 km down for every 1 km inland, a 1:2 slope.
3. Check the other rows: each 100 km inland adds 50 km of depth, so the pattern is steady.
4. A steady slope of earthquakes going deeper inland marks the sinking plate itself, bending down into the mantle at a slant.

Answer: Depth increases 50 km for every 100 km inland (a 1:2 slope). The earthquakes trace a subducting plate sinking at an angle beneath the trench.

PRACTICE

1. EASY Name the three types of plate boundaries and give one real example of each.
2. EASY How is a plate different from a continent?
3. EASY Where does new ocean floor form, and what kind of boundary is that?
4. MEDIUM The Pacific plate slides past the North American plate at about 5 cm per year. How long does it take to build up 1 m of motion? How long for 6 m?
5. MEDIUM Read the table of plate speeds measured by GPS. Mid-Atlantic Ridge: 2.5 cm/yr spreading. Red Sea: about 1 cm/yr spreading. East Pacific Rise: about 15 cm/yr spreading. San Andreas Fault: about 5 cm/yr sliding. (a) Which boundary is fastest? (b) How far will the East Pacific Rise spread in 50 years, in meters? (c) How many times faster is the East Pacific Rise than the Red Sea? (d) Which boundary in the table is a transform boundary?
6. MEDIUM Why do volcanoes form above a sinking plate at a convergent boundary?
7. HARD Earthquakes recorded near a trench: Distance inland 0 km, depth 15 km. 50 km, depth 40 km. 100 km, depth 65 km. 150 km, depth 90 km. 200 km, depth 115 km. (a) By how much does depth increase for every 50 km inland? (b) Predict the depth of earthquakes 300 km inland if the pattern continues. (c) Which boundary type do these data indicate, and which way is the plate sinking?
8. HARD Iceland is both a volcanic island and a place where the land is splitting apart. In two or three sentences, explain how the same boundary produces both.
9. HARD Design an experiment with crackers and frosting to test whether a thicker layer of frosting (asthenosphere) lets the crackers (plates) slide apart more easily. Name the independent variable, the dependent variable, two controls and how you would measure the result.

10. CHALLENGE Earthquakes at transform boundaries are almost all shallower than about 20 km, while earthquakes at some convergent boundaries occur as deep as 700 km. In three or four sentences, explain why.

COMMON MISTAKES

- Thinking the plates float on an ocean of liquid magma. The asthenosphere is solid rock that is hot enough to flow very slowly. Only small pockets of it melt into magma.
- Thinking a plate is the same thing as a continent. Plates are slabs of lithosphere, and most carry ocean floor and dry land together.
- Thinking every volcano and earthquake lies on a plate boundary. Most do, but hot-spot volcanoes such as Hawaii rise in the middle of a plate.

Make it a game · Boundary Charades. Use your two hands as plates. Your parent calls out a real place and you must act out the right boundary within three seconds: hands pulling apart for divergent (Iceland, Red Sea, East African Rift), one hand diving under the other for subduction (Andes, Mariana Trench, Japan), hands crumpling upward for continent collision (Himalaya), hands sliding past for transform (San Andreas). A wrong move gives the point to your parent. First to eight points wins. Bonus round: act out a hot spot (Hawaii) with one finger pushing up through a flat hand.

Scripture. “Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah.” (Psalm 46:2–3, KJV)

The psalmist had seen the ground shake and the sea rage. He did not pretend the earth was still; he trusted the God who holds it. Studying plate boundaries is one way to fear less by understanding more.

Practice answers

1. Divergent (Mid-Atlantic Ridge, Iceland, East African Rift), convergent (Peru–Chile Trench and Andes, Mariana Trench, Himalaya) and transform (San Andreas Fault).
2. A plate is a slab of lithosphere about 100 km thick, made of crust and the rigid top of the mantle. Most plates carry both ocean floor and continent, so a continent is only part of a plate.
3. At mid-ocean ridges, where hot rock rises to fill the gap between plates moving apart. That is a divergent boundary.
4. 1 m = 100 cm; 100 ÷ 5 = 20 years. 6 m = 600 cm; 600 ÷ 5 = 120 years.
5. (a) The East Pacific Rise. (b) 15 cm/yr × 50 yr = 750 cm = 7.5 m. (c) 15 ÷ 1 = 15 times faster. (d) The San Andreas Fault, where plates slide past each other.
6. The sinking ocean plate carries water-rich rock down into the hot mantle. The water it releases lowers the melting temperature of the rock above, which melts into magma. The magma rises through the overriding plate and erupts as a line of volcanoes inland from the trench.

7. (a) 25 km deeper for every 50 km inland. (b) 300 km is 100 km beyond the last row, so two more steps of 25 km: 115 + 50 = 165 km. (c) A convergent boundary with subduction. The plate is sinking from the trench down and inland, in the direction the earthquakes get deeper.
8. Iceland sits on the Mid-Atlantic Ridge, a divergent boundary between the North American and Eurasian plates. As the plates pull apart, hot rock rises to fill the gap, so the land cracks and rifts open while the rising rock erupts as volcanoes and lava. Splitting and volcanism are two results of the same rising, spreading motion.
9. Independent variable: thickness of the frosting layer (for example 0.5 cm, 1 cm, 2 cm). Dependent variable: how easily the crackers slide, measured as the force needed (count rubber bands stretched to a mark, or the number of coins placed in a cup pulling the cracker with string) or the distance moved under the same pull. Controls: the same crackers, the same frosting at the same temperature, the same starting gap and pulling method. Repeat each thickness three times and average.
10. At a transform boundary the plates slide past each other sideways within the cold, brittle lithosphere, which is only about 100 km thick, and faults there break mostly in the upper part, so quakes are shallow. At a convergent boundary a cold, brittle ocean plate sinks far down into the mantle. Because the slab stays cold and stiff for a long way, it can still crack and slip at great depth, producing earthquakes down to about 700 km. Deep earthquakes happen only where a plate is sinking.

2.4 Catastrophic Plate Tectonics: John Baumgardner's Flood Model

OBJECTIVES

- Describe John Baumgardner's model of catastrophic plate tectonics in order: cold ocean floor sinks, runaway subduction, new hot seafloor forms, the oceans flood the continents, and the motion slows to today's rates.
- Explain how a textbook turns a measured plate speed into an age by extrapolation, name the assumption behind it, and state the mainstream reading and the young-earth reading fairly.
- Convert between centimeters per year and meters per second and compute how long the same distance takes at different rates.

Warm-up. An hour before the lesson, put one spoonful of honey on a saucer in the refrigerator and leave another spoonful on a saucer at room temperature. At lesson time, tilt both saucers at the same angle and count seconds until each blob slides 5 cm. Write both times. Which honey flowed faster, and what does temperature do to how easily a thick substance flows?

Video. Coming soon. Mantle convection and runaway subduction computer models, seafloor spreading rates measured by GPS, and lectures by geophysicist John Baumgardner on catastrophic plate tectonics; also USGS and NASA animations of plate motion and Moody Science classics on the Flood.

KEY TERMS

catastrophic plate tectonics
A creationist model proposing that the plates moved rapidly, meters per second, during the Flood year, and then slowed to the centimeters per year measured today.

viscosity
A substance's resistance to flowing. Honey has high viscosity, water has low viscosity. Hot rock has very high viscosity, and it drops as the rock gets hotter.

runaway subduction
A sinking plate heats and weakens the mantle rock around it, which lets it sink faster, which weakens the rock more, so the sinking speeds up without limit until the plate is gone.

model
A simplified description, often a computer program, that imitates how part of the world works so its predictions can be tested.

extrapolation

Stretching a measured trend beyond the range where it was measured, such as assuming today's plate speed held for the whole past.

assumption
Something taken as true without being measured. Turning a rate into an age assumes the rate never changed.

CORE IDEAS

The story. In the 1980s, at Los Alamos National Laboratory in the mountains of New Mexico, a geophysicist named **John Baumgardner** was writing a computer program he called TERRA. It divided the earth's whole mantle into millions of small cells and calculated, step by step, how hot solid rock creeps and flows over time. He had built the first version for his doctoral degree at the University of California, Los Angeles, finished in 1983, and it ran on some of the fastest computers in the world. Baumgardner was also a Christian who read Genesis 6 to 9 as history. He asked a question most geologists did not ask: if the Flood of Noah's day really happened, what would it have done to the earth's plates? In 1986 he proposed an answer he called **catastrophic plate tectonics**, and in 1994 he and five other scientists presented a fuller version of the **model** at a conference in Pittsburgh.

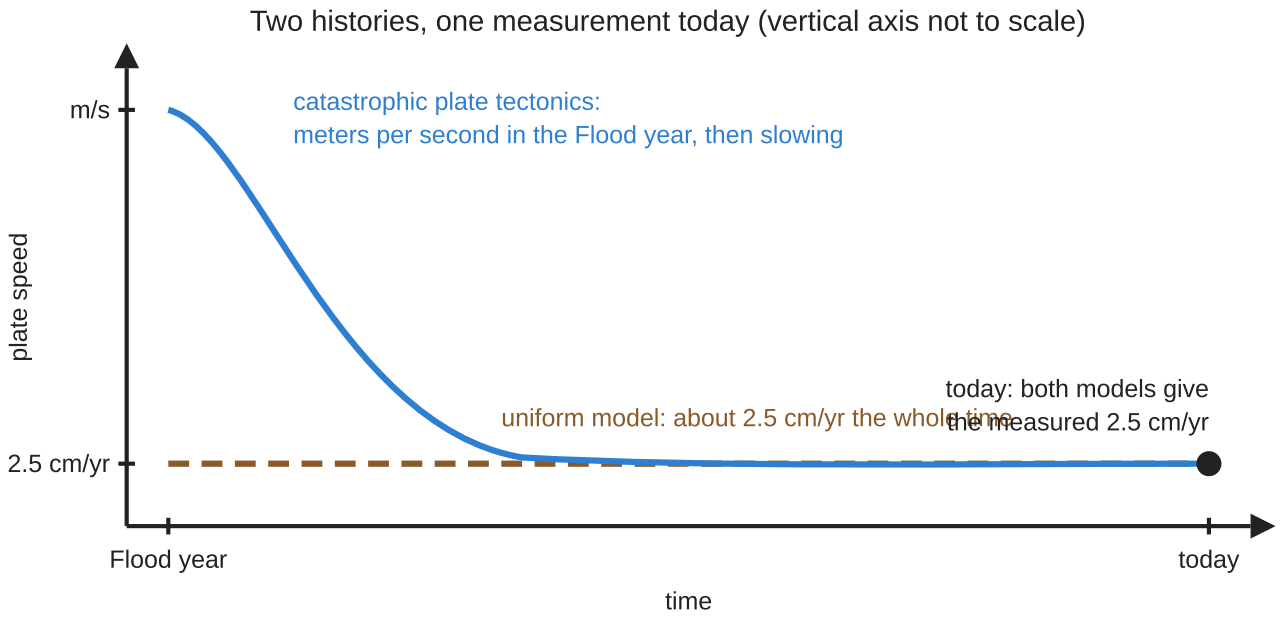
How they figured it out. The key is a property of rock called **viscosity**, its resistance to flowing. Honey has high viscosity and water has low. Hot mantle rock flows, but very slowly, because its viscosity is enormous. Laboratory tests show that when silicate rock is heated and stressed, its viscosity drops by large factors, so it flows far more easily. Baumgardner built on this fact. Suppose the ocean floor before the Flood was cold and dense, and some of it began to sink into the mantle. As the slab sank it would deform and heat the rock around it, which would weaken, which would let the slab sink faster, which would heat the rock more. Each step feeds the next. This is a runaway, like a snowball rolling downhill, and the model calls it **runaway subduction**. In TERRA, once it started, the sinking sped up from centimeters per year to meters per second. Within weeks the whole old ocean floor could plunge into the mantle, pulling the continents apart as it went, while hot rock rose at the ridges to make a new ocean floor thousands of kilometers wide.

The big idea. The model links this motion to the Flood that Genesis describes. Hot new ocean floor stands higher than cold old floor, so a new sea bottom rising all at once would lift the oceans over the continents. Seawater pouring across the hot ridges would flash into steam and shoot upward in great jets, falling back as weeks of rain. Baumgardner reads "the fountains of the great deep" and "the windows of heaven" of Genesis 7:11 in this light. When the old ocean floor was gone, the runaway ended. The new floor cooled and sank, the water drained off the continents, and the plates slowed to a crawl. On this view, the few centimeters a year we measure today are the dying tail of a motion that was once a billion times faster. It is important to be fair. Mainstream geologists do not accept this model, and it has hard, open questions, above all how so much heat could have been carried away so quickly. Creation geologists say so plainly and keep working on it.

In the world today. Both readings start from the same measurements: plates moving 1 to 15 centimeters per year by GPS, a ridge with a central valley, deep trenches, magnetic

stripes, cold slab-shaped masses deep in the mantle seen by seismic waves, and thick layers of water-laid sediment full of sea creatures across the continents. A textbook turns today's rate into an age by **extrapolation**: it divides the width of the Atlantic by 2.5 centimeters per year and gets about 200 million years. That number rests on an **assumption**, that the rate never changed. Catastrophic plate tectonics keeps the measurements and drops the assumption. It reads the cold deep slabs as having sunk recently and fast, the sediments as laid by the Flood, and the entire ocean floor, young even by the textbook's own counting when set beside the continents, as replaced in a single event. A good student learns to spot the measurement, spot the assumption, and state both readings clearly.

God's handiwork. The Flood was a judgment, but it was also a rescue. God shut Noah and his family into the ark before the fountains broke up, and when the waters had done their work He set His bow in the cloud and promised that the earth would never again be covered (Genesis 9:11). Psalm 104 remembers that day: "Thou coveredst it with the deep as with a garment: the waters stood above the mountains. At thy rebuke they fled; at the voice of thy thunder they hasted away" (Psalm 104:6–7). However the plates moved, the ground beneath you is steady tonight and the sea is in its bounds. That is the promise still being kept.



Two histories, one measurement. Both models predict the plate speed we measure today, so today's rate alone cannot tell them apart. The vertical axis is not to scale: meters per second is about a billion times faster than centimeters per year.

⏳ Thinking About Time

What the sign says. What the sign says: textbooks and museum signs say the Atlantic Ocean began opening about 180 to 200 million years ago and that the plates have crept along at a few centimeters per year ever since. The oldest ocean floor, they say, is about 180 million years old, from the time they call the Jurassic (a museum word). The number

comes from dividing the ocean’s width by today’s measured rate and from radiometric dates on seafloor rock, both of which assume rates that have never changed.

What we observe. What we observe: plates moving 1 to 15 centimeters per year, measured by GPS over about thirty years; a mid-ocean ridge with a central valley; deep trenches; magnetic stripes in the seafloor rock; cold, dense, slab-shaped rock imaged deep in the mantle by seismic waves; thick layers of water-laid sediment with sea fossils spread across the continents. No one has measured a plate’s speed in the distant past.

How Christians read it. How Christians read it: many creation geologists hold that the plates moved rapidly during the Flood year (Genesis 7–8), meters per second rather than centimeters per year, and that today’s slow creep is the tail end of that motion. On this reading the whole ocean floor is young because it formed during and just after the Flood, and the deep slabs are still cold because they sank recently. This model, catastrophic plate tectonics, has open questions, especially about heat, and mainstream geologists do not accept it. Both sides agree on what is measured; they differ on the history behind it.

Try it. Divide 5,000 km by 2.5 cm per year, then divide 5,000 km by 1 m per second. Write both answers and circle the one thing that changed between them.

Genesis 8:3

PICTURE STUDY



Winter, or The Flood (L’Hiver ou Le Déluge), Nicolas Poussin, 1660–1664 · Oil on canvas · Louvre Museum, Paris

Nicolas Poussin, a French painter who worked most of his life in Rome, painted four great landscapes of the seasons at the end of his career. For Winter he chose the Flood of Genesis

7. The scene is nearly colorless: gray water, black rock, a sky split by lightning. Water spills over a ledge in the middle of the picture, and tiny figures struggle in the foreground while the ark rides safely in the distance.

Poussin was not trying to show how the Flood worked. He was showing what it meant: a world undone by water, with one small vessel of safety floating through it. Keep that in mind as you study a scientific model of the same event. The model asks how; the painting asks what it was like.

Look closely

- Find the ark. Why do you think Poussin made it so small and far away?
- Follow the water. Where is it coming from, and where is it going? Find the place where it pours over rock.
- Look at the people in the boat. What are they doing with the child?
- Notice the lightning and the dark clouds. What does the sky tell you about the rain?

Talk about it

1. Genesis 7:11 names two sources of the Flood's water. Which one does the painting show, and which does catastrophic plate tectonics try to explain?
2. Why would an artist choose gray and black for this scene instead of bright colors?
3. The ark is the only safe place in the picture. What does that say about God's judgment and God's mercy together?

> **Safety first.** Use warm tap water only, never boiling water or the stove, and have a parent nearby. Honey jars can be slippery when wet; wipe spills right away.

EXPERIMENT: HOT HONEY, FAST MARBLE: TESTING THE RUNAWAY IDEA

The whole idea of runaway subduction rests on one fact: hot rock flows more easily than cold rock. You cannot heat the mantle in your kitchen, but you can test the same rule with honey. You will time a marble sinking through cold honey and through warm honey.

Question: Does warming honey make a marble sink through it faster, and by how much? Prediction: write the sinking time in seconds you expect for cold honey and for warm honey.

You will need

- Two identical tall clear jars or drinking glasses
- Enough honey (or corn syrup) to fill each jar about 10 cm deep
- Two identical marbles
- A bowl of ice water and a bowl of warm tap water (about 40 °C, comfortable to the hand)
- A kitchen thermometer if you have one, a stopwatch or phone timer, a ruler
- Science notebook and pencil

Steps

1. Pour honey into both jars to exactly the same depth, about 10 cm. Measure and record the depth.
2. Stand one jar in the ice water and the other in the warm tap water for 15 minutes. If you have a thermometer, record the honey temperature in each jar.
3. What we change: the temperature of the honey. What we keep the same: the honey depth, the marble, the drop height (release the marble just touching the surface), the jar. What we measure: seconds for the marble to reach the bottom.
4. Release a marble at the surface of the cold honey and start the timer. Stop when it touches the bottom. Record the time.
5. Do the same with the warm honey. Then fish out the marbles with a spoon, wipe them, and repeat each test two more times. Average the three times for each jar.
6. Divide the cold time by the warm time. That number tells you how many times faster the marble sank in warm honey.
7. Write a paragraph connecting your result to runaway subduction: a sinking slab heats the rock around it, the hotter rock weakens, and the slab sinks faster. Which part of that chain did your experiment test?

Tips

- Honey at refrigerator temperature can be so thick that the marble takes a minute or more. Be patient and keep timing.
- A rock slab in the mantle heats the rock around it by pushing and rubbing. Your marble does not heat the honey much, so you supplied the heat with the warm water bath. That is a difference between the model and the real earth worth writing down.

Check your work

- I can run a fair test by changing only the temperature and keeping depth, marble and drop height the same.
- I can average three trials and compare two averages as a ratio.
- I can explain how my result connects to the idea of a runaway: heat lowers viscosity, and lower viscosity means faster sinking.

FIELD NOTEBOOK

1. Draw a four-panel cartoon of catastrophic plate tectonics: cold ocean floor begins to sink; runaway sinking pulls continents apart while new seafloor rises; oceans flood the land and steam jets rise at the ridges; the new floor cools and sinks and the waters drain. Label each panel.
2. Copy the rate graph from this lesson. Mark where today’s GPS measurement sits and write why both curves pass through that point.
3. Record your honey data in a table with columns for jar, temperature, trial 1, trial 2, trial 3 and average. Write the ratio of cold to warm at the bottom.

From history. Baumgardner's TERRA program did not stay inside creation science. In the 1990s other geophysicists used it to study how the whole mantle flows, and in 1996 he was a co-author of a paper in the journal Nature that used TERRA to show how the mantle's flow pattern changes when rock deeper down is stiffer than rock near the surface. The same tool served mainstream research and a Flood model at once, because a good computer model simply follows the physics it is given. It was Snider-Pellegrini, back in 1858, who first tied the splitting of the continents to the Flood; Baumgardner gave that old idea equations and a computer.

WORKED EXAMPLES

Example 1. The Atlantic is about 5,000 km wide. (a) A textbook assumes it has always opened at today's 2.5 cm per year. How long would that take? (b) Catastrophic plate tectonics proposes speeds of about 1 m per second during the Flood year. How long would 5,000 km take at that rate?

1. (a) Convert the width to centimeters: 5,000 km × 1,000 m/km × 100 cm/m = 500,000,000 cm.
2. (a) Time = distance ÷ rate = 500,000,000 cm ÷ 2.5 cm/yr = 200,000,000 years. This is how a textbook gets about 200 million years. It assumes the rate never changed.
3. (b) Convert the width to meters: 5,000 km × 1,000 m/km = 5,000,000 m.
4. (b) Time = 5,000,000 m ÷ 1 m/s = 5,000,000 s. Divide by 86,400 s per day: 5,000,000 ÷ 86,400 ≈ 58 days.
5. Same distance, same arithmetic, different assumed rate: about 200 million years or about two months.

Answer: (a) About 200 million years if the rate was always 2.5 cm/yr. (b) About 58 days at 1 m/s. The age depends entirely on the rate you assume for the past.

Example 2. Convert a plate speed of 1 m per second into kilometers per day. Then find how many times faster it is than 2.5 cm per year.

1. Seconds in a day: 60 × 60 × 24 = 86,400 s. So 1 m/s × 86,400 s = 86,400 m per day = 86.4 km per day.
2. Seconds in a year: 86,400 × 365 = 31,536,000 s. So 1 m/s = 31,536,000 m per year = 3,153,600,000 cm per year.
3. Ratio: 3,153,600,000 cm/yr ÷ 2.5 cm/yr ≈ 1,260,000,000.

Answer: 1 m/s is 86.4 km per day, about 1.26 billion times faster than 2.5 cm per year. That is why the graph's vertical axis cannot be drawn to scale.

Example 3. Use the rate graph for this lesson. (a) Which model predicts a higher plate speed at the left side (the Flood year)? (b) What speed do both models predict at the right side (today)? (c) Why can a GPS measurement made today not decide between the two models?

(Use the map or drawing "Read the left end for the Flood year and the right end for today." shown earlier in this lesson.)

1. (a) Read the left side: the solid curve (catastrophic plate tectonics) is high, at meters per second; the dashed line (uniform model) is low, at 2.5 cm per year.
2. (b) Read the right side: both lines meet at about 2.5 cm per year.
3. (c) GPS has measured plates only since about the 1990s, which is at the far right of the graph where the curves overlap. A measurement inside the overlap fits both.

Answer: (a) Catastrophic plate tectonics. (b) About 2.5 cm per year for both. (c) Because both models predict the same speed today; only evidence about the past, such as the cold deep slabs, the sediments and the magnetic stripes, can test them against each other.

PRACTICE

1. EASY Who proposed catastrophic plate tectonics, where did he work, and what did his computer program TERRA calculate?
2. EASY What does the word runaway mean in runaway subduction?
3. EASY In the model, why would a brand-new hot ocean floor raise the sea over the continents?
4. MEDIUM Convert 2.5 cm per year to millimeters per year. At that rate, how many years would it take a plate to move 1 km?
5. MEDIUM A student timed a marble sinking through 10 cm of honey at three temperatures. At 5 °C: 48, 50, 46 seconds. At 20 °C: 20, 22, 21 seconds. At 40 °C: 6, 7, 6 seconds. (a) Find the average time at each temperature. (b) How many times faster did the marble sink at 40 °C than at 5 °C? (c) Which conclusion do the data support? A. Temperature has no effect on sinking time. B. Warmer honey slows the marble. C. Warmer honey lets the marble sink faster.
6. MEDIUM Explain in two sentences how the model connects "the fountains of the great deep" (Genesis 7:11) to the mid-ocean ridges.
7. HARD Look at the rate graph. (a) In which part of the graph do the two models disagree the most? (b) At what point do they agree exactly? (c) A friend says, "GPS proves the plates have always moved slowly." Using the graph, explain what is right and what is wrong about that sentence.
   (Use the map or drawing "Use this graph for item 7." shown earlier in this lesson.)
8. HARD A museum sign reads: "The Atlantic has been opening at about 2.5 cm per year for 200 million years." (a) Which part of the sentence is a measurement? (b) Which part is an assumption? (c) State in one sentence how a creation geologist reads the same ocean, and in one sentence how a mainstream geologist replies.

9. HARD Design an experiment to test whether a thicker (more viscous) liquid slows a sinking marble more than a thinner one, using water, cooking oil and honey. Name the independent variable, the dependent variable, three controls and how many trials you would run.
10. CHALLENGE In three or four sentences, explain why heat is the hardest open question for catastrophic plate tectonics, and why admitting an open question is a sign of good science rather than weak science.

COMMON MISTAKES

- Thinking that measuring today's plate speed proves how long the plates have been moving. A rate becomes an age only when you assume the rate never changed.
- Thinking creation geologists deny that the plates move. They accept the plates, the ridges, the trenches and the GPS measurements. They question the history and timescale.
- Thinking a scientific model is finished and final. Catastrophic plate tectonics has open questions, and so does the mainstream model. Good scientists on both sides say what they still do not know.

Make it a game · Sign, Observe, Read. Your parent reads a sentence a museum sign might say about the ocean floor, such as "This basalt formed 100 million years ago," "The plates move 2.5 cm a year," or "The seafloor has magnetic stripes." You sort each one into Sign (a claim about the past that rests on an assumption), Observe (something measured today) or Read (an interpretation either side could give). Explain your choice in one sentence to earn the point. Then switch roles and make up sentences for your parent to sort. Play to ten.

Scripture. "In the six hundredth year of Noah's life, in the second month, the seventeenth day of the month, the same day were all the fountains of the great deep broken up, and the windows of heaven were opened." (Genesis 7:11, KJV)

Genesis names a day, a month and a year, and two sources of water: the deep below and the heavens above. Catastrophic plate tectonics is one attempt to ask what "the fountains of the great deep" could have been. The Scripture is history; the model is a proposal to be tested.

Practice answers

1. John Baumgardner, a geophysicist at Los Alamos National Laboratory. TERRA divided the mantle into cells and calculated how hot solid rock flows over time.
2. Each step makes the next step stronger: the sinking slab heats and weakens the rock around it, which lets it sink faster, which heats the rock more. The process speeds itself up until the slab is gone.
3. Hot rock is less dense and stands higher than cold rock, so a new hot sea bottom would rise and push the ocean water up and out over the land.
4. 2.5 cm = 25 mm per year. 1 km = 100,000 cm; 100,000 ÷ 2.5 = 40,000 years.

5. (a) 5 °C: 144 ÷ 3 = 48 s. 20 °C: 63 ÷ 3 = 21 s. 40 °C: 19 ÷ 3 ≈ 6.3 s. (b) 48 ÷ 6.3 ≈ 7.6, about 7 to 8 times faster. (c) C.
6. In the model, hot new rock rose along thousands of kilometers of ridges while seawater poured over it, flashing into steam that jetted upward. Baumgardner reads those jets of water and steam from the sea floor as the fountains of the great deep breaking up.
7. (a) At the left, during the Flood year, where the catastrophic curve is at meters per second and the uniform line is at centimeters per year. (b) At the right end, today, where both give about 2.5 cm per year. (c) Right: GPS proves the plates move slowly now. Wrong: GPS has measured only the last few decades, where both curves overlap, so it says nothing about how fast they moved in the past.
8. (a) The rate, 2.5 cm per year, is measured by GPS. (b) That the rate has been the same for the whole past is an assumption; the 200 million years comes from that assumption. (c) A creation geologist reads the Atlantic as having opened rapidly during the Flood year with the motion slowing afterward. A mainstream geologist replies that radiometric dates and magnetic stripes on the seafloor fit a steady rate and that there is no known way to carry away the heat of such rapid motion.
9. Independent variable: the liquid (water, oil, honey). Dependent variable: time in seconds for the marble to sink to the bottom. Controls: same marble, same liquid depth, same temperature (all at room temperature), same release point at the surface, same jar shape. Run three trials in each liquid and average them. Prediction: honey slowest, water fastest.
10. Sinking an entire ocean floor and forming a new one in months would release an enormous amount of heat, and new seafloor normally takes a very long time to cool. The model needs a way to carry that heat away quickly, and proposals such as rapid cooling by steam are still being studied. Admitting this is good science because every model has limits, and saying where they are tells others exactly what to test next. A model that claimed to have no problems would be harder to trust, not easier.

Unit 2 review

Answer each question. Show your work for calculations, label every part of the diagram, and use complete sentences for explanations. The test is worth 60 points.

1. (4 pts) Antonio Snider-Pellegrini’s two maps of 1858 proposed that the continents were split apart: A. slowly over a very long time. B. suddenly during the Flood of Noah’s day. C. by the sinking of land bridges. D. by the tides.
2. (4 pts) Alfred Wegener, who presented continental drift in 1912, was by training a: A. geologist. B. meteorologist. C. sea captain. D. mapmaker.
3. (6 pts) Give two reasons most geologists rejected Wegener’s hypothesis in the 1920s, and name one discovery from the ocean floor in the 1950s or 1960s that changed their minds.
4. (6 pts) List the four kinds of evidence that the continents were once joined. Write one sentence for each, giving a real example.
5. (6 pts) On a map with the scale 1 cm = 500 km, the gap between Brazil and West Africa measures 5.8 cm. (a) How many kilometers is that? (b) Mesosaurus was about 1 m long. How many body lengths would it have had to swim to cross that gap? (c) Give one more reason it could not have swum across.
6. (4 pts) The continents fit together better along the edge of the continental shelf than along the shoreline because: A. the shelf is made of ocean-floor basalt. B. the shoreline is the true edge of the continent. C. the shelf is drowned continental rock, and the shoreline is just where the sea reaches today. D. maps of shorelines are less accurate.
7. (8 pts) Diagram: Draw a cross-section of a convergent boundary where an ocean plate meets a continent. Label the ocean, the trench, the sinking ocean plate, the continental plate, the asthenosphere beneath and a volcano on the continent. Add arrows showing the direction each plate moves, and name one real place where this happens.
8. (6 pts) (a) The Pacific plate slides past the North American plate along the San Andreas Fault at about 5 cm per year. If a fence crossing the fault jumps 4 m in an earthquake, how many years of stored motion were released? (b) The East Pacific Rise spreads at about 15 cm per year and the Mid-Atlantic Ridge at about 2.5 cm per year. How many times faster is the East Pacific Rise?
9. (4 pts) Which of these is a transform boundary, where plates slide past each other sideways? A. The Mid-Atlantic Ridge. B. The Mariana Trench. C. The San Andreas Fault. D. The East African Rift.
10. (6 pts) Describe John Baumgardner’s model of catastrophic plate tectonics in four steps, in order.
11. (6 pts) A textbook says: “The Atlantic has been opening at 2.5 cm per year for about 200 million years.” (a) Which part is a measurement and which part is an assumption? (b) Why do both the mainstream model and catastrophic plate tectonics predict the same plate speed today? (c) Name one observation that each side points to in support of its reading.

UNIT PROJECT: MY PLATE ATLAS

Make a large hand-drawn world map showing the seven major plates with their boundaries drawn in three colors: one for divergent, one for convergent (with small teeth pointing toward the overriding plate) and one for transform. Label at least ten real features from the unit, such as the Mid-Atlantic Ridge, Iceland, the East African Rift, the Peru–Chile Trench and Andes, the Mariana Trench, Japan, the Himalaya, the San Andreas Fault and Hawaii, and add arrows with plate speeds in centimeters per year where you know them.

Bind the map with three more pages: your fitted continent puzzle with the fossil zones colored and your gap measurements; your graham-cracker collision data and bar graph; and a "Two Readings" page that works the Atlantic's opening both ways (at 2.5 cm per year and at 1 m per second), names the assumption that changed, and states what the sign says, what we observe and how Christians read it.

- **Accuracy**: Plates, boundary types and the ten features are placed and labeled correctly, and plate speeds are the measured values from the unit.
- **Evidence**: The continent puzzle shows fossil zones that meet across the join and includes the measured gaps with their average and conversion to kilometers.
- **Data and calculation**: The cracker experiment table and bar graph are complete, and the Two Readings page shows both calculations with correct units and arithmetic.
- **Fair reasoning**: The Two Readings page states the measurement, the assumption and both readings accurately and respectfully, without mocking either side.

Answer key

1. B.
2. B. He was a meteorologist, a scientist of weather, which was one reason geologists did not take him seriously.
3. Reasons (any two): he could not supply a strong enough cause, since tides and pole-fleeing forces were far too weak; continents plowing through solid ocean floor seemed impossible; land bridges could explain some fossils; he was an outsider. Discovery (any one): the Mid-Atlantic Ridge with its central rift valley; seafloor spreading (Hess, 1962); the magnetic stripes on the ocean floor (1963); earthquake belts outlining the plates.
4. Fit of the coasts: South America and Africa fit tightly along the edge of the continental shelf. Fossils: Mesosaurus, a small freshwater reptile, is found only in Brazil and South Africa; Glossopteris is found on five continents including Antarctica. Rock belts: the Appalachians continue in the mountains of Scotland and Norway. Glacial evidence: ice scratches in Africa, India, Australia and South America point outward from one center when the continents are fitted together.
5. (a) 5.8 × 500 = 2,900 km. (b) 2,900 km = 2,900,000 m, so 2,900,000 body lengths. (c) Mesosaurus lived in fresh water and the Atlantic is salt water.
6. C.
7. The drawing shows an ocean plate bending down beneath the continental plate at a trench just offshore, with arrows on the ocean plate pointing toward the continent and down, the asthenosphere below both plates, and a volcano on the continent above the sinking slab. Real

example: the Peru–Chile Trench and the Andes, or Japan (ocean beneath island arc) with a note that it is similar. Full credit requires all six labels, the arrows and a real example.

8. (a) 4 m = 400 cm; 400 ÷ 5 = 80 years. (b) 15 ÷ 2.5 = 6 times faster.
9. C. The Mid-Atlantic Ridge and East African Rift are divergent; the Mariana Trench is convergent.
10. 1. Cold, dense pre-Flood ocean floor begins to sink into the mantle. 2. Runaway subduction: the sinking slab heats and weakens the surrounding rock, which lets it sink faster, until the whole old ocean floor plunges into the mantle within weeks, pulling the continents apart. 3. Hot new ocean floor rises at the ridges; it stands high and lifts the seas over the continents, while seawater flashing to steam at the ridges jets upward and falls as rain (the fountains of the great deep). 4. When the old floor is gone the runaway ends; the new floor cools and sinks, the waters drain off the land, and the plates slow to today's centimeters per year.
11. (a) The 2.5 cm per year is measured by GPS; that the rate has been the same for the whole past is an assumption, and the 200 million years follows from it. (b) Because GPS has only measured the last few decades, and in both models the plates move slowly now; the catastrophic model has the fast motion in the past and the slow tail today. (c) Mainstream: magnetic stripes and radiometric dates on the seafloor that fit a steady rate. Creation geologists: cold slab-shaped rock deep in the mantle, thick water-laid sediments with sea fossils across the continents, and an ocean floor that is young even by the textbook's own counting.

UNIT 3

Volcanoes

“He toucheth the hills, and they smoke” (Psalm 104:32). A volcano is a place where the hot interior of the earth, which you studied in Unit 1, breaks through the plates you studied in Unit 2. In this unit you will meet four real eruptions, each watched and written down by real people: Vesuvius in A.D. 79, seen across the bay by a seventeen-year-old named Pliny; Krakatoa in 1883, whose sound carried 4,800 km and whose pressure wave was recorded by instruments on every continent; Parícutin in 1943, a volcano that was born in a Mexican cornfield and watched for its whole nine-year life; and Surtsey in 1963, a brand-new island that rose from the sea off Iceland and turned to hard rock within a few years.

Along the way you will learn how pumice and ash fall, what a pyroclastic flow is, why some magma explodes and some flows gently, and how to tell a shield volcano from a composite cone from a cinder cone by its shape. You will measure like a volcanologist: rates in centimeters per hour and meters per day, the speed of sound from distance and time, height-to-width ratios, scale models and growth curves. Each lesson has an experiment with household materials, from a flour eruption column to honey lava to a sand island facing waves.

Above all you will practice the first rule of science, which Pliny the Younger, Rogier Verbeek, the watchers at Parícutin and the geologists on Surtsey all followed: observe carefully, measure what you can, write it down, and do not assume more than you have seen.

BEFORE YOU BEGIN

- Knows the crust, mantle and core and that the mantle is hot rock (Unit 1)
- Can name the three kinds of plate boundaries and locate the Mid-Atlantic Ridge and the Pacific Ring of Fire on a map (Unit 2)
- Can convert between meters and centimeters, kilometers and meters, and hours and minutes
- Can divide to find a rate (distance ÷ time, depth ÷ time) and read a simple line graph

MASTERY CHECKLIST

- I can retell the eruptions of Vesuvius (A.D. 79), Krakatoa (1883), Parícutin (1943) and Surtsey (1963) with their places, dates and the people who recorded them.
- I can explain the stages of a Plinian eruption: the eruption column, the pumice fall and the pyroclastic flows.
- I can explain how dissolved gas, silica and temperature control how violently a volcano erupts and what shape it builds.
- I can classify a volcano as shield, composite or cinder cone from its profile and name a real example of each.
- I can calculate a rate (cm per hour, m per day, km per hour) from measurements and judge whether that rate can be assumed to stay constant.

- I can read a data table or graph about an eruption and say which conclusion the data support.

OPTIONAL BOOKS AND RESOURCES

- **USGS Volcano Hazards Program** (https://www.usgs.gov/programs/VHP): Free. Photographs, maps and plain-language pages on volcano types, eruption products and current activity at U.S. volcanoes, including the Hawaiian Volcano Observatory. Good for checking facts in Lessons 3.3 and 3.4.
- **Smithsonian Global Volcanism Program** (https://volcano.si.edu/): Free. A searchable database of the world's volcanoes with eruption histories, photographs and a weekly activity report. Look up Vesuvius, Krakatau, Parícutin and Surtsey as you study each lesson.
- ***Letters of Pliny*** **(free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/2811): Free. An older English translation of Pliny the Younger's letters. A parent can read aloud the two letters to Tacitus about the eruption of Vesuvius (Book VI, letters 16 and 20) for Lesson 3.1.

3.1 Vesuvius and Pompeii, A.D. 79: Pliny Watches the Mountain ★

OBJECTIVES

- Retell the eruption of Vesuvius in A.D. 79 from the two letters of Pliny the Younger and explain why geologists call it a Plinian eruption.
- Describe the two stages of the eruption, the pumice fall and then the pyroclastic flows, and read a layer column of what buried Pompeii.
- Calculate a rate of pumice fall in centimeters per hour and the mass of pumice resting on a Roman roof.

Warm-up. Fill a tall glass with water. Drop in a small pinch of flour, then a pinch of sand, then a pinch of dry oats, and watch which settles fastest and which stays up longest. Write the order in your notebook. A volcano's cloud sorts its load the same way: heavy stones fall close to the mountain, and the finest dust drifts farthest and settles last.

Video. Coming soon. Vesuvius A.D. 79 eruption, Pompeii and Herculaneum, Plinian eruption column and pyroclastic flows, Pliny the Younger's letters; search USGS, Smithsonian, the British Museum, SciShow and documentary channels, and choose clips that show the ruins and the science without human remains.

KEY TERMS

eruption column
The tall, rising cloud of hot gas, ash and pumice that a powerful volcano pushes into the sky, sometimes more than 30 km high.

pumice
Frothy volcanic rock so full of gas bubbles that it is light enough to float on water.

volcanic ash
Tiny bits of volcanic rock and glass, smaller than 2 mm, blown out of a volcano. It is hard and gritty, not soft like fireplace ash.

tephra
All the solid material a volcano throws into the air, from fine ash to pumice to large blocks.

pyroclastic flow
A fast, ground-hugging avalanche of hot gas, ash and rock that rushes down a volcano's sides at more than 100 km per hour.

Plinian eruption
A very explosive eruption with a tall, steady column that rains pumice over a wide area, named after Pliny the Younger, who described the first one on record.

CORE IDEAS

The story. In the year A.D. 79 a Roman youth of seventeen named Pliny was studying at his uncle's house at Misenum, on the north point of the Bay of Naples. His uncle, Pliny the Elder, commanded the Roman fleet there and had written a thirty-seven book encyclopedia of nature. Early one afternoon (the traditional date is August 24, though some scholars now argue for autumn) his mother pointed out a strange cloud rising across the bay, about 30 km away. Pliny later wrote that it looked like an umbrella pine: a tall trunk that spread into branches at the top. His uncle, curious, ordered a boat to go and look, and when a message came from a friend trapped near the mountain, the trip became a rescue. Pumice stones and ash rained on the ships. The helmsman urged him to turn back, but the old admiral held his course, landed at Stabiae, calmed his frightened friends and even slept. By morning the courtyard was filling with pumice, and the party went down to the shore with pillows tied over their heads. There, in the thick fumes, Pliny the Elder died. Back at Misenum, young Pliny and his mother felt the ground shake, saw the sea drawn back from the shore, and walked out of town under a darkness he said was not like a cloudy night but like a lamp put out in a shut room. They lived, and about twenty-five years later he wrote two letters to the historian Tacitus telling exactly what he had seen.

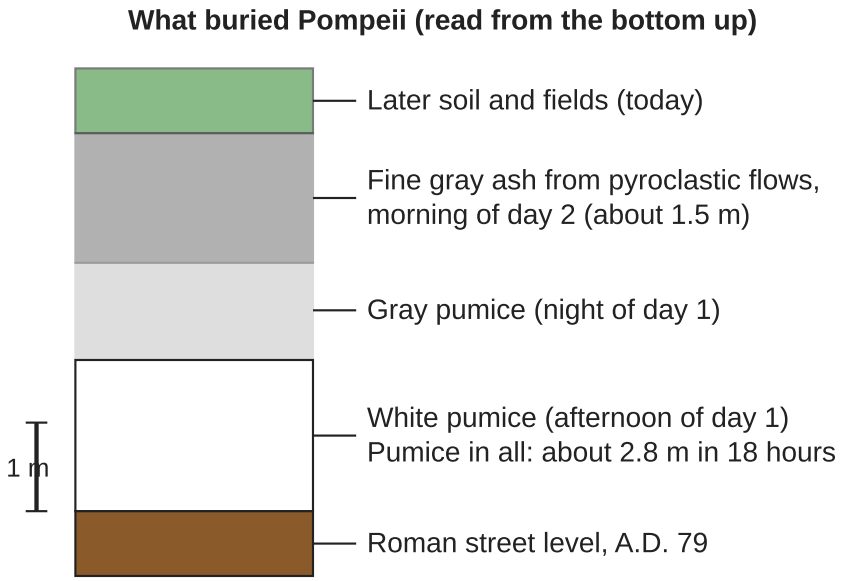
How they figured it out. Pompeii, 10 km southeast of the summit, and Herculaneum, 7 km to the west, lay buried and nearly forgotten until diggers found Herculaneum in 1738 and Pompeii in 1748. Geologists later read the ground like a book. At Pompeii the bottom layer is nearly 3 m of pumice, white below and gray above, that fell for about eighteen hours at roughly 15 cm an hour. Roofs sagged and then collapsed under its weight. Above the pumice lie thin gray beds of fine ash laid down the next morning by pyroclastic flows, hot avalanches of gas and ash that raced down the slopes faster than a car. Herculaneum, upwind, received almost no pumice but was buried under about 20 m of those flows. In the 1980s volcanologists such as Haraldur Sigurdsson matched the layers, hour by hour, to Pliny's letters. The young man's notes and the rocks agree: first the falling stones, then the deadly flows.

The big idea. Vesuvius erupted the way it did because its magma was thick and full of dissolved gas. When that gas came out of solution it blew the magma into frothy **pumice**, rock so full of bubbles that it floats, and into fine **ash**, which is tiny shards of volcanic glass, not the soft ash of a fireplace. The gas drove an **eruption column** more than 30 km into the sky, far higher than airliners fly. Wind carried the column's load southeast, so Pompeii received the pumice fall and Herculaneum did not. When the gas supply weakened, the column could no longer hold itself up and collapsed, sending **pyroclastic flows** down the mountain at more than 100 km per hour and several hundred degrees Celsius. Geologists now call any eruption with a tall, sustained column a **Plinian eruption**, after the young man who described the first one on record.

In the world today. Vesuvius stands 1,281 m tall and last erupted in 1944. About 600,000 people live in the zone an eruption could reach, so the Osservatorio Vesuviano, founded in 1841 as the world's first volcano observatory, watches the mountain day and night with seismometers, gas sensors and tiltmeters (you will meet these tools in Lesson 8.2). Pompeii

itself is now an open-air city of stone streets, bakeries, fountains and painted walls, visited by millions. Loaves of bread, turned to charcoal in a baker's oven on the day of the eruption, still sit in a museum case, and the vineyards on the mountain's slopes grow in soil made from its own ash.

God's handiwork. The Psalmist sang, "he toucheth the hills, and they smoke" (Psalm 104:32). A volcano is a window into the hot interior God made beneath our feet, and the same ash that buried a city makes some of the richest farmland on earth. Pliny the Younger shows us two kinds of courage: his uncle's, who sailed toward danger to help his friends, and his own, who kept his eyes open and wrote down what he saw. Observing carefully and telling the truth about it is the first work of a scientist.



What buried Pompeii, read from the bottom up: about 18 hours of pumice fall, then the thin ash beds of the next morning's pyroclastic flows.

PICTURE STUDY



Vesuvius in Eruption, with a View over the Islands in the Bay of Naples, Joseph Wright of Derby, about 1776–1780 · Oil on canvas · Tate Britain, London

Joseph Wright of Derby was an English painter who loved strong light in darkness: candlelit experiments, glowing iron forges and moonlit landscapes. In 1774 he traveled to Naples and saw Vesuvius restless and smoking. The mountain so gripped him that he painted it about thirty times after he came home.

Here he gives us the eruption at night. Fire bursts from the summit, a great cloud climbs over it, and lava glows down the slope, while the calm moon lights the bay and the islands beyond. Wright knew the ancient story of Pliny, and he wanted his viewers to feel both the terror and the wonder of the mountain.

Look closely

- Find the two kinds of light in the picture: the fire of the volcano and the cool light of the moon. Which parts of the scene does each one light up?
- Trace the shape of the eruption cloud. Does it look like the umbrella pine Pliny described, with a trunk and spreading top?
- Look for the glowing streams on the mountainside. Are these lava flows or falling pumice? How can you tell?
- Find the water and the islands. Where would Pliny have been standing, across the bay, to see a sight like this?

Talk about it

1. Why do you think Wright chose to paint the eruption at night instead of by day?

2. Pompeii was buried mostly by pumice and ash, not lava. Does the painting show that part of the danger? What would an ash fall look like in a painting?
3. What feeling does the painting give you: fear, beauty or both? What in the picture makes you feel that way?

EXPERIMENT: ASH-FALL MAP: HOW DOES FALLOUT CHANGE WITH DISTANCE?

Pompeii, 10 km downwind, was buried under nearly 3 m of pumice, while Herculaneum, 7 km upwind, got hardly any. In this experiment you will make a small eruption column of flour and measure how much lands at different distances, first in still air and then with a fan playing the part of the wind.

Question: How does the mass of fallen “ash” change with distance from the vent, and how does wind change the pattern? Write your prediction before you begin.

You will need

- 1 cup of flour (or fine dry sand)
- A kitchen sieve or flour sifter
- 8 squares of paper, each 10 cm by 10 cm, labeled N0, N10, N20, N30 and S0, S10, S20, S30
- A kitchen scale that reads in grams
- A ruler or tape measure and masking tape
- A large tray, a clean floor or an outdoor table, plus a broom
- A small fan (optional, for the wind trial)

Steps

1. Mark a “vent” with tape in the middle of the tray. Lay the N squares in a line out from the vent at 0, 10, 20 and 30 cm, and the S squares in the opposite direction at the same distances. Weigh each empty square and write the mass down.
2. Hold the sieve 30 cm above the vent (measure it). Pour in half a cup of flour and shake gently for 20 seconds. This is your eruption column: the sieve height, the amount of flour and the shaking time are the things you keep the same.
3. Carefully weigh each square with its flour. Subtract the empty mass to get the mass of fallout. Record it in a table with columns: Square, Distance (cm), Fallout (g).
4. Clean up, lay out fresh squares and repeat the whole trial once more. Average the two results for each distance.
5. Now add wind. Set a fan on low about 50 cm from the vent, blowing from N toward S, and repeat the eruption. Weigh and record again.
6. Draw two bar graphs, one for still air and one for wind, with distance on the bottom and fallout mass on the side. Mark which side of your map is the “Pompeii side.”
7. Write a conclusion: Was your prediction right? How did wind change the pattern? Which real town does each side of your map stand for?

Tips

- If the flour mass is too small to read on your scale, use a bigger sieve and a full cup of flour, or shake longer, but keep it the same in every trial.
- Real pumice falls are sorted by size too: big pieces land near the vent, fine ash far away. Look at your squares with a magnifier and see if your flour shows any sorting.

Check your work

- I kept the sieve height, flour amount and shaking time the same in every trial.
- I measured fallout by mass in grams at four distances and recorded it in a table.
- I can explain why Pompeii and Herculaneum received such different amounts of pumice.

FIELD NOTEBOOK

1. Draw a map of the Bay of Naples from memory of the lesson: Vesuvius, Pompeii (10 km southeast), Herculaneum (7 km west), Stabiae and Misenum (30 km away). Add an arrow for the wind on the day of the eruption.
2. Copy the Pompeii layer column from the figure, label each layer, and write beside it the time of day it was laid down.
3. Write a half-page letter in the voice of Pliny the Younger describing one thing he saw, using only plain observations and no guesses.

> **From history.** When the bakery of Modestus in Pompeii was excavated in the 1860s, workers opened its oven and found 81 round loaves of bread still inside, scored into wedges and turned to charcoal, left baking on the day the mountain erupted. Bread, eggs, walnuts and figs preserved by the eruption give historians a clearer picture of an ordinary Roman kitchen than any book.

WORKED EXAMPLES

Example 1. At Pompeii about 2.8 m of pumice fell in roughly 18 hours. What was the average rate of fall in centimeters per hour, and how deep was the pumice after the first 6 hours?

(Use the map or drawing “The pumice layer is the thick one at the bottom.” shown earlier in this lesson.)

1. Change meters to centimeters: 2.8 m = 280 cm.
2. Rate = depth ÷ time = 280 cm ÷ 18 h ≈ 15.6 cm per hour, or about 15 cm an hour.
3. After 6 hours: 15.6 cm/h × 6 h ≈ 93 cm, nearly a meter, already above an adult’s knees.

Answer: About 15.6 cm per hour; after 6 hours the pumice was roughly 93 cm deep (nearly 1 m).

Example 2. A Roman house roof measures 8 m by 5 m. Pumice fall has piled 1.0 m deep on it. If a loose pumice deposit has a density of about 500 kg per cubic meter, what mass is resting on the roof? Compare it to small cars of 1,500 kg each.

1. Roof area = 8 m × 5 m = 40 m^2.
2. Volume of pumice = area × depth = 40 m^2 × 1.0 m = 40 m^3.
3. Mass = volume × density = 40 m^3 × 500 kg/m^3 = 20,000 kg, which is 20 tonnes.
4. 20,000 kg ÷ 1,500 kg per car ≈ 13 cars' worth of weight on one roof.

Answer: About 20,000 kg (20 tonnes), roughly the mass of 13 small cars. No wonder roofs collapsed.

Example 3. Pliny watched from Misenum, about 30 km from Vesuvius. The eruption column is estimated to have reached about 32 km high, and the mountain itself is about 1.3 km tall. On a drawing with a scale of 1 cm = 5 km, how long is the line from Misenum to the volcano, how tall is the column, and how tall is the mountain? How many times taller than the mountain was the column?

1. Distance: 30 km ÷ 5 km per cm = 6 cm.
2. Column: 32 km ÷ 5 km per cm = 6.4 cm.
3. Mountain: 1.3 km ÷ 5 km per cm = 0.26 cm, barely a pencil line.
4. Ratio: 32 km ÷ 1.3 km ≈ 25. The column towered about 25 times higher than the mountain that made it.

Answer: 6 cm across, 6.4 cm up for the column, 0.26 cm for the mountain; the column was about 25 times the height of Vesuvius.

PRACTICE

1. EASY What is pumice, and why does it float on water?
2. EASY Who wrote the two letters that describe the A.D. 79 eruption, to whom were they written, and about how long after the event?
3. EASY Put these events in the order they happened: pyroclastic flows reach Pompeii; eruption column rises; pumice falls on Pompeii for many hours; roofs collapse under pumice.
4. MEDIUM If pumice fell at 15 cm per hour, how deep was it after 4 hours? After 12 hours? Give both answers in meters.
5. MEDIUM Data reading. The table shows deposits at three places around Vesuvius.

   Place | Distance from summit | Direction | Pumice fall | Pyroclastic flow deposits
   Pompeii | 10 km | southeast | about 2.8 m | thin ash beds on top
   Herculaneum | 7 km | west | less than 0.2 m | about 20 m

Misenum | 30 km | northwest | a light dusting | none

Which conclusion is best supported by the table? (a) Pumice fall is always thickest closest to the summit. (b) The wind during the eruption blew toward the southeast. (c) Pyroclastic flows travel farther than falling pumice. (d) Misenum was in more danger than Pompeii.

6. MEDIUM Data reading. Geologists reconstruct the eruption timeline roughly like this:

   Time | Event
   Day 1, about 1 p.m. | Eruption column first seen
   Day 1, afternoon to night | Pumice falls on Pompeii
   Day 2, about 1 a.m. | First pyroclastic flows reach Herculaneum
   Day 2, about 7 a.m. | Pyroclastic flows reach Pompeii
   Day 2, morning | Darkness and ash reach Misenum

   About how many hours passed between the column being seen and the flows reaching Pompeii? Why does that number matter for the people of Pompeii?
7. MEDIUM Explain in two or three sentences why Herculaneum received almost no pumice but was buried about 20 m deep.
8. HARD Experiment design. You want to test whether the height of the “eruption column” changes how far flour fallout spreads. Name the independent variable, the dependent variable, two things you must keep the same, and how you would measure the result.
9. HARD A shop roof of 12 m^2 carries the full 2.8 m of pumice. Using a deposit density of 500 kg/m^3, find the mass on the roof.
10. CHALLENGE Write a paragraph answering this: Why do scientists treasure Pliny’s letters, and what do the rock layers add that the letters cannot?

COMMON MISTAKES

- Thinking lava buried Pompeii. No lava reached the city; it was buried by falling pumice and then by pyroclastic flows of hot ash and gas.
- Thinking volcanic ash is soft like fireplace ash. It is tiny, sharp bits of rock and glass, heavy enough to collapse roofs and harmful to breathe.
- Thinking the city vanished in a single instant. Pumice fell for about 18 hours first, and many people fled during that time; the deadly flows came the next morning.

Make it a game · Pliny’s Hourglass. Your parent calls out an hour since the eruption column was first seen (1, 4, 8, 12, 18). You must say how deep the pumice is in Pompeii at 15 cm per hour, round to the nearest 10 cm, and name one thing Pliny saw or did at about that time. A correct depth scores a point; a correct event scores another. Then swap roles. First to ten wins, and the loser must describe the umbrella-pine cloud in one sentence.

Scripture. “He looketh on the earth, and it trembleth: he toucheth the hills, and they

> smoke.” (Psalm 104:32, KJV)

The Psalmist knew smoking mountains and trembling ground, and he saw in them the power of the God who made the earth. A volcano is frightening, but it is not out of His hand.

Practice answers

1. Pumice is frothy volcanic rock full of gas bubbles. The trapped bubbles make it less dense than water, so it floats.
2. Pliny the Younger wrote them to the historian Tacitus, about 25 years after the eruption.
3. Eruption column rises; pumice falls for many hours; roofs collapse under pumice; pyroclastic flows reach Pompeii the next morning.
4. 4 hours: 60 cm = 0.6 m. 12 hours: 180 cm = 1.8 m.
5. (b). Herculaneum is closer than Pompeii but got far less pumice, so distance alone does not explain the pattern; the pumice went downwind, to the southeast. Choice (a) is contradicted by Herculaneum, (c) is contradicted by the dusting at 30 km, and (d) is the opposite of what the data show.
6. About 18 hours. It means there was most of a day to leave the city before the flows came, and many people did escape during the pumice fall, though the deep pumice and collapsing roofs made leaving harder as the hours passed.
7. Herculaneum lay west of the volcano, upwind, so the pumice carried by the eruption column fell mostly to the southeast. But pyroclastic flows run down every side of the mountain regardless of wind, and Herculaneum, only 7 km away, was buried by flow after flow.
8. Independent variable: the height of the sieve above the vent (for example 20, 40 and 60 cm). Dependent variable: how far the flour spreads, measured as the mass on squares at set distances or the distance to the edge of the fallout. Keep the same: the amount of flour, shaking time, sieve, and no wind (fan off). Measure by weighing the squares in grams at each distance, repeating each height at least twice and averaging.
9. Volume = 12 m^2 × 2.8 m = 33.6 m^3. Mass = 33.6 m^3 × 500 kg/m^3 = 16,800 kg, almost 17 tonnes.
10. A strong answer says that Pliny’s letters are the first written eyewitness record of a great eruption, with real times, directions, the shape of the column, the earthquakes, the sea pulling back and the darkness, so they let geologists put a clock on the event. The layers add what no one could see from Misenum: exactly how much pumice fell at each place, the direction the wind carried it, the temperature and number of the pyroclastic flows, and what happened in Herculaneum and Pompeii themselves. Letters and layers checked against each other give a fuller and more trustworthy history than either alone.

3.2 Krakatoa, 1883: The Loudest Sound in Recorded History ★

OBJECTIVES

- Retell the eruption of Krakatoa on August 26 and 27, 1883, with its place, its stages and its effects on the Sunda Strait and the world.
- Explain how gas-rich magma and seawater made the explosions, how the island collapsed into a caldera, and how barographs recorded the pressure wave around the globe.
- Compute the speed of sound from distance and time data and read a distance-time graph.

Warm-up. Over the sink, with a parent's permission, open a fresh bottle of soda slowly and listen to the hiss. Now shake a second closed bottle hard for ten seconds, point it away from everyone and open it slowly. Write down what was different. The gas was dissolved in both bottles; shaking only helped it come out of solution all at once. Magma works the same way, and Krakatoa was a bottle shaken very hard.

Video. Coming soon. Krakatoa 1883 eruption, Sunda Strait, caldera collapse, barograph pressure wave and Anak Krakatau; search USGS, Smithsonian Global Volcanism Program, NOAA, SciShow and documentary channels, and choose clips that focus on the geology and the records rather than on the loss of life.

KEY TERMS

caldera
A large bowl-shaped hollow left when a volcano collapses into the emptied magma chamber beneath it.

magma chamber
A pocket of molten rock and gas under a volcano that feeds its eruptions.

pressure wave
A ripple of squeezed and stretched air that travels outward from an explosion at about the speed of sound.

barograph
An instrument that draws a continuous line of air pressure on a slowly turning paper drum.

tsunami
A series of long sea waves set off when a large amount of water is suddenly pushed, as by a collapsing volcano or an undersea earthquake.

Volcanic Explosivity Index (VEI)

A scale from 0 to 8 that ranks eruptions by how much tephra they throw out; each step up means about ten times more material.

CORE IDEAS

The story. Krakatoa was a small, forested island in the Sunda Strait between Java and Sumatra, then part of the Dutch East Indies and now Indonesia. It was about 9 km long, with three volcanic peaks, the tallest, Rakata, rising 813 m. It had been quiet for about two centuries. On May 20, 1883, it began to steam and throw ash, and through the summer sightseers took boats out to look. Then on the afternoon of Sunday, August 26, the eruption turned fierce. A black column climbed more than 25 km, ships in the strait were pelted with pumice, and explosions boomed through the night. On the morning of August 27 came four tremendous blasts, the greatest at about 10:02 a.m. People in Perth, Australia, about 3,100 km away, heard it. On the island of Rodrigues, 4,800 km across the Indian Ocean, the chief of police wrote down the sound of what he took to be distant gunfire. It is the loudest sound in recorded history. At Batavia (today's Jakarta), about 160 km away, the sky went dark at midday. Most of the island collapsed into the sea, and the collapse drove sea waves more than 30 m high onto the coasts of Java and Sumatra. About 36,000 people died, nearly all of them from the waves.

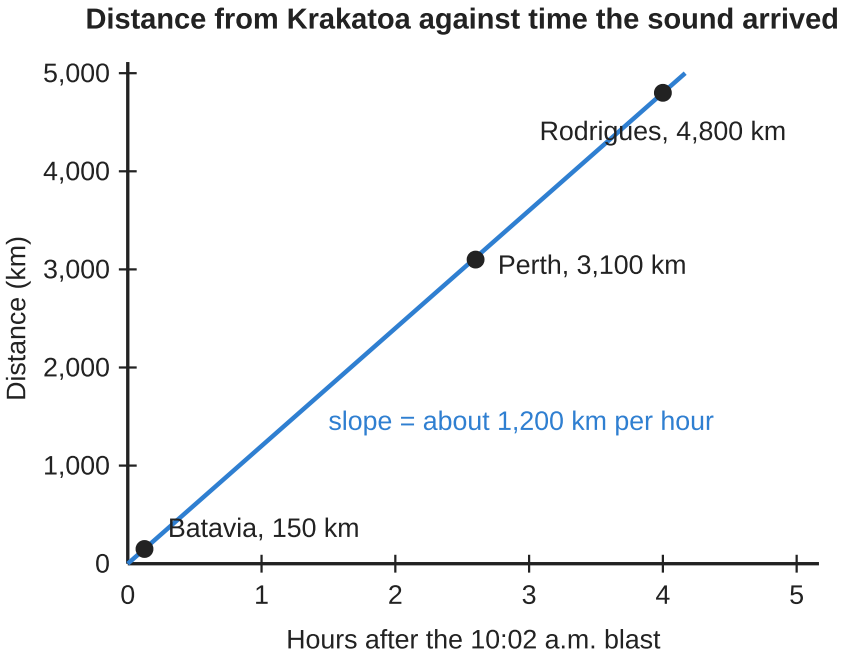
How they figured it out. The eruption was studied as no eruption had been before. The Dutch mining engineer Rogier Verbeek surveyed the ruined island within weeks and published his report in 1885. In Britain the Royal Society gathered ship logs, telegraph reports, tide-gauge records and barograph charts from around the world into a thick report in 1888. The barographs told the most surprising story. Stations around the world, from Tokyo to Greenwich to Washington, showed a sudden wiggle in air pressure hours after the big blast, then another wiggle going the other way, then more. The pressure wave had circled the globe, passing some stations seven times over five days, each lap taking about 36 hours. Tide gauges as far as the English Channel recorded tiny ripples. For the first time a single event had been measured by instruments on every continent at once.

The big idea. Why so violent? Krakatoa's magma was thick and loaded with dissolved gas, like a shaken soda, and the vent sat at sea level, so seawater could pour in and flash to steam. As the magma chamber emptied, the mountain above it lost its support and fell in, making a **caldera** about 6 km wide under the sea. Geologists rank the eruption at VEI 6, with roughly 20 km^3 of tephra thrown out, about twenty times the 1980 eruption of Mount St. Helens. The explosions sent a **pressure wave** through the air at close to the speed of sound, about 1,200 km per hour. A pressure wave is not a wind; it is a pulse of squeezed air, like the thump you feel from a firework, strong enough to be felt by instruments on the far side of the planet.

In the world today. Fine ash and sulfur droplets lofted into the stratosphere drifted around the world for months. In the autumn of 1883 people from New York to London saw sunsets so red that some called out the fire brigades, and the sun sometimes looked blue or green through the haze. Scientists later estimated that summer temperatures in the Northern Hemisphere were roughly half a degree Celsius lower the next year because the haze

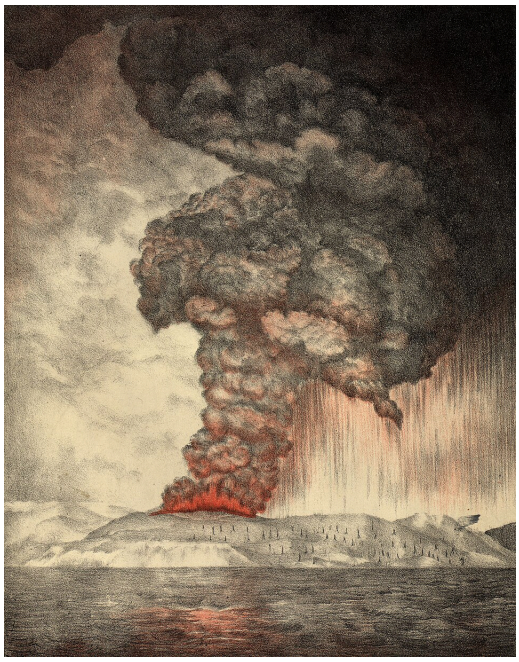
scattered sunlight back to space. Verbeek predicted that the volcano would build itself again at the same spot, and in 1927 a new cone, Anak Krakatau (“child of Krakatoa”), rose from the caldera. It still grows and erupts, and in December 2018 part of it slid into the sea and set off another tsunami. The Sunda Strait is watched today with seismometers, tide gauges and satellites, as you will see in Lesson 8.2.

God’s handiwork. Krakatoa taught scientists that the air, the sea and the rock of the earth are one connected system: a blast on one island moved the needles of barographs in every nation, dyed the sunsets of two hemispheres and cooled the following summer. The Psalmist wrote of mountains “carried into the midst of the sea” and waters that “roar and be troubled” (Psalm 46:2–3), and that is nearly a description of August 27, 1883. His answer was not that such things cannot happen, but that God is a refuge when they do. Learning how the world works is one way we care for the people who live in its dangerous places.



The sound of the 10:02 a.m. explosion reached each place at a time that fits a speed of about 1,200 km per hour, which is the speed of sound in air.

PICTURE STUDY



The Eruption of Krakatoa (lithograph from the Royal Society report), Parker & Coward, lithographers, after an 1883 view of the early stage of the eruption, 1888 · Color lithograph · Published in *The Eruption of Krakatoa and Subsequent Phenomena*, Royal Society, London, 1888

When the Royal Society of London published its great report on Krakatoa in 1888, it included this lithograph of the volcano in eruption on May 27, 1883, a week after it began and three months before the final collapse. Steamship passengers had sailed out to see the island in May and June, when its column of ash was already a wonder.

A lithograph is a print drawn on stone and pressed onto paper, and colored copies like this one let people everywhere see what only a few sailors had seen. Compare it with Wright of Derby's painting of Vesuvius: one is art made for feeling, the other is a scientific record made for a report.

Look closely

- Follow the column of ash from the island up to the top of the picture. Where does it begin to spread sideways? Why might that happen high in the sky?
- Look at the size of the island compared to the cloud. What does that tell you about how much material was coming out?
- Find the sea. Is it calm or rough? This picture shows the early, smaller stage of the eruption, months before the great waves.
- Notice that there are no people or ships in the picture. Why might a scientific report prefer a picture with no people?

Talk about it

1. What can a picture like this record that a barograph cannot? What can a barograph record that a picture cannot?
2. If you were a passenger on a sightseeing ship in June 1883, what would you want to measure or write down?
3. The island in this picture no longer exists in this shape. What happened to it?

> **Safety first.** The bottle barometer uses scissors to cut a balloon; a parent should do the cutting. Keep the jar away from windowsills where the sun will heat it and spoil the readings.

EXPERIMENT: A BOTTLE BAROGRAPH: CAN I FEEL THE AIR CHANGE?

The Royal Society learned how far Krakatoa's pressure wave traveled from barographs, instruments that write air pressure on paper. You will build a simple barometer from a jar and a balloon and keep a week of readings, the way a weather station does. Your instrument will not feel a volcano, but it will feel the weather, which works by the same squeezing and stretching of the air.

Question: Does the air pressure at my house change from day to day, and does a change go with a change in the weather? Write your prediction.

You will need

- A wide-mouth glass jar
- A balloon and a strong rubber band
- A drinking straw and a toothpick (or a sewing needle), with tape
- A piece of card, a ruler and a pencil
- Scissors (parent) and a notebook

Steps

1. Have a parent cut the neck off the balloon. Stretch the balloon flat and tight over the mouth of the jar and fix it with the rubber band. The jar now holds a sample of air sealed off from outside.
2. Tape one end of the straw to the center of the balloon so the straw sticks out past the jar's edge. Tape the toothpick to the free end as a fine pointer.
3. Stand the card upright behind the pointer and tape it to a wall or box. Rule marks every 2 mm up the card and label the middle mark 0. The jar must stay in the same spot, indoors, away from sun and heaters, for the whole week.
4. When the outside air pressure rises, it presses the balloon down and the pointer tips up. When pressure falls, the balloon bulges up and the pointer dips. Read the pointer at the same two times every day, morning and evening, and record the mark in a table: Date, Time, Reading (mm), Weather (clear, cloudy, rain, wind).
5. Keep the record for at least 7 days. Each day also note the official pressure from a weather site or radio in hectopascals (hPa), if you can.

6. Graph your readings as a line graph with days along the bottom. Mark rainy days with a small cloud.
7. Write your conclusion: Did the pressure change? Did falling pressure come before cloudy or rainy weather? What might make your instrument give false readings (think about temperature)?

Tips

- Temperature changes the air inside the jar too, so keep the jar in a room with steady temperature. A reading taken next to a cold window is not a fair reading.
- A real barograph moves the paper with clockwork so the record is continuous. If you want, read yours four times a day for one day and see what you miss with only two.

Check your work

- I built an instrument, kept it in one place, and read it at the same times each day.
- I recorded at least 7 days of readings in a table and graphed them.
- I can explain what a barograph is and what Krakatoa's pressure wave looked like on one.

FIELD NOTEBOOK

1. Draw a simple map of the Sunda Strait with Java, Sumatra and Krakatoa, and add a scale bar. Mark Batavia about 160 km away.
2. Sketch a barograph trace of a quiet day, then draw on it the kind of sharp wiggle the Krakatoa pressure wave made, with a label for the hour it arrived at a station 12,000 km away.
3. Draw "before" and "after" profiles of the island: three peaks with Rakata at 813 m before, and the half-cone of Rakata beside a 6 km caldera after.

> **From history.** Rogier Verbeek, the Dutch mining engineer who mapped the wrecked island in 1883 and 1884, ended his report with a prediction: new eruptions would one day build a cone at the same place in the caldera. He was right. In 1927 fishermen saw steam and ash boiling up from the sea there, and by 1930 a new island stood above the waves. The Indonesians named it Anak Krakatau, the child of Krakatoa.

WORKED EXAMPLES

Example 1. The great explosion came at about 10:02 a.m. on August 27, 1883. On Rodrigues Island, about 4,800 km away, the sound was heard about 4 hours later. What speed does that give for the sound, in km per hour and in meters per second? Compare it with the speed of sound in air, 343 m/s at 20 °C.

(Use the map or drawing "The slope of the line is the speed of sound." shown earlier in this lesson.)

1. Speed = distance ÷ time = 4,800 km ÷ 4 h = 1,200 km/h.
2. Change to meters per second: 1,200 km/h × 1,000 m/km ÷ 3,600 s/h ≈ 333 m/s.
3. The textbook value is 343 m/s. The two agree within about 3 percent, which is remarkable for a time read off a police chief's notes.

Answer: About 1,200 km/h, or roughly 333 m/s, within a few percent of the speed of sound in air.

Example 2. The pressure wave traveled around the world at about 1,100 km/h. Earth's circumference is about 40,000 km. How long did one lap take? How long did the wave take to reach the point on the far side of the earth from Krakatoa?

1. One lap: 40,000 km ÷ 1,100 km/h ≈ 36 hours, which matches the time between repeated wiggles on the barographs.
2. The far side of the earth is half a lap away: 20,000 km ÷ 1,100 km/h ≈ 18 hours.
3. At that far point the wave arrived from every direction at once, about 18 hours after the blast, and then kept going.

Answer: About 36 hours per lap; about 18 hours to reach the far side of the globe.

Example 3. Krakatoa threw out roughly 20 km^3 of tephra. Mount St. Helens in 1980 threw out about 1 km^3. How many times larger was Krakatoa? Express 20 km^3 in cubic meters.

1. Ratio: 20 km^3 ÷ 1 km^3 = 20. Krakatoa was about twenty times the size of St. Helens.
2. 1 km = 1,000 m, so 1 km^3 = 1,000 × 1,000 × 1,000 m^3 = 1,000,000,000 m^3 (one billion cubic meters).
3. 20 km^3 = 20 × 1,000,000,000 m^3 = 20,000,000,000 m^3, or 2 × 10^{10} m^3.
4. On the Volcanic Explosivity Index, 20 km^3 places Krakatoa at VEI 6; St. Helens at 1 km^3 is VEI 5. One step on the scale means about ten times more material.

Answer: About 20 times larger; 20 km^3 = 2 × 10^{10} m^3 (twenty billion cubic meters).

PRACTICE

1. EASY Where is Krakatoa, and between which two large islands does it lie?
2. EASY What caused most of the deaths in 1883: lava, ash fall or tsunamis?
3. EASY What is a caldera, and how did Krakatoa get one?
4. MEDIUM Sound travels at about 1,200 km/h. Perth is about 3,100 km from Krakatoa. About how long after 10:02 a.m. did people in Perth hear the blast? Give the answer in hours and minutes.
5. MEDIUM Data reading. A weather station 12,000 km from Krakatoa records the pressure wave. The table is simplified from the Royal Society's method, using a wave speed of about 1,100 km/h.

   Pass | Direction of travel | Hours after the blast
   1 | short way around | 11
   2 | long way around | 25
   3 | short way, second lap | 47
   4 | long way, second lap | 61

   (a) How many hours separate pass 1 from pass 3? (b) What does that number represent? (c) Predict when pass 5 would arrive.
6. MEDIUM Data reading. Use the distance-time graph in this lesson. (a) What is the slope of the line in km per hour? (b) If a town 2,400 km away had kept a record, at about what time after the blast should the sound have arrived? (c) A report claims a village 6,000 km away heard the sound 3 hours after the blast. Is that claim consistent with the graph?
7. MEDIUM Explain in two or three sentences why the sunsets were so red around the world for months after the eruption, using only physical science.
8. HARD Experiment design. You want to test whether warmer soda holds less dissolved gas and so "erupts" higher when opened. Describe the independent and dependent variables, what you would keep the same, how you would measure the result, and one safety step.
9. HARD Krakatoa's pressure wave arrived at a station 9,000 km away about 8 hours after the blast. What speed does that give? Is a pressure wave a wind? Explain.
10. CHALLENGE Write a paragraph: Why was Krakatoa the first eruption measured all over the world, and what new instruments and inventions made that possible?

COMMON MISTAKES

- Thinking the whole island was blown into the sky. Much of it collapsed downward into the emptied magma chamber, forming a caldera under the sea.
- Thinking the wiggle on far-off barographs was an earthquake. It was a pressure wave in the air, traveling at about the speed of sound, not a shaking of the ground.
- Thinking lava killed the people of Java and Sumatra. The waves did; lava barely figured in the disaster at all.

Make it a game · Sound Race Around the World. Your parent names a city and a distance from Krakatoa in whole thousands of kilometers (Perth 3,000, Rodrigues 5,000, Cape Town 9,000, Tokyo 6,000). Using 1,200 km per hour, you have fifteen seconds to say how many hours the sound would take, rounded to the nearest half hour. Score a point for each correct time, and a bonus point if you can also say whether anyone really heard it there (only places within about 5,000 km did). Play to ten.

Scripture. “Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah.” (Psalm 46:2–3, KJV)

The Psalmist did not pretend that mountains never fall into the sea; he had seen the earth’s power. His confidence was in the God who made the mountains and the sea, and who is a refuge whatever they do.

Practice answers

1. In the Sunda Strait, in Indonesia (then the Dutch East Indies), between Java and Sumatra.
2. Tsunamis. The collapse of the island drove sea waves more than 30 m high onto the nearby coasts.
3. A caldera is a large bowl-shaped hollow formed when a volcano collapses into its emptied magma chamber. As Krakatoa’s chamber emptied during the eruption, most of the island fell in and left a caldera about 6 km wide under the sea.
4. 3,100 ÷ 1,200 ≈ 2.6 hours, which is about 2 hours 35 minutes, so a little after 12:35 p.m. Krakatoa time (ignoring time zones).
5. (a) 47 − 11 = 36 hours. (b) The time for the wave to go once around the whole earth. (c) Pass 5 is the short-way wave on its third lap: 47 + 36 = 83 hours after the blast.
6. (a) About 1,200 km/h (for example 4,800 km ÷ 4 h). (b) 2,400 ÷ 1,200 = 2 hours. (c) No. At 1,200 km/h, sound takes 5 hours to go 6,000 km; 3 hours would need 2,000 km/h, far faster than sound, so the report is probably mistaken.
7. The eruption pushed fine ash and sulfur droplets high into the stratosphere, above the weather, where winds spread them around the globe. Those tiny particles scatter blue light out of the sun’s rays, so when the sun is low and its light passes through a long path of haze, the light that gets through is deep red and orange.
8. Independent variable: the temperature of the soda (for example cold from the fridge, room temperature, and warm from a bowl of warm tap water). Dependent variable: how high the foam rises, measured with a ruler against the bottle or by how much liquid is lost on a kitchen scale. Keep the same: the brand and size of soda, how long and hard each bottle is shaken (or not shaken), how fast the cap is opened, and the bottle shape. Repeat each temperature at least twice. Safety: open the bottles outdoors or over a sink, pointed away from faces, with a parent present.
9. 9,000 km ÷ 8 h ≈ 1,125 km/h, about the speed of sound. A pressure wave is not a wind. The air does not travel 9,000 km; each bit of air is squeezed and then stretched in turn, passing the pulse along, just as a sound passes through air without the air blowing from the speaker to your ear.

10. A strong answer names the telegraph, which carried news of the eruption to newspapers within a day; the growing network of weather stations with barographs that wrote continuous pressure records; tide gauges that tracked the sea; and the many steamships whose captains kept careful logs of ash, sound and waves. Because all these instruments were running at once, the Royal Society could assemble readings from every continent into one report and discover that the pressure wave had circled the earth, which no one had ever been able to measure before.

3.3 Volcano Types: The Mountain That Grew in a Cornfield

OBJECTIVES

- Classify a volcano as a shield volcano, a composite volcano or a cinder cone from its shape, its lava and its style of eruption, and name a real example of each.
- Explain how silica content, temperature and dissolved gas control the viscosity of magma and so the shape of the mountain and the violence of its eruptions.
- Compute a growth rate for a new volcano and a height-to-width ratio for a mountain, and use a scale model to compare shapes.

Warm-up. On a tray, pour a cup of dry rice into a pile, then a cup of flour, then a cup of granulated sugar. Measure the height and the width of each pile with a ruler and write them down. Which material makes the steepest pile? Loose grains can only stack up to a certain slope before they slide, and a cinder cone is a pile of volcanic grains that obeys the same rule.

Video. Coming soon. Types of volcanoes: shield, composite (stratovolcano) and cinder cone, Parícutin 1943, Mauna Loa, lava viscosity and silica; search USGS, Smithsonian, NOAA SciJinks, SciShow Kids, Science Max and Hawaiian Volcano Observatory footage.

KEY TERMS

magma and lava
Magma is molten rock under the ground; once it flows out onto the surface it is called lava.

viscosity
How much a liquid resists flowing. Honey has high viscosity; water has low viscosity.

silica
Silicon dioxide, the main ingredient of most magma. More silica makes magma stickier and more explosive.

shield volcano
A very broad mountain with gentle slopes built from many flows of runny basalt lava, like Mauna Loa in Hawaii.

composite volcano (stratovolcano)
A tall, steep cone built of alternating layers of lava and tephra, like Mount Fuji or Vesuvius; it often erupts explosively.

cinder cone
A small, steep cone of loose cinders piled around a single vent, like Parícutin in Mexico; most are short-lived.

CORE IDEAS

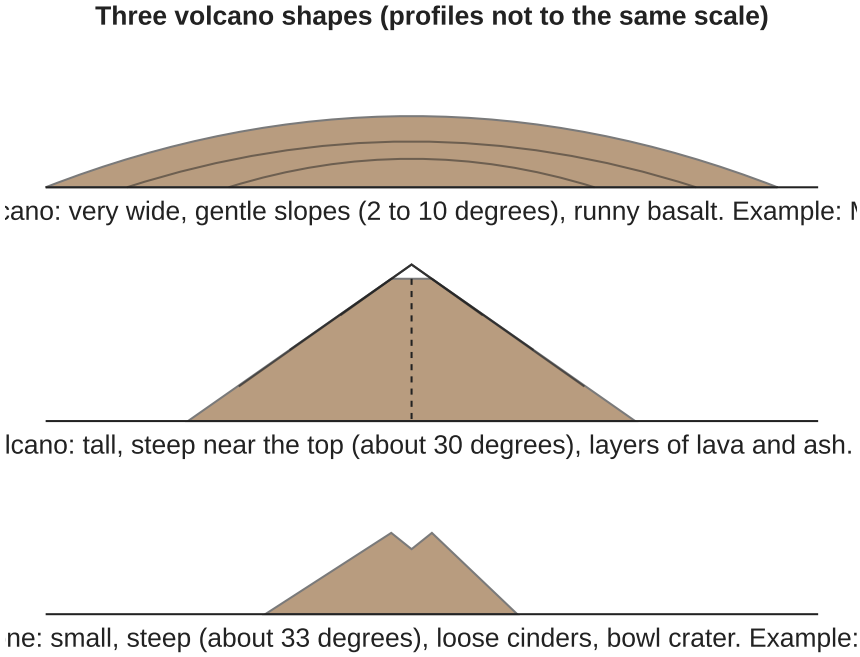
The story. On the afternoon of February 20, 1943, a farmer named Dionisio Pulido was burning brush and plowing his cornfield near the village of Parícutin, in the state of Michoacán, Mexico. He had noticed a small hollow in the field that sometimes gave off a little warmth. That afternoon the ground near it swelled, a crack opened, and with a hiss and a rumble, smoke, sparks and a smell of sulfur came out of the earth. Pulido ran for the village. By the next morning a cone of cinders about 50 m high stood in his field. Within a week it was about 100 m, and by the end of a year it was 336 m. Lava poured out and slowly buried the village of Parícutin and the nearby town of San Juan Parangaricutiro, though so slowly that everyone walked away safely. The volcano kept at it for nine years, until 1952, and ended 424 m above the old field. Scientists from Mexico and the United States had the rare gift of watching a volcano from its first breath to its last.

How they figured it out. Parícutin is a **cinder cone**: a steep pile of glassy, bubble-filled cinders thrown out of one vent and heaped at the steepest slope loose grains can hold, about 30 to 35 degrees, the same reason your pile of rice stops at a certain steepness. Geologists sort volcanoes into three main shapes. A **shield volcano** like Mauna Loa in Hawaii is built from thousands of thin flows of runny lava and spreads out like a warrior's shield laid on the ground, with slopes of only 2 to 10 degrees. A **composite volcano**, or stratovolcano, like Fuji, Rainier or Vesuvius is a tall cone of alternating layers of lava and tephra, steep near the top, and it erupts explosively now and then over thousands of eruptions. A fourth shape, the lava dome, is a steep plug of lava too stiff to flow far, often growing inside a crater. Shape, it turns out, is a fingerprint of the lava.

The big idea. The key is **viscosity**, how much the molten rock resists flowing, and viscosity depends mostly on silica and temperature. Basalt magma has about 50 percent silica and erupts very hot, near 1,200 °C; it runs like warm syrup, lets its gas escape gently, and builds shields and lava fountains. Andesite, with about 60 percent silica, is stiffer, and rhyolite, with about 70 percent silica and lower temperatures near 800 °C, is as stiff as cold tar. Stiff magma traps its gas. Pressure builds until the magma shatters into ash and pumice, which is why composite volcanoes made of andesite and rhyolite are the dangerous ones. Plate boundaries from Unit 2 explain where each kind forms: basalt rises at spreading ridges and hot spots like Hawaii, while subduction zones, where water-soaked ocean crust sinks and melts, make the gas-rich andesite of the Pacific Ring of Fire.

In the world today. Mauna Loa rises 4,170 m above the sea, but it starts on the ocean floor about 5 km down, so from base to summit it is taller than Everest, and its lavas cover half the island of Hawaii. Fuji, a composite cone 3,776 m tall, is steep enough that pilgrims climb it by switchback trails. The United States has about 160 volcanoes that could erupt again, most of them composite cones in the Cascades and Alaska, and the Hawaiian Volcano Observatory, founded in 1912, has watched Kilauea and Mauna Loa for more than a century. You can walk up to a cooled Hawaiian lava flow and see the ropy surface that geologists call pahoehoe; you would not want to stand that close to a composite volcano in eruption.

God’s handiwork. Sorting is the beginning of science. Linnaeus sorted plants, and geologists sort volcanoes, because God made a world of real kinds with real differences that a careful eye can learn to read. A gentle shield and an explosive composite cone are not random; each follows from the chemistry of its magma as surely as honey follows its own nature when you tip the jar. And the ash and lava that frighten us weather into the dark, rich soils of Hawaii, Java and Michoacán, where coffee, corn and avocados grow. “The mountains quake at him, and the hills melt” (Nahum 1:5), and from the melted hills come fields.



The three main volcano shapes. Runny basalt builds shields; stiff, gas-rich magma builds steep composite cones; loose cinders pile up at about 33 degrees.

PICTURE STUDY



Fine Wind, Clear Morning (Red Fuji), from Thirty-six Views of Mount Fuji, Katsushika Hokusai, about 1830–1832 · Woodblock print, ink and color on paper · Metropolitan Museum of Art, New York (one of many impressions)

Katsushika Hokusai was a Japanese artist who, in his seventies, made a famous series of prints showing Mount Fuji from thirty-six different places. This is one of the simplest and most loved: the mountain alone, flushed red by the morning sun under a clear sky with a fine wind.

Fuji is a composite volcano, 3,776 m high, and its last eruption was in 1707. Hokusai drew its shape so truly that a geologist can read the volcano type straight off the print.

Look closely

- Look at the slope of the mountain. Is it steeper near the summit or near the base? Which volcano type has this shape?
- Find the snow streaks near the top. Why does snow stay on a volcano that was once hot?
- Count the colors Hokusai used. How does he show the whole huge mountain with so few?
- Notice how the clouds are drawn with lines and the mountain with flat color. What does this contrast do to your eye?

Talk about it

1. Compare Fuji’s profile with the shield and cinder cone in the lesson figure. How would the print look if Fuji were a shield volcano?

2. Why do you think people in Japan have loved this mountain for so long, even though it is a volcano?
3. Fuji is made of layers of lava and ash from many eruptions. Where in the print might you look for signs of those eruptions?

> **Safety first.** Warm the honey only in a bowl of warm tap water, never on the stove or in the microwave, and have a parent help. Keep syrup off floors to avoid slips.

EXPERIMENT: HONEY VOLCANOES: DOES VISCOSITY SHAPE THE MOUNTAIN?

Geologists say the shape of a volcano is a fingerprint of its lava. You will test this with honey at two temperatures, pouring the same amount at the same rate and measuring the "mountain" each one makes.

Question: Does a thicker (more viscous) liquid build a taller, narrower mound than a thinner one? Write your prediction and your reason.

You will need

- Honey (about half a cup) and a jar of the same honey chilled in the refrigerator for 2 hours
- Two flat plates and a bowl of warm tap water
- A tablespoon, a ruler, a stopwatch and a notebook
- A piece of card and a book to make a ramp (optional)

Steps

1. Set one jar of honey in the bowl of warm tap water for 10 minutes (the "basalt," hot and runny). Keep the other jar cold from the refrigerator (the "rhyolite," cool and stiff).
2. Hold a tablespoon of cold honey 5 cm above the center of a plate and let it pour out, counting the seconds until the spoon is empty. Wait 60 seconds, then measure the height of the mound and its width with the ruler. Record both in millimeters.
3. Do exactly the same with a tablespoon of warm honey on the second plate: same spoon, same height above the plate, same 60 seconds before measuring. Those are the things you keep the same.
4. Calculate the height-to-width ratio for each mound: height ÷ width. A shield volcano's ratio is tiny; a cinder cone's is larger.
5. Repeat the whole test once more and average your results.
6. Optional ramp test: prop the card at a gentle slope, pour a spoonful of each honey at the top and time how long it takes to travel 10 cm. Record the speed in cm per second.
7. Write your conclusion. Which honey built the taller, narrower mound? Which volcano type does each stand for? What did temperature do to viscosity?

Tips

- If the warm honey spreads too far to measure, use a plate with a rim or measure the width of the puddle after 30 seconds instead of 60, for both samples.
- Real lava also loses its gas as it goes; honey has none. Ask what your model leaves out and whether that matters for the shape.

Check your work

- I changed only the temperature of the honey and kept the amount, spoon, height and timing the same.
- I measured height and width in millimeters and calculated a height-to-width ratio for each mound.
- I can explain which real volcano type each mound stands for and why.

FIELD NOTEBOOK

1. Draw the three volcano profiles to the same height and label the slope angle, the kind of lava and one real example under each.
2. Make a table with three rows (basalt, andesite, rhyolite) and three columns (silica percent, approximate temperature, viscosity) and fill it in from the lesson.
3. Draw Parícutin at the end of day 1, week 1, year 1 and year 9 as four little cones side by side, each to the same scale, with the heights labeled.

> **From history.** The lava from Parícutin crept into the town of San Juan Parangaricutiro in 1944 and buried it house by house, but it stopped partway up the stone church. Today the church tower and part of the altar still stand above the black lava field, and the townspeople, who rebuilt their town a few kilometers away as Nuevo San Juan, still walk out to visit it.

WORKED EXAMPLES

Example 1. Parícutin was about 50 m tall after its first day, 336 m after one year, and 424 m when it stopped after about 9 years. Find the growth rate (a) on the first day in meters per day, (b) averaged over the first year in meters per day, and (c) averaged over the whole 9 years in meters per year. What do the three numbers tell you?

1. (a) First day: 50 m ÷ 1 day = 50 m per day.
2. (b) First year: 336 m ÷ 365 days ≈ 0.92 m per day.
3. (c) Whole life: 424 m ÷ 9 years ≈ 47 m per year, which is about 0.13 m per day.
4. The cone grew fastest at the very start and more and more slowly afterward. An average rate hides this: if you only knew the 9-year average, you would never guess the mountain was 50 m tall after one day.

Answer: (a) 50 m/day; (b) about 0.92 m/day; (c) about 47 m/year. Growth was fast at first and slowed greatly, so averages over long spans can be misleading.

Example 2. Cinders pile up at about 33 degrees. If a cinder cone is 424 m tall and has straight sides at that angle, how far out from the center does its base reach, and how wide is the whole cone? (Use tan 33° ≈ 0.65.)

1. In a right triangle made by the height and the half-width, tan(angle) = height ÷ half-width.
2. Half-width = height ÷ tan 33° = 424 m ÷ 0.65 ≈ 650 m.
3. Whole width = 2 × 650 m = 1,300 m, or about 1.3 km.
4. Height-to-width ratio = 424 ÷ 1,300 ≈ 0.33. A cinder cone is about a third as tall as it is wide.

Answer: About 650 m from center to edge; about 1.3 km across; height-to-width ratio about 0.33.

Example 3. Mauna Loa rises 4,170 m above sea level and its above-water part is about 120 km across. Mount Fuji is 3,776 m tall and about 40 km across at its base. Build a 1:100,000 scale model of each on paper: how tall and how wide is each model in centimeters? Compare their height-to-width ratios.

1. At 1:100,000, 1 km in the world = 1 cm on paper, and 1 m in the world = 0.001 cm.
2. Mauna Loa: height 4,170 m × 0.001 = 4.2 cm; width 120 km = 120 cm. The model is a bump 4 cm high stretched across a whole table.
3. Fuji: height 3,776 m × 0.001 = 3.8 cm; width 40 km = 40 cm.
4. Ratios: Mauna Loa 4.17 km ÷ 120 km ≈ 0.035; Fuji 3.776 km ÷ 40 km ≈ 0.094. Fuji is nearly three times as steep in proportion, though a little lower.
5. Compare both to the cinder cone's 0.33: cinder cones are steep, composite cones middling, shields very flat.

Answer: Mauna Loa: 4.2 cm high by 120 cm wide (ratio about 0.035). Fuji: 3.8 cm high by 40 cm wide (ratio about 0.094). The shield is far flatter than the composite cone.

PRACTICE

1. EASY Name the three main volcano shapes and give one real example of each.
2. EASY What is the difference between magma and lava?
3. EASY Which magma is runnier, basalt at 1,200 °C with 50 percent silica, or rhyolite at 800 °C with 70 percent silica? Why?
4. MEDIUM A new cinder cone grows from 0 to 120 m in 6 days. What is its average growth rate in meters per day? If it kept that rate, how tall would it be after 30 days? Why is that prediction probably wrong?
5. MEDIUM Data reading. The table gives properties of three magma types.

Magma | Silica (%) | Typical temperature (°C) | Viscosity | Gas escapes
Basalt | about 50 | about 1,200 | low | easily
Andesite | about 60 | about 1,000 | medium | with difficulty
Rhyolite | about 70 | about 800 | high | trapped

Which statement is best supported? (a) Higher silica goes with higher temperature. (b) As silica rises, viscosity rises and gas is trapped more. (c) Gas escapes most easily from the coolest magma. (d) Temperature has no effect on viscosity.

6. MEDIUM Data reading. A student poured syrup at three temperatures and measured each mound after 60 seconds.

   Temperature (°C) | Height (mm) | Width (mm)
   5 | 18 | 60
   20 | 10 | 90
   40 | 4 | 150

   (a) Calculate the height-to-width ratio at each temperature. (b) Which temperature stands for basalt and which for rhyolite? (c) Predict the ratio at 30 °C.
7. MEDIUM Why do composite volcanoes erupt explosively while shield volcanoes usually do not? Answer in two or three sentences.
8. HARD Experiment design. Design a test of whether adding fine sand (standing for silica) to corn syrup makes it flow more slowly down a ramp. State the independent and dependent variables, three things to keep the same, what you would measure and how many trials you would run.
9. HARD A composite volcano is 3,000 m tall and 30 km wide at its base. A shield volcano is 2,000 m tall and 80 km wide. Calculate the height-to-width ratio of each and say which is steeper in proportion.
10. CHALLENGE Write a paragraph explaining why Parícutin was so valuable to science, and what geologists could learn from it that they could not learn from Vesuvius or Fuji.

COMMON MISTAKES

- Thinking every volcano is a steep cone. Shield volcanoes like Mauna Loa are so broad and gentle that from the ground they hardly look like mountains at all.
- Thinking thicker lava must be hotter. It is the reverse: stiff, silica-rich lava is cooler than runny basalt, and its stiffness is what makes it dangerous.
- Thinking volcanoes only occur at plate edges. Hot-spot volcanoes like Hawaii sit in the middle of a plate, far from any boundary.

> **Make it a game · Which Volcano Am I?.** Your parent reads three clues one at a time, such as: I am wider than I am tall; my lava is runny basalt; I rise from the floor of the Pacific. Guess the volcano type after the first clue for 3 points, the second for 2, the third for 1. Then name a real example for a bonus point. Make up clues for Parícutin, Fuji, Mauna Loa, Vesuvius, Kilauea and a lava dome. First to twelve points wins.

> **Scripture.** “The mountains quake at him, and the hills melt, and the earth is burned at his presence, yea, the world, and all that dwell therein.” (Nahum 1:5, KJV)

The prophet Nahum knew that hills could melt and the earth could burn, and he saw in such power the greatness of God. The rock that melts under a volcano is the same rock He made in the beginning.

Practice answers

1. Shield volcano (Mauna Loa or Kilauea, Hawaii); composite volcano or stratovolcano (Fuji, Vesuvius, Rainier); cinder cone (Parícutin, Mexico).
2. Magma is molten rock below the ground; lava is the same molten rock after it comes out onto the surface.
3. Basalt. It has less silica and is hotter, and both make a magma flow more easily (lower viscosity).
4. 120 ÷ 6 = 20 m per day. At that rate, 30 days would give 600 m. The prediction is probably wrong because cinder cones grow fastest at first and then slow down, as Parícutin did.
5. (b). Down the table silica rises, temperature falls, viscosity rises and gas is more trapped. Choice (a) is backward, (c) is backward, and (d) cannot be concluded from the table because silica and temperature change together.
6. (a) 5 °C: 18 ÷ 60 = 0.30; 20 °C: 10 ÷ 90 ≈ 0.11; 40 °C: 4 ÷ 150 ≈ 0.027. (b) 40 °C (runny, flat) stands for basalt; 5 °C (stiff, steep) for rhyolite. (c) Somewhere between 0.11 and 0.027, about 0.05 to 0.06, since the ratio keeps falling as the syrup warms.
7. Composite volcanoes are fed by stiff, silica-rich magma (andesite or rhyolite) that traps dissolved gas. Pressure builds until the magma bursts apart into ash and pumice. Shield volcanoes erupt runny basalt that lets gas bubble out gently, so the lava flows instead of exploding.
8. Independent variable: the amount of sand mixed into the syrup (for example 0, 1 and 2 teaspoons per quarter cup). Dependent variable: flow speed, measured as the time for the front of the syrup to travel 10 cm down the ramp, converted to cm per second. Keep the same: the ramp angle, the amount of syrup poured, the temperature of the syrup, and the starting point. Run at least three trials for each mixture and average them.
9. Composite: 3 km ÷ 30 km = 0.10. Shield: 2 km ÷ 80 km = 0.025. The composite volcano is four times steeper in proportion.
10. A strong answer says that Parícutin was born, grew and died within nine years in front of trained observers, so geologists could measure its growth day by day, map every lava flow, record how a cinder cone takes shape and how long it lasts, and watch how a volcano ends. Vesuvius and Fuji are composite cones built by thousands of eruptions over long spans no one has watched from the start, so their history must be pieced together from layers. Parícutin gave a complete, measured life story of one volcano, which also helps geologists check how well their methods of reading older volcanoes from their rocks really work.

3.4 New Rock in Days: Surtsey, 1963

OBJECTIVES

- Retell the birth of the island of Surtsey off Iceland in November 1963 and describe its two stages: explosive tephra cone, then lava armor.
- Explain how loose ash became hard rock within a few years, how waves cut cliffs and beaches, and how plants and birds colonized bare rock.
- Compute rates of growth and erosion for a new island and explain why a rate measured today cannot simply be assumed to stay constant.

Warm-up. Put two tablespoons of baking soda in a cup and pour in a quarter cup of vinegar. Watch how the escaping gas tears the liquid into a frothy spray. Now imagine 1,000 °C lava meeting cold seawater on the ocean floor: the water flashes to steam and blasts the lava into millions of glassy grains. Write down what you think a pile of such grains would look like after a week of waves.

Video. Coming soon. Surtsey 1963 eruption and the birth of a volcanic island, Surtseyan steam explosions, Iceland on the Mid-Atlantic Ridge, first plants and birds on Surtsey; search NOAA, USGS, Smithsonian Global Volcanism Program, Icelandic film archives and nature-documentary channels.

KEY TERMS

Surtseyan eruption
An eruption in shallow water where seawater meets magma and flashes to steam, blasting out jets of wet ash. Named after Surtsey.

tephra cone
A hill of loose ash and cinders piled around a vent, easily washed away by waves until something hardens or covers it.

palagonite tuff
A hard brownish rock formed when loose volcanic glass is altered and cemented by warm water and steam.

cementation
The gluing together of loose grains into solid rock by minerals that form between them.

colonization
The arrival and settling of living things on bare new ground.

wave erosion
The wearing away of a coast by the pounding of waves, which cuts cliffs and rounds stones into boulders and pebbles.

CORE IDEAS

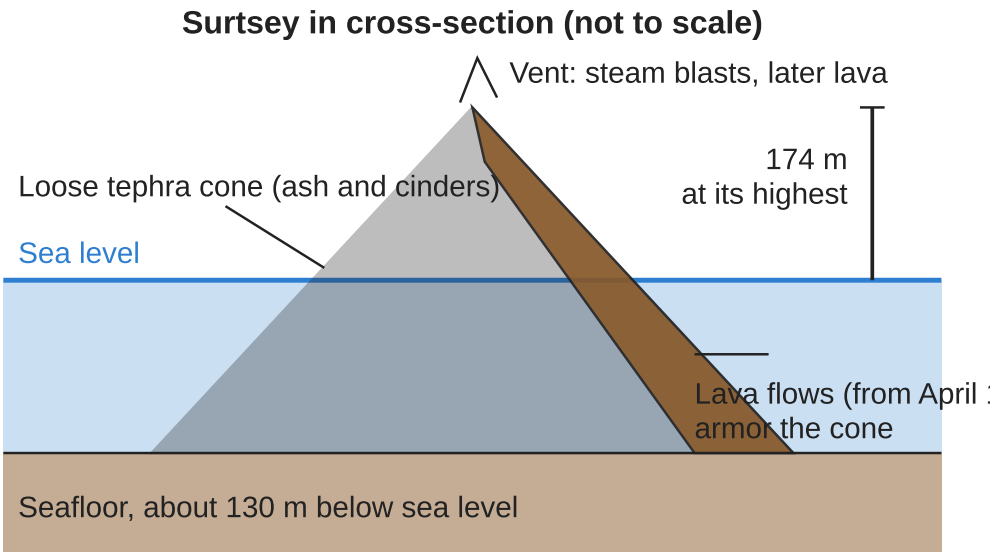
The story. Early on the morning of November 14, 1963, the cook aboard the fishing boat Ísleifur II, working the cold water off the south coast of Iceland, noticed a dark cloud rising from the sea. The crew thought a ship was on fire. As they drew closer they saw black columns of ash shooting up out of the waves, hundreds of meters high, and the sea boiling around them. A volcano was erupting on the seafloor, about 130 m down, some 32 km off the coast at the southwest end of the Westman Islands. By the next day a ridge of black cinders stood above the water. Within weeks it was hundreds of meters long and tens of meters high. Icelanders named it Surtsey, after Surtur, the fire giant of their old sagas. Iceland sits astride the Mid-Atlantic Ridge, the great spreading boundary you learned about in Unit 2, and Surtsey was that boundary making new land in front of cameras.

How they figured it out. The Icelandic geologist Sigurdur Thorarinsson and his colleagues watched the island almost daily. At first, every time seawater poured into the vent it flashed into steam and blew out jets of wet ash that fanned up like a rooster's tail; geologists now call this a **Surtseyan eruption**. The loose **tephra cone** it built was at the mercy of the winter storms, and two small neighboring islands that formed the same way in 1965 and 1966, Syrtlingur and Jólnir, were washed away within months. Surtsey survived because in April 1964 the cone grew high enough to shut the sea out of the vent, and the eruption changed character. Red, runny basalt lava welled up and flowed over the loose ash, armoring it with hard rock. The eruption finally ended on June 5, 1967. At its largest the island covered about 2.7 km² and rose 174 m above the sea.

The big idea. Surtsey showed, in a human lifetime, how fast rock and landscape can form. The lava hardened within hours of flowing. Deeper inside the island, loose ash sitting in warm water and steam from the cooling vent turned into solid **palagonite tuff** in just a few years, the glassy grains altering and cementing together into brown rock hard enough to stand as cliffs. Meanwhile the Atlantic went to work on the edges. By the 1970s the island already had wave-cut cliffs, a boulder beach of rounded stones, a sandy spit and a lagoon, the kinds of features a visitor might guess took a very long time to make. Geologists who landed there remarked that the island looked far older than it was. The lesson is one to keep for your whole life in science: never assume how long something took; measure the rate if you can, and if you cannot, say so.

In the world today. Iceland made Surtsey a nature reserve in 1965, before the eruption was even over, and only scientists may land, so that they can watch life arrive on its own. The first plant, a sea rocket grown from a seed carried in by the waves, was found in 1965. Mosses came in 1967 and lichens by 1970, the year the first birds nested, black guillemots and fulmars on the cliffs. A gull colony settled in the mid-1980s, and the birds' droppings fertilized the ground so that grasses and flowers spread around it; by 2008, when UNESCO listed Surtsey as a World Heritage site, about seventy kinds of plants had been recorded. The island is also shrinking. Waves and wind have worn it down to about half its largest size, though the hard lava and tuff core erodes far more slowly than the loose ash did.

God’s handiwork. “Let the dry land appear: and it was so,” says Genesis 1:9, and off the coast of Iceland a small piece of dry land appeared in a single November week. Surtsey is a reminder that God’s world is not a finished museum but a working creation, where rock is still made, cliffs still cut, soil still built and empty ground still filled with living things that spread “after his kind.” It is also a reminder of good stewardship: by keeping their feet off the island, Icelanders have let the whole world learn from it.



ter and steam inside the cone cemented loose ash into palagonite tuff within a f

Surtsey in cross-section (vertical scale exaggerated). Steam blasts built the loose tephra cone first; from April 1964 lava flows armored it against the waves.

PICTURE STUDY



Surtsey erupting, 1963, Howell Williams, for the National Oceanic and Atmospheric Administration (NOAA), November 30, 1963 · Photograph · National Oceanic and Atmospheric Administration (NOAA) image library, United States

This photograph was taken in the weeks after Surtsey first broke the surface. A jet of wet black ash, mixed with white steam, shoots up from the vent, and the young island lies low and dark beside it. The pale, feathery edges of the column are where the hot ash and the cold Atlantic air meet.

Photographs like this are scientific records as much as pictures. Geologists used them to estimate the height and speed of the jets, the shape of the growing cone and the way the plume leaned with the wind.

Look closely

- Trace the shape of the column. Does it rise straight or lean? What could that tell you about the wind that day?
- Find the island itself. How tall does it look compared with the column? Remember that the island was only tens of meters high at this stage.
- Look at the different shades in the cloud. Which parts are ash and which are steam? How can you tell?
- Is there any lava in the picture? Why not, if you remember the two stages of the eruption?

Talk about it

1. If you were on the boat, what three measurements would you try to make from this view?

2. The ash in this picture is loose. What happened to the loose ash of the two neighboring islands, and why did Surtsey last?
3. Compare this photograph with the Krakatoa lithograph and Wright's painting of Vesuvius. What can a photograph record that the others cannot?

> **Safety first.** This experiment uses a tub of water; work outdoors or in a bathtub, mop spills at once, and keep younger children supervised around the water.

EXPERIMENT: ISLAND VERSUS WAVES: DOES A HARD CAP SAVE A SAND ISLAND?

Syrtlingur and Jólnir were washed away within months; Surtsey has stood for more than sixty years. The difference was the cap of hard lava that covered its loose ash. You will build two sand islands in a tub, cap only one, and count how many waves each survives.

Question: Does a hard cap protect a loose island from wave erosion? Predict how many "waves" each island will take before half of it is gone.

You will need

- A large plastic tub or a bathtub and a jug of water
- Damp sand (about 4 cups) and a measuring cup
- Modeling clay or play dough, or a thin layer of plaster of Paris (parent mixes)
- A flat piece of plastic or a short board for making waves
- A ruler, a stopwatch and a notebook

Steps

1. Build two identical islands of damp sand at the same end of the tub, each from exactly 2 cups of sand, patted into cones about 10 cm across. Measure and record the height of each.
2. Cap one island with a layer of clay or plaster about 5 mm thick, pressing it down over the top and sides but leaving the bottom 2 cm of sand bare, as Surtsey's lava covered only part of the cone. Leave the other island bare. Let plaster set for the time the package says.
3. Add water slowly until it stands 3 cm up the sides of the islands. Do not pour onto the islands.
4. Make waves by pushing the board back and forth at the far end of the tub once every 2 seconds, with the same size of push each time. Count the waves.
5. Every 20 waves, stop and measure the height of each island. Record a table: Waves, Height of bare island (cm), Height of capped island (cm).
6. Continue until one island has lost half its height, then keep going until the other does too, or until 200 waves.
7. Graph both islands on one line graph: waves along the bottom, height up the side. Write a conclusion: Which lasted longer, by how many waves, and what does that show about Surtsey?

Tips

- Make your waves as even as you can. If someone else takes a turn, have them practice first so the push is the same size.
- Watch where the capped island fails. Does the water attack the bare sand under the cap, the way the Atlantic undercuts Surtsey’s cliffs?

Check your work

- My two islands started with the same sand, size and height, and only the cap was different.
- I counted waves and measured heights at regular intervals in a table and graph.
- I can explain why Surtsey survived when its neighboring islands did not.

FIELD NOTEBOOK

1. Draw a timeline of Surtsey from November 14, 1963 to today, marking the first lava (April 1964), the end of the eruption (June 5, 1967), the first plant (1965), the first bird nests (1970) and the World Heritage listing (2008).
2. Copy the cross-section figure and add labels for a wave-cut cliff, a boulder beach and the warm zone where loose ash turned to palagonite tuff.
3. Make a two-column list titled “Looks old / Was measured”: on the left, features of Surtsey that look as if they took ages (cliffs, boulders, soil, bird colonies); on the right, how many years each actually took.

> **From history.** Ten years after Surtsey, in January 1973, a fissure opened on the neighboring island of Heimaey, the only one of the Westman Islands with a town. The 5,000 residents were evacuated by fishing boats overnight. As lava crept toward the harbor, which the town depended on for its living, Icelanders pumped seawater onto the flow’s front for months to cool and stiffen it. The lava stopped short of closing the harbor, and the people returned to a town with a new mountain, Eldfell, standing over it.

WORKED EXAMPLES

Example 1. The vent lay about 130 m below the surface. Suppose the eruption began two days before the cone broke the surface. What was the average rate at which the cone grew, in meters per day and meters per hour?

(Use the map or drawing "The cone had to climb 130 m before anyone could see it." shown earlier in this lesson.)

1. Height gained: 130 m (from seafloor to sea level).
2. Rate per day: 130 m ÷ 2 days = 65 m per day.
3. Rate per hour: 65 m ÷ 24 h ≈ 2.7 m per hour, about the height of a room every hour.
4. This is an average; the cone probably grew in bursts, faster during the biggest blasts.

Answer: About 65 m per day, or roughly 2.7 m per hour, averaged over the two days.

Example 2. The eruption began on November 14, 1963 and ended on June 5, 1967. How many days did it last? If about 1 km³ of lava and tephra was erupted in all, what was the average output in cubic meters per day?

1. November 14, 1963 to November 14, 1966 is three years. 1964 was a leap year, so that is 366 + 365 + 365 = 1,096 days.
2. November 14, 1966 to June 5, 1967: 16 + 31 + 31 + 28 + 31 + 30 + 31 + 5 = 203 days.
3. Total: 1,096 + 203 = 1,299 days, about 1,300 days or three and a half years.
4. 1 km³ = 1,000,000,000 m³. Output ≈ 1,000,000,000 m³ ÷ 1,300 days ≈ 770,000 m³ per day, roughly the volume of 300 Olympic swimming pools every day on average.

Answer: About 1,300 days; about 770,000 m³ of new rock per day on average.

Example 3. Surtsey covered about 2.7 km² in 1967. By about 2002 it was close to 1.4 km². (a) Find the average rate of loss in km² per year. (b) If that rate never changed, in what year would the island vanish? (c) Why is the answer to (b) probably wrong?

1. (a) Area lost: 2.7 − 1.4 = 1.3 km² over 2002 − 1967 = 35 years. Rate = 1.3 ÷ 35 ≈ 0.037 km² per year (about 3.7 hectares a year).
2. (b) Remaining in 2002: 1.4 km². Time to vanish at the same rate: 1.4 ÷ 0.037 ≈ 38 years, so about the year 2040.
3. (c) The early loss was mostly loose ash, which washes away quickly. What remains is mostly hard lava and palagonite tuff, which erode far more slowly, so the rate has already dropped and the island should last much longer. A rate measured over one stretch of time cannot be assumed to hold for another.

Answer: (a) About 0.037 km² per year. (b) Around 2040 if the rate were constant. (c) The rate is not constant; the soft ash went first and the hard core erodes much more slowly, so the island will outlast that prediction by a long way.

PRACTICE

1. EASY Where is Surtsey, when was it born, and what plate boundary runs through Iceland?
2. EASY What happens in a Surtseyan eruption, and what does it build?
3. EASY Why did Surtsey survive when the islands Syrtlingur and Jólnir washed away?
4. MEDIUM A new tephra island is 120 m long on day 3 and 600 m long on day 10. What was its average growth in length per day over that week?
5. MEDIUM Data reading. A student’s results from the island-versus-waves experiment:

   Waves | Bare island height (cm) | Capped island height (cm)
   0 | 8.0 | 8.0
   20 | 6.5 | 7.9
   40 | 4.8 | 7.8
   60 | 3.6 | 7.6
   80 | 2.5 | 7.3

   (a) After how many waves had the bare island lost half its height? (b) What fraction of its height had the capped island lost by 80 waves? (c) Which conclusion is supported: the cap stopped all erosion, or the cap slowed erosion greatly?
6. MEDIUM Data reading. Surtsey’s arrivals:

   Year | Event
   1965 | First plant (sea rocket)
   1967 | First moss
   1970 | First lichens; first bird nests

mid-1980s | Gull colony settles
2008 | About 70 plant species recorded

(a) How many years after the island appeared did the first bird nest? (b) What change in the mid-1980s would you expect to speed up plant growth, and why? (c) Which came first on Surtsey, soil or plants?

7. MEDIUM In two or three sentences, explain how loose ash inside Surtsey became hard rock, and about how long it took.
8. HARD Experiment design. You want to find out whether the thickness of the cap matters. Describe the independent variable, the dependent variable, three controls and how you would record results.
9. HARD Surtsey's highest point was 174 m above sea level and the vent was about 130 m below it. What was the total height of the volcano from seafloor to summit? If the island's base on the seafloor was about 2 km across, what was its height-to-width ratio? Which volcano type from Lesson 3.3 is it closest to?
10. CHALLENGE Write a paragraph: What does Surtsey teach a scientist about judging how long a landform took to form? Use at least two examples from the island.

COMMON MISTAKES

- Thinking rock always takes an immense time to form. Surtsey's lava hardened in hours and its loose ash was cemented into tuff within a few years.
- Thinking a volcanic island is made only of lava. Surtsey began as a cone of loose steam-blasted ash; the lava came later and saved it.
- Thinking plants must wait for soil. The first sea rocket grew in bare ash; the plants and the birds helped make the soil afterward.

> **Make it a game · Surtsey Timeline Scramble.** Write these events on cards: fishing crew sees the cloud; cone breaks the surface; first lava flows; nature reserve declared; first plant; eruption ends; first bird nests; gull colony; World Heritage listing. Shuffle them. Lay them in order against the clock; a parent checks against the lesson. Every card in the right place scores a point, and a correct year on any card scores a bonus. Then play again with your eyes shut while a parent reads the cards aloud in random order and you call out "before" or "after" the one before it.

> **Scripture.** "And God said, Let the waters under the heaven be gathered together unto one place, and let the dry land appear: and it was so. And God called the dry land Earth; and the gathering together of the waters called he Seas: and God saw that it was good." (Genesis 1:9–10, KJV)

God made dry land rise out of the waters at the beginning, and in 1963 the world saw a small picture of dry land appearing from the sea. The earth is still a working creation under His hand.

Practice answers

1. Off the south coast of Iceland, at the southwest end of the Westman Islands; it first rose above the sea on November 14, 1963; Iceland sits on the Mid-Atlantic Ridge, a spreading boundary.
2. Seawater reaches the magma and flashes to steam, blasting out jets of wet ash. It builds a loose tephra cone.
3. In April 1964 Surtsey’s cone sealed the sea out of its vent, and lava flows then covered the loose ash with hard rock. The two smaller islands never got a lava cap, so waves washed their loose ash away within months.
4. (600 − 120) m ÷ (10 − 3) days = 480 ÷ 7 ≈ 69 m per day.
5. (a) Between 40 and 60 waves; half of 8.0 is 4.0 cm, and it passed that between 4.8 cm (40 waves) and 3.6 cm (60 waves), so at about 50 waves. (b) 8.0 − 7.3 = 0.7 cm; 0.7 ÷ 8.0 ≈ 0.09, about 9 percent. (c) The cap slowed erosion greatly but did not stop it, since the capped island still lost 0.7 cm.
6. (a) 1970 − 1963 = 7 years. (b) The gull colony; the birds’ droppings and food scraps fertilized the bare ground with nutrients, so grasses and flowers could spread around the colony. (c) Plants came first; the sea rocket grew in bare ash, and soil built up afterward as plants and bird droppings added organic matter.
7. Warm water and steam from the cooling vent soaked the loose glassy ash inside the island. The glass altered and new minerals formed between the grains, cementing them into brown palagonite tuff. This took only a few years, not ages.
8. Independent variable: cap thickness (for example no cap, 3 mm, 6 mm and 10 mm of clay). Dependent variable: how many waves until the island loses half its height (or the height remaining after a fixed number of waves). Controls: the same amount and dampness of sand, the same island shape and starting height, the same water depth, and the same size and timing of each wave push. Record the height of each island every 20 waves in a table and graph the results, repeating each thickness at least twice.
9. Total height = 174 + 130 = 304 m, about 0.3 km. Ratio = 0.3 ÷ 2 = 0.15. That is between a composite cone and a cinder cone; Surtsey is a tephra cone, steep like a cinder cone, later flattened a little by its lava cap.
10. A strong answer says that Surtsey’s cliffs, boulder beach, hardened tuff and bird-fertilized soil all looked as though they had taken a very long time, yet every one was measured to form within a few years to a few decades. The scientist’s rule is therefore to measure rates when possible instead of assuming them, to remember that rates change (the loose ash eroded quickly, the hard core slowly), and to be honest about uncertainty when something could not be watched. Looks are not a clock; measurements are.

Unit 3 review

Answer each question. Show your work for calculations, use complete sentences for explanations, and label every part of your diagram. The test is worth 60 points.

1. (4 pts) Multiple choice. What buried the city of Pompeii in A.D. 79? (a) Lava flows from Vesuvius. (b) Nearly 3 m of falling pumice followed by pyroclastic flows. (c) A tsunami from the Bay of Naples. (d) Mud from heavy rain on the volcano.
2. (4 pts) Multiple choice. Why is the A.D. 79 eruption called a Plinian eruption? (a) Pliny the Elder caused it by sailing too close. (b) Pliny the Younger wrote the first careful eyewitness description of its tall column and ash fall. (c) It happened in the town of Pliny. (d) Pliny was the name of the mountain before Vesuvius.
3. (6 pts) At Pompeii pumice fell at about 15 cm per hour. (a) How deep was it after 10 hours, in meters? (b) A flat roof of 30 m² carries 1.0 m of pumice with a density of 500 kg/m³. What mass rests on the roof?
4. (4 pts) Multiple choice. What caused most of the deaths in the Krakatoa eruption of 1883? (a) Lava. (b) Breathing ash. (c) Tsunamis driven by the collapse of the island. (d) The sound of the explosion.
5. (6 pts) The great blast of August 27, 1883 was heard on Rodrigues Island, 4,800 km away, about 4 hours later. (a) Calculate the speed in km per hour. (b) Using that speed, how long would the sound take to reach a place 2,400 km away? (c) In one sentence, explain what a barograph recorded that ears could not.
6. (6 pts) Data reading. A station records Krakatoa’s pressure wave passing at 11 hours, 25 hours, 47 hours and 61 hours after the blast. (a) How long did one trip around the world take? (b) Explain why the passes come in pairs (11 and 25, then 47 and 61).
7. (8 pts) Diagram. Draw and label side-view profiles of a shield volcano, a composite volcano and a cinder cone. For each, label (1) the name, (2) the approximate slope (gentle, steep near the top, or about 33 degrees), (3) the kind of material it is made of, and (4) one real example.
8. (4 pts) Multiple choice. Which magma is most likely to erupt explosively? (a) Hot basalt with 50 percent silica. (b) Cool rhyolite with 70 percent silica and lots of dissolved gas. (c) Any magma that reaches the surface at night. (d) Magma with no dissolved gas.
9. (6 pts) Parícutin was about 50 m tall after one day and 424 m tall after nine years. (a) Find the first-day growth rate in m per day. (b) Find the average growth rate over nine years in m per year. (c) In one sentence, say what comparing the two rates tells you.
10. (6 pts) Explain in three or four sentences the two stages of Surtsey’s eruption and why the second stage let the island survive when its neighbors Syrtlingur and Jólnir were washed away.
11. (6 pts) Surtsey covered 2.7 km² in 1967 and about 1.4 km² in 2002. (a) Find the average rate of loss in km² per year. (b) Give one reason the island will probably last much longer than that rate predicts. (c) In one sentence, state the rule about rates that Surtsey teaches.

UNIT PROJECT: A FIELD GUIDE TO FOUR VOLCANOES

Make a hand-drawn field guide with one page for each eruption in this unit: Vesuvius (A.D. 79), Krakatoa (1883), Parícutin (1943) and Surtsey (1963). Each page has a map with a scale bar, a labeled profile showing the volcano type, a short timeline of the eruption, one calculation (a rate, a speed, a ratio or a scale model) with its working shown, and a sentence naming the person who recorded it and what instrument or method they used.

Add a fifth page with your own results from the honey-volcano and island-versus-waves experiments, including a data table, a graph and a conclusion that says what you kept the same and what you changed. Finish with a short paragraph on what these four volcanoes teach about observing and measuring before assuming.

- **Accuracy**: Places, dates, volcano types, stages of each eruption and all numbers are correct and match the lessons.
- **Calculations**: Each page includes a correct rate, speed, ratio or scale calculation with units and the working shown.
- **Experiment records**: Data tables and graphs are complete and labeled, with variables, controls and a conclusion stated plainly.
- **Care**: Maps, profiles and timelines are neat, labeled, drawn with scale bars, and easy to read.

Answer key

1. (b).
2. (b).
3. (a) 15 × 10 = 150 cm = 1.5 m. (b) Volume = 30 × 1.0 = 30 m³; mass = 30 × 500 = 15,000 kg (15 tonnes).
4. (c).
5. (a) 4,800 ÷ 4 = 1,200 km/h. (b) 2,400 ÷ 1,200 = 2 hours. (c) A barograph recorded the pressure wave as a wiggle in air pressure, even on the far side of the world where no one could hear anything, and showed the wave circling the globe several times.
6. (a) 47 − 11 = 36 hours (or 61 − 25 = 36). (b) The wave left Krakatoa in all directions; one part reached the station the short way around and another part the long way around, so each lap gives two passes, 14 hours apart at this station.
7. Shield: very wide and low, gentle slopes of 2 to 10 degrees, thin flows of runny basalt lava, example Mauna Loa or Kilauea. Composite (stratovolcano): tall cone, steep near the summit (about 30 degrees), alternating layers of lava and tephra, example Fuji, Vesuvius or Rainier. Cinder cone: small steep cone with a bowl crater, slopes about 33 degrees, loose cinders, example Parícutin. Award 2 points for each correctly drawn and labeled profile and 2 points for correct examples.
8. (b).
9. (a) 50 m/day. (b) 424 ÷ 9 ≈ 47 m/year. (c) The volcano grew far faster at the start than its long-term average suggests, so an average rate can hide how growth really happened.
10. In the first stage seawater reached the magma and flashed to steam, blasting out wet ash that piled into a loose tephra cone (a Surtseyan eruption). In April 1964 the cone sealed the sea out of the vent and the second stage began: runny basalt lava flowed over the ash and

armored it with hard rock. The neighboring islands were only loose ash with no lava cap, so the winter waves washed them away within months, while Surtsey’s hard cover resisted the sea.

11. (a) (2.7 − 1.4) ÷ 35 = 1.3 ÷ 35 ≈ 0.037 km² per year. (b) The loose ash eroded first and quickly; the remaining core is hard lava and palagonite tuff, which erode far more slowly. (c) Measure rates rather than assuming them, and do not assume a rate measured over one period stays constant.

UNIT 4

Earthquakes

On the morning of November 1, 1755, the city of Lisbon shook, burned and was flooded by the sea in a single day. Out of that disaster came the first organized survey of an earthquake and, slowly, a science. In this unit you will follow that science from the Marquis of Pombal's parish questionnaire to Charles Richter's magnitude scale, from Zhang Heng's bronze dragons to John Milne's worldwide network of seismographs, and from the drawback of the sea at Lisbon to the ocean buoys that listen for tsunamis today.

You will measure as seismologists measure. You will build a fault from sandpaper and find how much energy it stores before it slips, make a kitchen-floor intensity map, build a seismograph and read its trace, and time waves in a tub to test the rule that a tsunami's speed depends only on the depth of the water. Along the way you will learn to read a seismogram, turn an S minus P time into a distance, and compare earthquakes by ratios of ten and thirty-two.

Through it all you will hold two things together, as the Christians of 1755 did: the earth shakes, and the Lord is our refuge (Psalm 46). Knowing how earthquakes work is part of loving our neighbors, because the shaking itself is a warning that can save lives on a shore, and because careful observation is one way we honor the One who "looketh on the earth, and it trembleth."

BEFORE YOU BEGIN

- Knows that the earth's crust is broken into plates that move slowly at their boundaries (Unit 2).
- Can multiply and divide with decimals, convert minutes to hours and seconds to minutes, and find an average.
- Can read a simple data table and a bar or line graph.
- Has met seismic waves and the layered earth (Lesson 1.1, Lehmann and the core).

MASTERY CHECKLIST

- I can tell the story of Lisbon in 1755 in order (shaking, sea wave, fire) and explain elastic rebound, focus and epicenter.
- I can explain that each whole step of magnitude means a wiggle 10 times taller and about 32 times more energy, and I can compare two earthquakes by ratio.
- I can tell the difference between magnitude and intensity and describe at least three Modified Mercalli levels.
- I can explain how a seismograph uses inertia, read P, S and surface waves on a seismogram, and turn an S minus P time into a distance.
- I can calculate a tsunami's speed from the water depth and explain why it grows tall near the shore.

- I can name the natural warning signs of a tsunami and the right response, and describe how seismographs and DART buoys give warnings today.

OPTIONAL BOOKS AND RESOURCES

- **USGS Latest Earthquakes map** (https://earthquake.usgs.gov/earthquakes/map/): Free. A live map of earthquakes around the world with magnitude, depth and time. Have your student find today's largest earthquake, write its magnitude and work out how many times more energy it released than a magnitude 4.
- **NOAA Tsunami Warning Centers (tsunami.gov)** (https://www.tsunami.gov/): Free. The official U.S. tsunami warning page. Look at the map of current messages and find the Pacific Tsunami Warning Center's area. Good for Lesson 4.4 and for the portfolio.
- **USGS Earthquake Hazards Program: Earthquakes for Kids and education pages** (https://www.usgs.gov/programs/earthquake-hazards): Free. Explanations of magnitude, intensity, seismographs and the "Did You Feel It?" citizen survey, with photographs and diagrams a parent can read aloud.

4.1 Lisbon (1755): The Earthquake That Started a Science ★

OBJECTIVES

- Tell what happened in Lisbon on November 1, 1755, in order (shaking, sea wave, fire) and explain why a single earthquake can cause all three.
- Explain how rock along a fault stores energy and snaps (elastic rebound), and use the words fault, focus, epicenter, seismic wave and aftershock correctly.
- Describe Pombal's parish survey and explain why gathering observations from many places is the first step of earthquake science.

Warm-up. Press your palms together hard and try to slide them slowly past each other. Notice that they stick, stick, stick, and then jerk. Now do the same with two wooden blocks, or two paperback books, pressed face to face. Where did the energy for the jerk come from? Write one sentence. That stick-and-jerk is the smallest earthquake you will ever feel.

Video. Coming soon. Lisbon earthquake 1755 history and earthquake basics (fault, focus, epicenter, elastic rebound); look for USGS, Smithsonian, SciShow Kids, Homeschool Pop (Alternate), Science Max and documentary clips on the 1755 Lisbon earthquake and the Marquis of Pombal.

KEY TERMS

fault
A crack in the earth's crust along which blocks of rock slide past each other.

focus
The point underground where the rock first slips and the earthquake begins (also called the hypocenter).

epicenter
The point on the earth's surface directly above the focus.

seismic waves
Vibrations that travel outward from the focus through rock, carrying the earthquake's energy.

elastic rebound
Rock on both sides of a fault bends slowly and stores energy, then snaps back when friction gives way, sending out seismic waves.

aftershock
A smaller earthquake that follows the main shock as the rocks along the fault settle, sometimes for days or months.

CORE IDEAS

The story. November 1, 1755, was All Saints' Day, and the churches of Lisbon, Portugal, were full. At about 9:40 in the morning the ground began to shake, in three shocks over several minutes, long enough for stone walls to crack, sway and fall. Thousands ran from the dust to the open quays along the River Tagus. There they saw something strange: the river drained away, leaving boats on the mud. Within about an hour the water came back as a wall several meters high and swept over the waterfront. Then candles knocked over in the churches and fires left in kitchens spread through the ruins, and the city burned for days. Tens of thousands of people died; no one knows the exact number. The earthquake came from a fault under the Atlantic, roughly 200 km southwest of Cape St. Vincent, and seismologists who study the old reports estimate it at magnitude 8.5 or higher. The shaking was felt across Portugal, Spain and Morocco, and the sea wave reached Morocco, Cornwall and, that same afternoon, the Caribbean. King Joseph I was outside the city at Belém and lived, but he was so shaken that for years afterward he lived in a great tent rather than inside stone walls.

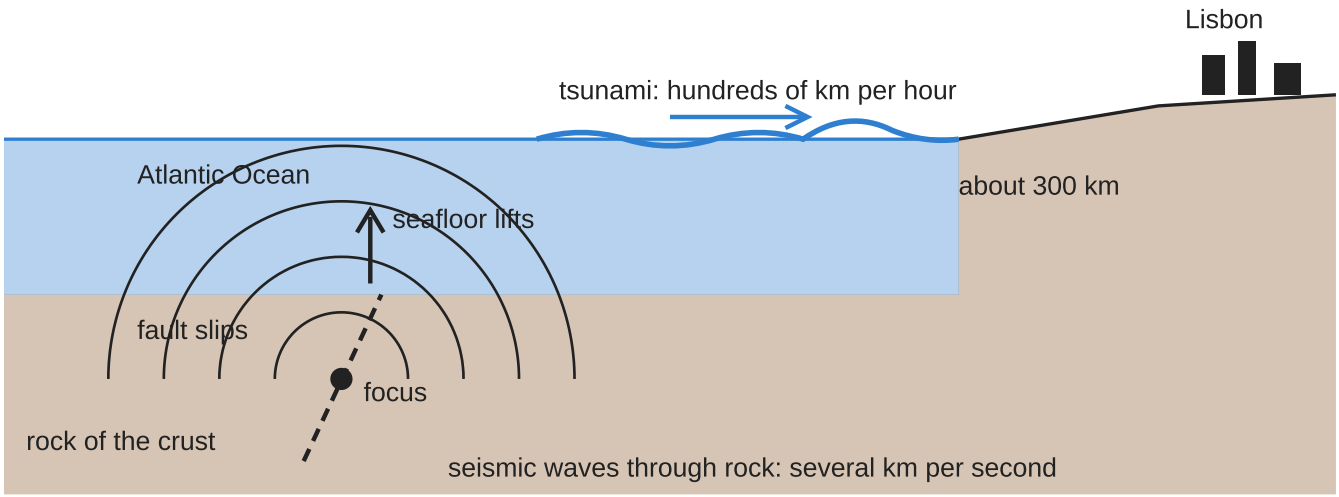
How they figured it out. The king's chief minister, Sebastião José de Carvalho e Melo, later known as the Marquis of Pombal, took charge within hours. His first orders were practical: bury the dead quickly, feed the living, post soldiers against looting, fix the price of bread. Then he did something new. In 1756 he sent a list of questions to every parish priest in Portugal. At what time did the earthquake begin, and how long did it last? Did the ground seem to shake more from one direction? Did the sea rise first or fall first, and how many times? How many houses fell? Were there aftershocks, and when? The answers are still kept in Portugal's national archive. It was the first time anyone had gathered earthquake observations from a whole country in one organized set, and from answers like these a scientist can map where the shaking was strongest, which points toward the source. Pombal also rebuilt the flattened center of Lisbon on a grid of wide streets, and his builders put a wooden cage, the *gaiola*, inside the walls of the new buildings so they could flex instead of crumble.

The big idea. Earthquakes happen because the earth's plates (Unit 2) push slowly on each other, but the rock along a **fault** does not slide smoothly. Friction holds it. The rock on both sides bends, like a ruler you push on from the ends, and stores energy. When the stored force finally beats the friction, the rock snaps back toward its unbent shape in seconds. That snap is called **elastic rebound**, and it sends **seismic waves** out in every direction at several kilometers per second. The spot underground where slipping begins is the **focus**; the spot on the surface straight above it is the **epicenter**. In Lisbon's case the fault lay under the sea. When a fault lifts or drops the seafloor, the whole column of water above it is lifted or dropped too, and that moving water becomes a tsunami (Lesson 4.4). The shaking also topples lamps and stoves, so one earthquake made three disasters: shaking, sea wave and fire. The smaller quakes that follow, as the rocks settle into their new positions, are **aftershocks**.

Try it and see. Build a fault on your kitchen table: a wooden block faced with sandpaper, set on more sandpaper and pulled by a rubber band. Pull slowly. The band stretches (energy

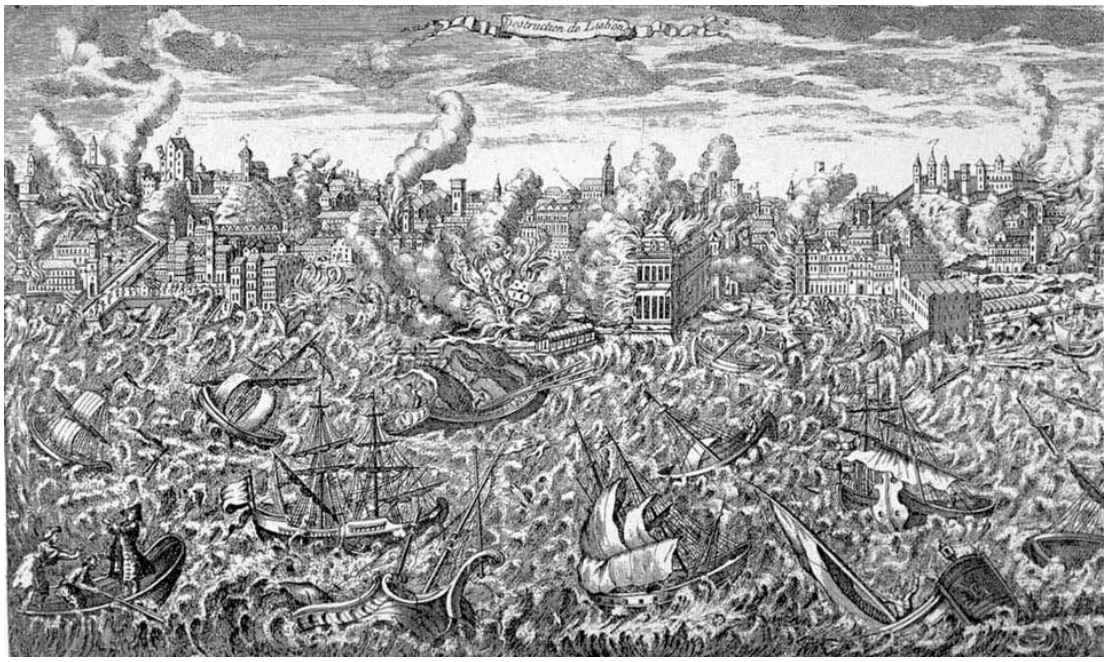
stored) while the block sits still (friction holding). Then the block jumps (the earthquake) and the band goes slack (energy released). Measure how far the band stretched before each jump and you are measuring, as seismologists do, how much energy a fault can store before it lets go.

God's handiwork. Lisbon shook more than buildings. The French writer Voltaire wrote a bitter poem asking how a good God could allow such a day. In England, John Wesley answered with a pamphlet, *Serious Thoughts Occasioned by the Late Earthquake at Lisbon*, reminding readers that the earth is not a machine running by itself but belongs to the Lord, and that the right response is humility, not pride. The Christians of 1755 did two things at once, and so should we. They trusted that the earth is the Lord's, and they went to work: feeding the hungry, rebuilding wisely, and collecting careful observations so the next city might be better prepared. Psalm 46 was written for days like November 1, 1755: "Therefore will not we fear, though the earth be removed."



One slip, three disasters. The fault under the Atlantic sent seismic waves through the rock (reaching Lisbon in under a minute) and lifted the sea above it, which arrived as a tsunami within about an hour.

PICTURE STUDY



The Ruins of Lisbon (copper engraving of the 1755 earthquake), Unknown German engraver, 1755 · Copperplate engraving · Printed in Germany soon after the disaster; copies in several European libraries

Within weeks of November 1, 1755, printers across Europe were selling pictures of the disaster to readers who could hardly believe the news. This engraver had probably never seen Lisbon. He put everything into one scene: towers cracking, flames pouring from windows, and great waves in the harbor overturning ships. It is not a photograph, but it shows what people in 1755 understood had happened: shaking, fire and sea all at once.

Pictures like this one spread the story of Lisbon from London to Moscow and made people ask what could cause such a thing. Within a few months, scholars were collecting reports and writing the first careful essays on earthquakes as natural events.

Look closely

- Find the three disasters in the picture: falling buildings, fire and the sea. Which one takes up the most space?
- Look at the ships in the harbor. What is the water doing to them?
- Look at the people. Where are they running, toward the water or away from it? Was that wise?
- The engraver drew everything happening at the same moment. From the lesson, in what order did these things really happen?

Talk about it

1. Why would an artist who had never seen Lisbon still make a picture of the earthquake? Who was the picture for?

2. What would a scientist want that this picture cannot give? (Think about times, measurements and directions.)
3. Pombal's survey gathered facts from witnesses. How is a survey different from a picture like this one?

EXPERIMENT: THE SANDPAPER FAULT: MEASURING STORED ENERGY BEFORE A SLIP

A fault sticks because of friction and snaps when the stored force wins. In this experiment you will build a fault from sandpaper and a block, pull it with a rubber band, and measure how much the band stretches before each slip. Then you will change the roughness of the fault and see what happens.

Question: Does a rougher fault store more energy before it slips? Prediction: write yours before you begin.

You will need

- A small wooden block or a brick-shaped box with a little weight inside (about the size of a soap bar)
- Three sheets of sandpaper: fine, medium and coarse (plus the bare tabletop as the smooth fault)
- Glue or tape to attach one sheet of sandpaper to the bottom of the block
- A thick rubber band and a small screw hook or a loop of string on the block
- A ruler (30 cm) laid along the path and a notebook

Steps

1. Tape a sheet of fine sandpaper to the bottom of the block. Tape a second sheet of sandpaper, same grit, to the table. Set the block at the 0 cm mark of the ruler.
2. Hook the rubber band to the block. Hold the far end of the band at the ruler and pull it slowly along the table at a steady pace (a finger-width every second).
3. Watch the band stretch while the block stays still. The moment the block jumps, note how long the band had stretched (in cm) and how far the block jumped (in cm). Record both.
4. Repeat until you have five slips. Write every number in a table with columns: Trial, Stretch before slip (cm), Jump distance (cm).
5. Change only the fault: medium sandpaper on both surfaces, then coarse, then the bare table. Keep the same block, band and pulling speed. Collect five slips for each.
6. Find the average stretch before slip for each surface. Make a bar graph: surface on the bottom, average stretch (cm) up the side.
7. Write your conclusion: Which fault stored the most energy before slipping? Did rougher faults also make bigger jumps? Was your prediction right?

Tips

- Pull slowly and steadily. If you jerk, you are adding energy that the fault did not store.

- If the block slides smoothly without sticking, add a little weight inside it to increase the friction.
- Small slips between big ones are like foreshocks and aftershocks. Record them too.

Check your work

- I kept the block, the band and my pulling speed the same and changed only the surface.
- I recorded five trials for each surface and found the averages.
- I can explain where the energy of each jump came from.

FIELD NOTEBOOK

1. Draw a cross-section of a fault with the focus marked underground and the epicenter marked on the surface. Add arrows for the seismic waves spreading out.
2. Make a timeline strip for the morning of November 1, 1755: shaking, river drains, wave returns, fires begin. Beside each event, write what a wise person on the quay should have done.
3. Copy Pombal's five best survey questions into your notebook and write the answers a parish priest 100 km from the coast might have given.

> **From history.** Pombal's questionnaire was an early form of what scientists now call citizen science. The U.S. Geological Survey still does the same thing with its "Did You Feel It?" web page: after any earthquake, people type in where they were, what they felt and what fell, and within minutes the USGS turns thousands of answers into a map of shaking intensity. Pombal needed months and horseback messengers; the idea is the same.

WORKED EXAMPLES

Example 1. Suppose the fault that caused the Lisbon earthquake was about 300 km from the city and the first sea wave arrived about 45 minutes after the shaking. What was the wave's average speed in km/h?

1. Change the time to hours: 45 minutes = 45 ÷ 60 = 0.75 h.
2. Speed = distance ÷ time = 300 km ÷ 0.75 h.
3. 300 ÷ 0.75 = 400.

Answer: About 400 km/h, faster than any ship and faster than a high-speed train.

Example 2. Seismic P waves travel through the crust at about 6 km/s. How long did the first shaking take to reach Lisbon from a fault 300 km away? How many times faster is that than the 400 km/h sea wave?

1. Time = distance ÷ speed = 300 km ÷ 6 km/s = 50 s. The shaking arrived in under a minute.
2. Change the P wave speed to km/h: 6 km/s × 3,600 s/h = 21,600 km/h.
3. Compare: 21,600 ÷ 400 = 54.

Answer: About 50 seconds; the seismic waves were about 54 times faster than the sea wave. That gap of nearly 45 minutes is why the shaking itself is a warning to leave the shore.

Example 3. Suppose five parish reports from Pombal's survey gave these durations for the shaking: 3 minutes, 6 minutes, 4 minutes, 5 minutes and 7 minutes. Find the average and the range, and explain why the reports differ.

1. Add the values: 3 + 6 + 4 + 5 + 7 = 25 minutes.
2. Average = 25 ÷ 5 = 5 minutes.
3. Range = largest − smallest = 7 − 3 = 4 minutes.
4. Reports differ because no one was holding a stopwatch. Frightened people guess time poorly, some counted only the strongest shock, and the ground shakes longer on soft soil than on hard rock.

Answer: Average 5 minutes, range 4 minutes. A single report is a guess; many reports together give a dependable picture, which is why Pombal asked everyone.

PRACTICE

1. EASY On what date did the Lisbon earthquake strike, and why were so many people inside churches that morning?
2. EASY Put these events of November 1, 1755, in the order they happened: fires spread through the ruins; the river drained and then returned as a great wave; the ground shook for several minutes.
3. EASY What is the difference between the focus and the epicenter of an earthquake?
4. MEDIUM People on the Lisbon quays saw the river drain away before the big wave came. Explain why the water pulled back, and what they should have done the moment they saw it.
5. MEDIUM A fault slips 120 km from a town. P waves travel at about 6 km/s. How many seconds pass before the first shaking reaches the town?
6. MEDIUM Data reading. A historian compared four towns hit by a tsunami from the same earthquake. Town A: 250 km from the fault, first wave 40 min after the shaking. Town

B: 400 km, 65 min. Town C: 550 km, 90 min. Town D: 700 km, 115 min. Which statement is best supported by the data? (a) The wave sped up as it traveled. (b) The wave traveled at a roughly steady average speed of about 6 km per minute. (c) The wave slowed to half speed after 400 km. (d) The data show no pattern.

7. MEDIUM Data reading. Suppose Pombal's clerks sorted the parish answers about how long the shaking lasted into groups: 1–2 minutes, 18 parishes; 3–4 minutes, 61 parishes; 5–6 minutes, 44 parishes; 7 or more minutes, 12 parishes. Which answer was most common? What fraction of the 135 parishes reported 5 minutes or more? Why might a parish on soft river mud report a longer time than one on hard rock?
8. HARD Experiment design. A student wants to know whether pulling the rubber band faster changes how far the sandpaper block jumps. Name the independent variable, the dependent variable, two things that must be kept the same, and how many trials you would run for each condition.
9. HARD Explain in three or four sentences how one slip on a fault under the sea could cause shaking, a sea wave and fire in a city 300 km away.
10. CHALLENGE Pombal asked every parish whether the sea rose first or fell first. Explain what a scientist could learn from hundreds of answers to that one question, if they were marked on a map.

COMMON MISTAKES

- Thinking the ground opens up and swallows people in an earthquake. The danger is shaking; cracks in the ground are usually small, and a fault does not gape open.
- Mixing up focus and epicenter. The focus is underground where the slip starts; the epicenter is the map point above it. Newspapers report the epicenter.
- Believing in "earthquake weather." Hot, still days do not cause earthquakes. The USGS says there is no connection between weather and earthquakes; the stress is stored kilometers down in the rock.

> **Make it a game · Pombal's Survey.** Send family members to different rooms. One person is the earthquake: at a secret moment, they jump hard three times somewhere in the house. Everyone else must write, without talking, the time on the nearest clock, how many jumps they felt or heard, how strong it seemed (1 to 5), and which direction it came from. Then gather and compare. Can the group work out which room the earthquake was in from the reports alone? Score a point for each correct guess, and play three rounds with a new earthquake each time.

> **Scripture.** "Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah." (Psalm 46:2–3, KJV)

The psalm does not say the earth will never shake. It says that when it does, God is our refuge. The people of Lisbon who trusted Him and then went to work rebuilding show what that trust looks like.

Practice answers

1. November 1, 1755. It was All Saints' Day, a church holiday, and services were being held.
2. 1. The ground shook for several minutes. 2. The river drained and then returned as a great wave (within about an hour). 3. Fires spread through the ruins and burned for days.
3. The focus is the point underground where the rock first slips. The epicenter is the point on the surface directly above the focus.
4. The trough (low part) of the tsunami arrived first, pulling the water out, with the crest following close behind. They should have run inland or uphill at once instead of walking out to look.
5. 120 ÷ 6 = 20 seconds.
6. (b). Dividing distance by time: 250 ÷ 40 ≈ 6.3, 400 ÷ 65 ≈ 6.2, 550 ÷ 90 ≈ 6.1, 700 ÷ 115 ≈ 6.1 km per minute, all close to 6 km/min (about 370 km/h). The speed is steady, not increasing or halving.
7. Most common: 3–4 minutes. Five minutes or more: (44 + 12) ÷ 135 = 56 ÷ 135, about 41%. Soft, wet soil keeps sloshing after the waves pass (it shakes longer and harder than solid rock), so people on mud feel a longer quake.
8. Independent variable: pulling speed (slow, medium, fast). Dependent variable: jump distance in cm. Keep the same: the block and its weight, the sandpaper grit, the rubber band, the starting position. Run at least five trials per speed and average them so one odd jump does not decide the result.
9. The slip released stored energy as seismic waves that raced through the rock at several km/s and shook the city within a minute, cracking and toppling buildings. The same slip lifted the seafloor and the water above it, which spread out as a tsunami and reached the coast in under an hour. The shaking knocked over candles, lamps and cooking fires in the ruins, and with no one to fight them the fires spread for days.
10. Whether the sea first rose or fell at a coast depends on whether the seafloor nearest that coast was pushed up or dropped down by the fault. Mapping "rose first" and "fell first" along the coast shows which way the seafloor moved and helps locate the fault that moved it. Many answers give a pattern; one answer alone could be a mistake.

4.2 Richter and Moment Magnitude: Measuring the Size of an Earthquake

OBJECTIVES

- Explain how Charles Richter built the first magnitude scale in 1935 and why each whole number means a wiggle 10 times larger and about 32 times more energy.
- Tell the difference between magnitude (one number for the whole earthquake) and intensity (the shaking felt at a particular place) and read a Modified Mercalli description.
- Explain why moment magnitude replaced the Richter scale for large earthquakes and compare the sizes of famous earthquakes with ratios.

Warm-up. Put 1 grain of rice on the table. Beside it put 10 grains. Beside that, count out 100 grains. Now imagine the next pile: 1,000 grains, then 10,000. Each pile is 10 times the one before, but you only added one “step.” Write down how many steps it takes to go from 1 grain to a million grains. Earthquake magnitudes count in steps like this.

Video. Coming soon. Earthquake magnitude explained: Richter scale, logarithmic scale, moment magnitude, magnitude versus intensity (Modified Mercalli); look for USGS, Smithsonian, SciShow, Science Max, Homeschool Pop (Alternate) and short Caltech history clips about Charles Richter.

KEY TERMS

magnitude
A single number that tells the size of an earthquake at its source, worked out from seismograph records.

amplitude
The height of the biggest wiggle on a seismogram; how far the ground moved.

logarithmic scale
A scale in which each step up means multiplying by the same number (on the magnitude scale, each whole number means 10 times the wiggle).

seismic moment
A measure of an earthquake’s true size: the stiffness of the rock times the area of the fault that slipped times how far it slipped.

moment magnitude (Mw)
The modern magnitude scale, calculated from the seismic moment, used by the USGS for large earthquakes.

intensity
How strong the shaking was at one place, judged by what people felt and what was damaged; given in Roman numerals I to XII on the Modified Mercalli scale.

CORE IDEAS

The story. In 1935 a quiet young physicist named Charles F. Richter worked at the Seismological Laboratory of the California Institute of Technology in Pasadena. Southern California had earthquakes every week, and reporters kept asking the same question: how big was it? Richter could only describe the wiggles on the seismograph, and that satisfied no one. With his senior colleague Beno Gutenberg, he looked for a way to give every earthquake one number. A Japanese seismologist, Kiyoo Wadati, had already (in 1931) plotted the size of earthquake wiggles against distance from the source, and Richter built on that idea. He also borrowed a trick from astronomy, where stars are ranked by magnitude in steps. Richter decided that magnitude 0 would be a wiggle one thousandth of a millimeter high on a standard Wood-Anderson seismograph 100 km from the epicenter, and that every whole number up would mean a wiggle 10 times taller. Reporters soon called it “the Richter scale,” and the name stuck.

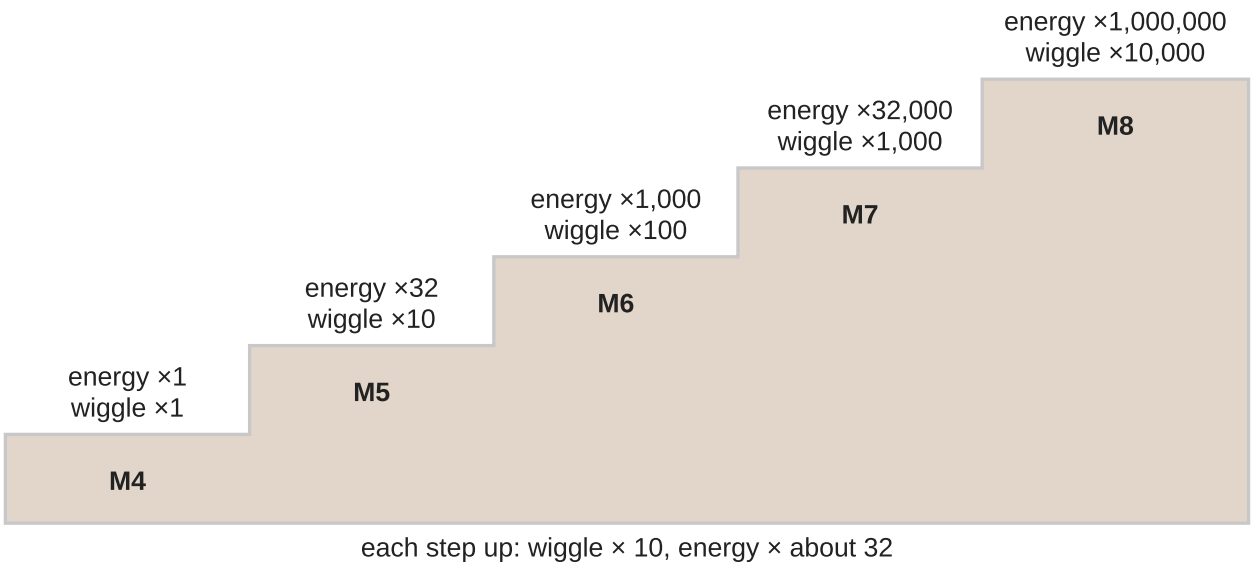
How they figured it out. Richter’s scale is **logarithmic**. A magnitude 6 earthquake makes a wiggle 10 times taller than a magnitude 5, and 100 times taller than a magnitude 4. Energy grows even faster, because a bigger earthquake shakes longer as well as harder: each whole step releases about 32 times more energy, and two steps about 1,000 times more. So a magnitude 7 is not “a little bigger” than a magnitude 5; it is a thousand times more energetic. Richter’s scale worked well for California’s local quakes, but it had a flaw. The Wood-Anderson instrument was tuned to quick, short vibrations, and the biggest earthquakes put most of their energy into slow, long waves that it hardly noticed. Above about magnitude 7 the Richter scale stopped climbing even as the earthquakes got far larger; seismologists say it “saturates.” In 1979 Thomas Hanks of the U.S. Geological Survey and Hiroo Kanamori of Caltech published the **moment magnitude** scale (written Mw). It is built from the **seismic moment**: the stiffness of the rock multiplied by the area of fault that slipped multiplied by how far it slipped. It matches Richter’s numbers for ordinary earthquakes but keeps counting for giant ones. By this scale the largest earthquake ever recorded, in Chile on May 22, 1960, was magnitude 9.5; its fault broke along roughly 1,000 km of coast. The Alaska earthquake of Good Friday, 1964, was 9.2; the Sumatra earthquake of 2004 and the Japan earthquake of 2011 were each 9.1.

The big idea. Magnitude is not the same as damage. Magnitude is one number for the whole earthquake, measured at the source. **Intensity** is how hard the ground shook in one particular place, and it is different in every town. Giuseppe Mercalli made an intensity scale in 1902; the Modified Mercalli scale of 1931 runs from I to XII in Roman numerals. Intensity I is not felt at all. At IV, dishes rattle and parked cars rock. At VI, everyone feels it and some heavy furniture moves. At VIII, ordinary buildings are badly damaged and chimneys fall. At X, most brick and stone buildings are destroyed. At XII, damage is total and objects are thrown into the air. The same earthquake gives high intensities near the epicenter and low ones far away, and soft soil shakes harder than solid rock. A magnitude 6 earthquake directly under a city can do more harm than a magnitude 8 far out at sea. There are also many more small earthquakes than large ones. The USGS long-term averages are about 1 earthquake of

magnitude 8 or above each year, about 15 of magnitude 7 to 7.9, about 134 of magnitude 6 to 6.9, and about 1,300 of magnitude 5 to 5.9: roughly ten times more for each step down.

In the world today. When the news says an earthquake “measured 7.1 on the Richter scale,” the number almost always came from the moment magnitude scale, because the USGS and other agencies have used Mw for large earthquakes for decades. The USGS also makes a ShakeMap within minutes of a big earthquake, drawing the intensity across the region from seismograph readings and from the “Did You Feel It?” reports you met in Lesson 4.1. Engineers use intensity, not magnitude, when they decide how strong to build (Unit 8).

Try it and see. Drop a heavy book onto the floor from a set height and watch the ripples in cups of water placed 1 m, 2 m and 4 m away. The drop height is like magnitude: one number, set at the source. The ripples at each cup are like intensity: they shrink with distance. Raise the drop height and every cup shows more, but the far cups still show less than the near ones.



Each whole number of magnitude multiplies the wiggle by 10 and the energy by about 32. From magnitude 4 to magnitude 8 the energy grows about one million times.

PICTURE STUDY



Looking Down Sacramento Street, San Francisco, April 18, 1906, Arnold Genthe, 1906 · Photograph · Library of Congress, Washington, D.C.

Arnold Genthe was a portrait photographer who lived on Sacramento Street. On the morning of April 18, 1906, an earthquake now estimated at magnitude 7.9 shook San Francisco at 5:12 a.m. Genthe's studio was wrecked, so he borrowed a camera from a shop and walked out to record what he saw. This picture, taken later that day, became the most famous image of the disaster.

The earthquake lasted less than a minute, but the fires it started burned for three days and destroyed far more of the city than the shaking did. Genthe's neighbors in the photograph are watching that fire come toward them.

Look closely

- Find the people. What are they doing? Do they look as if they are in a hurry?
- Look at the buildings on the left. What has the shaking done to them? What has the fire not yet done?
- Find the smoke. How large is it compared with the buildings?
- The street slopes steeply. How might soft or filled ground at the bottom of the hill have shaken differently from solid rock at the top?

Talk about it

1. A magnitude 7.9 earthquake is one number. The people on this street felt a high intensity; people in Los Angeles felt almost nothing. Explain the difference in your own words.

2. Genthe took a picture instead of running. What did his photograph give to the people who studied the earthquake afterward?
3. If seismologists in 1906 had no magnitude scale, how could they have compared this earthquake with others? (Hint: intensity maps.)

EXPERIMENT: MAGNITUDE AND INTENSITY ON THE KITCHEN FLOOR

You will make a tiny earthquake with a dropped book and measure its intensity at different distances. Then you will change the “magnitude” by raising the drop height. By the end you will have your own intensity scale and a map of shaking, just as the USGS makes after a real earthquake.

Question: How does shaking intensity change with distance from the source, and with the size of the source? Prediction: write it down before you begin.

You will need

- A heavy book (a dictionary or large atlas) and a hard floor (wood or tile works better than carpet)
- Four identical cups filled to the brim with water
- A tape measure or meter stick, masking tape, a notebook
- A ruler held upright to set the drop height (15 cm, 30 cm, 60 cm)

Steps

1. Mark a drop point on the floor with tape. Place the four cups on the floor in a line at 0.5 m, 1 m, 2 m and 3 m from the drop point.
2. Write your intensity scale first, like Mercalli: I, no ripple seen; II, faint ripple at the edge; III, clear ripples across the cup; IV, water sloshes; V, water spills.
3. Drop the book flat from 15 cm. Four observers (or one observer and three trials) watch the cups and call out the intensity. Record each cup’s reading in a table: Height, Distance, Intensity.
4. Repeat three times at 15 cm and record the most common reading for each cup.
5. Now change only the magnitude: drop from 30 cm, then from 60 cm. Keep the same book, same cups, same floor, same observers.
6. Draw a simple map of the floor from above and write the intensity readings beside each cup for the 60 cm drop. Draw a curved line around all the cups with intensity III or more. That is an isoseismal line, like the ones on a USGS ShakeMap.
7. Make a line graph: distance on the bottom, intensity up the side, one line for each drop height. Write a conclusion that answers the question with your evidence.

Tips

- Drop the book flat so it lands the same way each time. A corner landing is a different earthquake.
- If the far cups never show a ripple, move everything closer or use a heavier book.

- Try the same drop on carpet and on tile. Which floor is the “soft soil”?

Check your work

- I wrote my intensity scale before I took readings so that every reading used the same rules.
- I changed only one thing at a time: first the distance, then the drop height.
- I can explain why the drop height is like magnitude and the cup reading is like intensity.

FIELD NOTEBOOK

1. Draw a staircase of five steps labeled M4 to M8. On each step write the wiggle size (×1, ×10, ×100 …) and the energy (×1, ×32, ×1,000 …).
2. Make a two-column chart: Magnitude on the left, Intensity on the right. Under each, write three facts that belong to it only.
3. Copy five Modified Mercalli levels (I, IV, VI, VIII, X) with a small sketch of what happens at each: a sleeping person, rattling dishes, a walking chair, a fallen chimney, a ruined wall.

> **From history.** Charles Richter was born on an Ohio farm in 1900 and was studying physics at Caltech when, in 1927, he was offered a job at the Seismological Laboratory in Pasadena. He never liked the name “Richter scale,” insisting that Beno Gutenberg deserved equal credit. He kept a seismograph in his own living room and, for the rest of his life, answered reporters’ telephone calls whenever an earthquake struck, at any hour of the night.

WORKED EXAMPLES

Example 1. The 1906 San Francisco earthquake is estimated at magnitude 7.9. A moderate aftershock measured 5.9. How many times taller was the main shock’s wiggle on a seismogram, and about how many times more energy did it release?

1. Find the difference in magnitude: $7.9 - 5.9 = 2$ whole steps.
2. Wiggle: each step multiplies by 10, so $10 \times 10 = 100$ times taller.
3. Energy: each step multiplies by about 32, so $32 \times 32 \approx 1{,}000$ times more energy.

Answer: The wiggle was 100 times taller and the energy about 1,000 times greater, from only a two-step difference in the magnitude number.

Example 2. The 1960 Chile earthquake was magnitude 9.5. Lisbon in 1755 is estimated at about 8.5. Compare the two by wiggle size and by energy. Then compare a magnitude 6.5 earthquake with a magnitude 6.0 (a half step).

1. Chile minus Lisbon: 9.5 − 8.5 = 1 step. Wiggle 10 times taller; energy about 32 times greater.
2. A half step: wiggle grows by the square root of 10, about 3.2 times (because two half steps must make 10, and 3.2 × 3.2 ≈ 10).
3. Energy for a half step grows by the square root of 32, about 5.6 times (5.6 × 5.6 ≈ 32).

Answer: Chile 1960 released about 32 times the energy of Lisbon 1755 with wiggles 10 times taller. A 6.5 has wiggles about 3.2 times taller and about 5.6 times the energy of a 6.0.

Example 3. USGS long-term yearly averages: magnitude 8 and above, 1; magnitude 7 to 7.9, 15; magnitude 6 to 6.9, 134; magnitude 5 to 5.9, 1,319. By about what factor does the number of earthquakes grow for each step down in magnitude? Use the table to predict how many magnitude 4 to 4.9 earthquakes occur each year.

1. Compare neighboring rows: 15 ÷ 1 = 15; 134 ÷ 15 ≈ 8.9; 1,319 ÷ 134 ≈ 9.8.
2. The factor is close to 10 for each step down (the first row has only one earthquake, so its ratio is rough).
3. Predict the next row: 1,319 × 10 ≈ 13,000.

Answer: About 10 times more earthquakes for each step down in magnitude; roughly 13,000 earthquakes of magnitude 4 to 4.9 per year, which matches the USGS estimate of about 13,000.

PRACTICE

1. EASY In what year did Charles Richter publish his magnitude scale, and at what laboratory did he work?
2. EASY A magnitude 5 earthquake makes a seismogram wiggle 2 mm tall at a station. How tall would the wiggle be for a magnitude 7 earthquake recorded the same way at the same distance?
3. EASY Which is a measure of intensity and which is a measure of magnitude? (a) “Chimneys fell and plaster cracked in the town of Oakdale.” (b) “The earthquake registered 6.3.”
4. MEDIUM About how many times more energy does a magnitude 8 earthquake release than a magnitude 5? Show the steps.
5. MEDIUM Why did seismologists need the moment magnitude scale when the Richter scale already existed?

6. MEDIUM Data reading. After a magnitude 6.4 earthquake, a seismologist collected Modified Mercalli intensities: 10 km from the epicenter, VIII; 30 km, VI; 60 km, V; 120 km, III; 250 km, II. Which conclusion is supported? (a) Intensity does not depend on distance. (b) Intensity falls as distance increases, dropping fastest near the epicenter. (c) Intensity rises with distance. (d) The magnitude changed as the waves traveled.
7. MEDIUM Data reading. A table lists four earthquakes: Chile 1960, Mw 9.5; Alaska 1964, Mw 9.2; Sumatra 2004, Mw 9.1; San Francisco 1906, about 7.9. (a) Rank them from most to least energy. (b) About how many times more energy did Alaska 1964 release than a magnitude 7.2 aftershock? (c) Did Chile 1960 release more or less than 100 times the energy of San Francisco 1906? Explain.
8. HARD Experiment design. You want to test whether soft ground shakes harder than hard ground. You have a tray of dry sand, a tray of packed gravel, a cup of water for each tray and a book to drop beside them. Describe your procedure, name the independent and dependent variables, and list three things to keep the same.
9. HARD A magnitude 6.0 earthquake strikes 10 km beneath a city of 2 million people. A magnitude 8.0 earthquake strikes 600 km out at sea. Explain in three sentences why the smaller earthquake might cause far more damage, using the words magnitude and intensity.
10. CHALLENGE Richter borrowed the idea of a magnitude scale from astronomy, where a star one magnitude brighter is about 2.5 times as bright. Why do scientists use logarithmic scales for things like earthquakes and star brightness instead of ordinary counting scales? Give one advantage and one thing a reader must remember.

COMMON MISTAKES

- Thinking a magnitude 8 is “twice as big” as a magnitude 4. Magnitude steps multiply: four steps up means wiggles 10,000 times taller and about a million times more energy.
- Using “magnitude” and “intensity” as if they were the same word. An earthquake has one magnitude but a different intensity in every town.
- Believing the magnitude scale stops at 10. It has no top number; it is just that the earth’s faults are not long enough to make an earthquake much above magnitude 9.5.

Make it a game · Step It Up. Players sit in a circle. The leader names a magnitude, such as 5. Going around, each player must name the next step up and say how much taller the wiggle is than the leader’s number (“6: ten times taller,” “7: a hundred times taller,” “8: a thousand times taller”). Then go around again with energy (“6: about 32 times,” “7: about 1,000 times,” “8: about 32,000 times”). Anyone who adds instead of multiplying sits out a round. Finish by letting each player describe one Mercalli intensity level in words while the others guess the Roman numeral.

Scripture. “The mountains quake at him, and the hills melt, and the earth is burned at his presence, yea, the world, and all that dwell therein.” (Nahum 1:5, KJV)

Our scales measure the largest earthquakes at magnitude 9.5. Nahum reminds us that the One who made the earth is greater than all its power, and that the measuring we do is a way

of taking His works seriously.

Practice answers

1. 1935, at the Seismological Laboratory of the California Institute of Technology (Caltech) in Pasadena, California.
2. Two steps up means 10 × 10 = 100 times taller: 2 mm × 100 = 200 mm (20 cm).
3. (a) is intensity, describing the shaking and damage at one place. (b) is magnitude, one number for the whole earthquake.
4. Three steps. 32 × 32 × 32 ≈ 32,000 times more energy (more exactly, about 31,600).
5. The Richter scale was based on a Wood-Anderson seismograph tuned to short, quick vibrations. Giant earthquakes put most of their energy into long, slow waves that the instrument barely recorded, so above about magnitude 7 the Richter scale stopped climbing (it saturated). Moment magnitude is based on the fault area, the slip and the rock stiffness, so it keeps counting for the largest earthquakes.
6. (b). Intensity drops from VIII to VI in the first 20 km but only from III to II over the last 130 km. The magnitude (6.4) is one number and does not change with distance, so (d) is wrong.
7. (a) Chile 1960, Alaska 1964, Sumatra 2004, San Francisco 1906 (higher magnitude means more energy). (b) 9.2 − 7.2 = 2 full steps, so 32 × 32 ≈ 1,000 times more energy. (c) More. 9.5 − 7.9 = 1.6 steps. One and a half steps alone give 32 × 5.6 ≈ 180 times, which already passes 100; the full 1.6 steps give roughly 250 times.
8. Procedure: place a brim-full cup of water on top of each tray, set each tray the same distance from the drop point, drop the book from the same height three times for each tray and rate the ripple intensity on the same scale each time. Independent variable: the ground type (sand or gravel). Dependent variable: ripple intensity in the cup. Keep the same: drop height, distance from drop point, the book, the cup size and water level, the observer and the intensity scale.
9. Magnitude measures the energy released at the source, and the 8.0 releases about 1,000 times more energy than the 6.0. Intensity measures shaking at a particular place, and it falls off quickly with distance. The city sits almost on top of the 6.0, so it feels a high intensity, while the 8.0 is 600 km away and its waves have spread out and weakened before reaching anyone; unless the 8.0 makes a tsunami, the small nearby earthquake does more harm.
10. The quantities range over enormous spans (the energy of earthquakes differs by a factor of a billion or more), so a counting scale would need numbers with many zeros; a logarithmic scale fits the whole range into small, handy numbers (0 to 10). The reader must remember that each step is a multiplication, not an addition: a 7 is not two units bigger than a 5 but 100 times bigger in wiggle and about 1,000 times in energy.

4.3 Seismographs: Catching the Earth's Trembling on Paper

OBJECTIVES

- Explain how a seismograph uses inertia (a heavy mass that stays still while the ground moves) to record ground motion, and tell the stories of Zhang Heng (A.D. 132) and John Milne (1880).
- Read a seismogram: identify the P wave, S wave and surface wave arrivals and measure the S minus P time.
- Use the S minus P time to find the distance to an earthquake and explain how three stations locate the epicenter.

Warm-up. Tie a washer, a key or a small toy to 40 cm of string and hold the top end so the weight hangs just above a sheet of paper on the table. Keeping your hand still, have a partner slide the paper quickly back and forth under it. Does the weight follow the paper, or does it hang still while the paper moves? Now imagine the weight holds a pen. What would it draw on the moving paper?

Video. Coming soon. How a seismograph works, inertia, reading a seismogram (P waves, S waves, surface waves), locating an earthquake with three stations, Zhang Heng seismoscope and John Milne; look for USGS, IRIS/EarthScope education, Smithsonian, SciShow Kids, Science Max and Homeschool Pop (Alternate).

KEY TERMS

seismograph
An instrument that records the shaking of the ground; the old ones used a pen on a rotating drum, modern ones use a magnet, a coil and a computer.

seismogram
The record a seismograph makes: a wiggly line showing ground motion against time.

inertia
The tendency of a mass to stay still (or keep moving the same way) unless a force acts on it; a heavy hanging mass lags behind when the ground jerks.

P wave
The primary wave, fastest of the seismic waves, which squeezes and stretches the rock as it passes (about 6 km/s in the crust) and arrives first.

S wave
The secondary wave, which shakes the rock from side to side (about 3.5 km/s in the crust), arrives second and cannot pass through liquid.

triangulation

Finding the epicenter by drawing a circle around each of three stations with radius equal to its distance from the earthquake; the circles cross at the epicenter.

CORE IDEAS

The story. In A.D. 132, at the Han court in Luoyang, China, the astronomer Zhang Heng presented the emperor with a bronze vessel nearly 2 m across. Around its outside were eight dragons, each holding a bronze ball in its mouth, and under each dragon sat a bronze toad with its mouth open. When the earth shook, one dragon dropped its ball into the toad below with a clang, and that dragon pointed toward the earthquake. The old history tells that one day a ball dropped and no one in the capital felt a thing; days later a messenger rode in with news of an earthquake in Longxi, hundreds of kilometers to the west. Zhang Heng's instrument was a seismoscope: it could tell that an earthquake had happened, and roughly which way, but it recorded nothing. In 1876 a young English mining engineer named John Milne arrived in Tokyo to teach at the Imperial College of Engineering and felt his first earthquake within days. After a sharp earthquake near Yokohama in 1880, Milne and two colleagues founded the Seismological Society of Japan, the first in the world, and set to work on an instrument that would draw a true picture of the ground's motion.

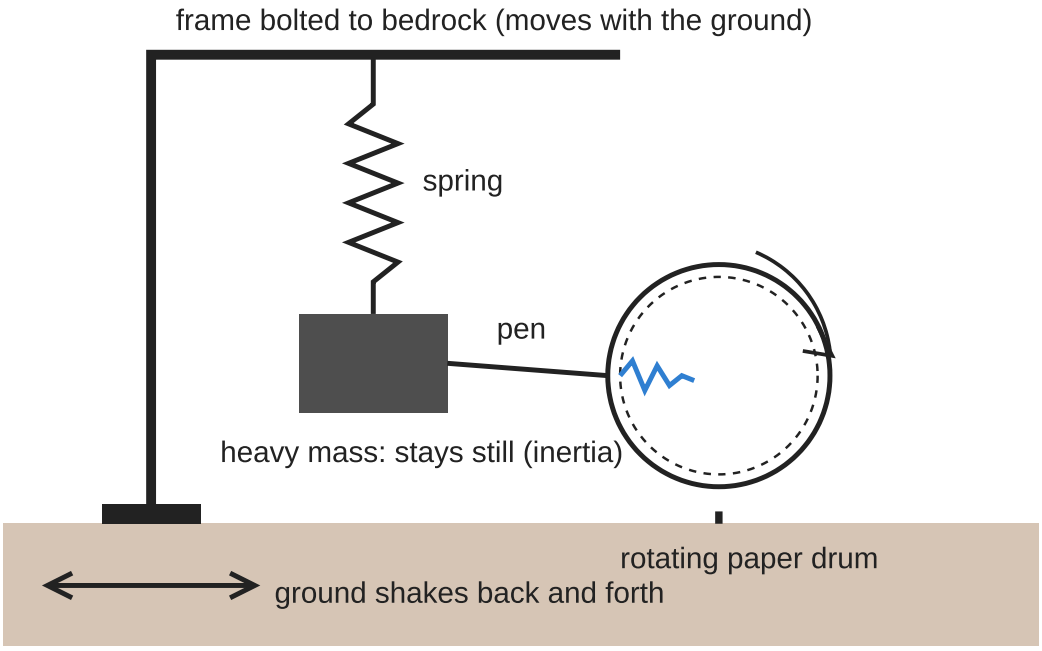
How they figured it out. The secret of every seismograph is **inertia**. Hang a heavy mass from a spring or a long pendulum and bolt the frame to solid rock. When the ground jerks, the frame jerks with it, but the heavy mass lags behind and stays nearly still. A pen on the mass, touching a paper drum that turns with the frame, draws the difference between the still mass and the moving ground. That drawing is a **seismogram**. Milne's seismograph of the 1890s was simple, sturdy and cheap. He went home to England in 1895, set up an observatory at Shide on the Isle of Wight, and persuaded observatories across the British Empire and beyond to install his instruments. By 1900 there were Milne seismographs at observatories in many parts of the world, all reporting to Shide: the first worldwide seismic network. Modern seismometers replace the pen with a magnet moving inside a coil of wire, which makes a tiny electric signal that a computer records many times a second. They are so sensitive that they record the beat of ocean waves on coasts hundreds of kilometers away. The Global Seismographic Network, run by the USGS and its partners, has more than 150 stations around the world.

The big idea. A seismogram is a story in order of speed. The first wiggle is the **P wave** (primary), a push-and-pull wave that travels through the crust at about 6 km/s. Next comes the **S wave** (secondary), which shakes the rock sideways at about 3.5 km/s. Last and largest come the surface waves, which roll along the ground like ripples on a pond and do most of the damage to buildings. Because the P wave is faster, the farther the station is from the earthquake, the longer the S wave lags behind it, just as a faster runner pulls farther ahead the longer the race. Seismologists measure the gap, the S minus P time, and turn it into distance: with the speeds above, each second of lag means about 8 km. One station gives only a distance, which could be in any direction, so draw a circle. A second station's circle crosses the first in two places. A third settles it: the three circles cross at one point, the epicenter. This is **triangulation**. The height of the wiggles gives the magnitude (Lesson 4.2).

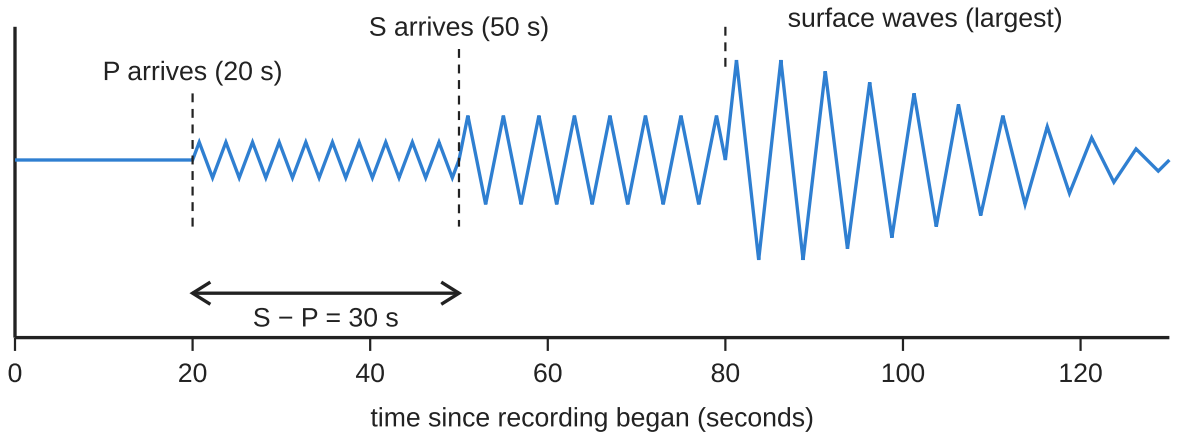
In Lesson 1.1 you met Inge Lehmann, who found the earth’s inner core in 1936 by reading seismograms like these.

Try it and see. Build a seismograph from a cardboard box, string, a weighted cup and a marker. Hang the cup inside the box so the marker just touches a strip of paper on the table, then pull the paper steadily while a partner bumps the table. The box jumps, the hanging marker lags behind, and the line wiggles. Bump harder and the wiggles grow: you are reading amplitude. A heavier cup draws a cleaner line, because more mass means more inertia.

In the world today. The USGS National Earthquake Information Center in Golden, Colorado, locates about 20,000 earthquakes a year from seismograph networks around the world. Seismographs now give warnings, too. Radio signals travel at the speed of light, while S waves creep along at a few kilometers per second. So when stations near an epicenter detect the P wave, a computer can alert telephones farther away a few seconds to a minute before the heavy shaking arrives. Japan has run such a system since 2007, and ShakeAlert now covers the West Coast of the United States. A few seconds is enough to stop a train or get under a desk.

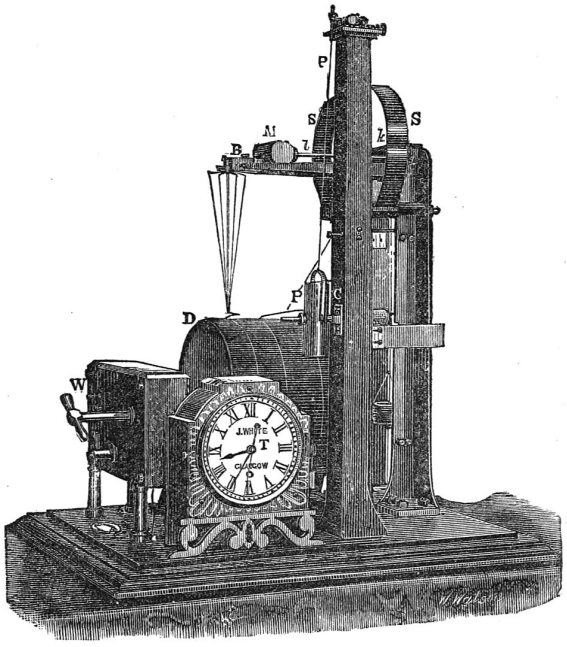


A pen-and-drum seismograph. The ground and frame move; the heavy mass hangs still because of inertia; the pen draws the difference.



Reading a seismogram. P arrives first, S second, surface waves last and largest. The S minus P gap (here 30 s) tells the distance: about 250 km.

PICTURE STUDY



The Gray–Milne Seismograph with Its Recorder (engraving, 1886), Unknown engraver, for Popular Science Monthly, 1886 · Wood engraving, printed in Popular Science Monthly, volume 29 · Popular Science Monthly, New York, 1886; copies in many libraries and on Wikimedia Commons

In the early 1880s, while teaching in Tokyo, John Milne and his Scottish colleague Thomas Gray built an instrument that did what Zhang Heng's dragons could not: it drew the ground's motion as it happened. Two pendulums hung from the frame to catch the sideways motion of the ground in two directions, and a weight on a spring caught the up-and-down motion. Each carried a fine pointer resting on a sheet of smoked paper wrapped around a drum, and the drum was turned steadily by clockwork, so that time ran along the paper. When the earth shook, the frame and drum moved with it, the heavy pendulums lagged behind, and three wiggly lines appeared on the soot.

An American magazine printed this engraving in 1886 to show its readers the new science of seismology. A clock linked to the instrument marked the moment the shaking began. For the first time, the beginning of an earthquake could be fixed to the second and the shape of the shaking compared from one station to the next, which is exactly what Milne needed when he later set up his worldwide network.

Look closely

- Find the drum. Paper was wrapped around it and it turned slowly by clockwork. Which way would the time run on the paper?
- Find the hanging weights, the pendulums. When the ground jerks, which parts of the picture move with it and which parts lag behind?
- Find the places where a pointer touches the drum. How many separate lines would this instrument draw at once?
- The whole machine stands on a solid base. Why must a seismograph be fastened firmly to the ground, when the whole point is that part of it stays still?

Talk about it

1. Zhang Heng’s seismoscope dropped a ball; this instrument drew a line. Name two things a line on paper can tell a scientist that a dropped ball cannot.
2. Why did Milne and Gray want three separate records, two sideways and one up and down, instead of one?
3. If this instrument drew a trace at Tokyo and another just like it drew a trace at Shide in England, what could Milne learn by comparing the two?

> **Safety first.** Cutting the cardboard box needs a strong pair of scissors or a box cutter; ask an adult to make those cuts.

EXPERIMENT: BUILD A SEISMOGRAPH AND TEST IT

You will build a pen-and-paper seismograph from a box, a weighted cup and a marker, then test how well it records shakes of different sizes. Milne’s first instruments were not much more complicated.

Question: Does a bigger shake make a taller trace, and does a heavier mass make a cleaner one? Prediction: write both before you build.

You will need

- A sturdy cardboard box (shoebox size or larger) with the top and one long side removed, set open-side toward you
- A paper or plastic cup, string, a felt-tip marker, tape, and weights (coins, washers or dry beans)
- A roll of paper or a strip made from taped-together sheets, about 1 m long and as wide as the box

- A ruler marked in millimeters and your notebook

Steps

1. Ask an adult to cut two small holes in the top edges of the box. Tie the string to the cup’s rim so it hangs level, and thread the string up through the holes so the cup hangs inside the box. Poke the marker through the bottom of the cup so its tip points down, and tape it in place.
2. Half fill the cup with coins or beans so it is heavy. Adjust the string until the marker tip just touches the paper strip laid on the table under the box.
3. Have one partner pull the paper strip slowly and steadily from the far side of the box (about 2 cm per second). With no shaking, the marker should draw a straight line. That is your quiet baseline.
4. Make three sizes of earthquake while the paper moves: a gentle tap on the table edge, a firm bump, and a hard thump with a fist (or drop a book from 10 cm, 20 cm and 40 cm beside the box). Do each one three times with a short pause between.
5. Label each wiggle on the paper. For every shake, measure the tallest peak-to-peak wiggle in millimeters and record it in a table: Shake size, Trial, Amplitude (mm).
6. Now change only the mass: empty the cup and repeat the firm bump three times. Compare the traces. Which is cleaner and which jiggles on its own?
7. Find the average amplitude for each shake size and draw a bar graph. Write a conclusion: did amplitude grow with shake size? What did the extra mass do?

Tips

- If the marker skips, lower it a little; if it drags and stops the paper, raise it a hair. Pulling the paper from a steady height keeps the baseline straight.
- A real seismograph bolts to rock. Put the box on a hard floor rather than a wobbly table for cleaner traces.
- Keep your traces. You will need one for your unit portfolio.

Check your work

- My baseline was a nearly straight line before I started shaking.
- I measured amplitudes in millimeters and found averages from three trials each.
- I can explain why the hanging cup stays still while the box moves.

FIELD NOTEBOOK

1. Draw your seismograph and label frame, mass, pen, paper and the direction the ground moves. Write the word inertia beside the mass.
2. Copy the seismogram figure from this lesson and label the P arrival, S arrival, surface waves and the S minus P time.
3. Draw three stations on a simple map with circles of 2 cm, 4 cm and 3 cm around them (scale 1 cm = 100 km) so that the circles cross at one point. Mark the epicenter with a star.

From history. John Milne nearly lost everything in 1895 when a fire destroyed his house and laboratory in Tokyo, along with his library, instruments and many of his records. He returned to England the same year with his Japanese wife, Tone, set up again at Shide on the Isle of Wight, and from that small observatory built the first worldwide earthquake network. By his death in 1913 he was known everywhere as the father of modern seismology.

WORKED EXAMPLES

Example 1. On the seismogram in this lesson, the P wave arrives 20 s after the recording starts and the S wave arrives at 50 s. Using P = 6 km/s and S = 3.5 km/s, how far away was the earthquake?

(Use the map or drawing "The S minus P gap on this record is 30 s." shown earlier in this lesson.)

1. S minus P time = 50 s − 20 s = 30 s.
2. For a distance d, the P wave takes d ÷ 6 seconds and the S wave takes d ÷ 3.5 seconds. The lag is d ÷ 3.5 − d ÷ 6 = d × (0.286 − 0.167) = d × 0.119.
3. Set the lag equal to 30 s: d × 0.119 = 30, so d = 30 ÷ 0.119 ≈ 252 km.
4. Check: P would take 252 ÷ 6 = 42 s and S would take 252 ÷ 3.5 = 72 s; the gap is 30 s.

Answer: About 250 km. The quick rule "about 8 km for every second of S minus P time" gives 240 km, close enough for a first guess.

Example 2. Three stations record the same earthquake. Station A has an S minus P time of 30 s, station B 48 s and station C 18 s. Using the rule of about 8 km per second, find each distance. On a map with a scale of 1 cm = 50 km, what radius circle should be drawn around each station?

1. A: 30 × 8 = 240 km. B: 48 × 8 = 384 km. C: 18 × 8 = 144 km.
2. Change each distance to map centimeters by dividing by 50: A: 240 ÷ 50 = 4.8 cm. B: 384 ÷ 50 ≈ 7.7 cm. C: 144 ÷ 50 ≈ 2.9 cm.
3. Draw the three circles. The one point where all three cross is the epicenter.

Answer: Distances of about 240 km, 384 km and 144 km; circle radii of about 4.8 cm, 7.7 cm and 2.9 cm. Station C, with the shortest lag, is closest to the earthquake.

Example 3. Milne's station at Shide, on the Isle of Wight, recorded earthquakes from Japan, about 9,500 km away. Surface waves travel at roughly 3.5 km/s. About how long after a Japanese earthquake would its surface waves reach Shide?

1. Time = distance ÷ speed = 9,500 km ÷ 3.5 km/s ≈ 2,714 s.
2. Change to minutes: 2,714 ÷ 60 ≈ 45 minutes.

Answer: About 45 minutes. In 1900 that was far faster than the news could travel, so Milne often knew about a distant earthquake before the newspapers did.

PRACTICE

1. EASY What is the difference between a seismograph and a seismogram?
2. EASY In a pen-and-drum seismograph, which part moves with the ground and which part stays nearly still? Why?
3. EASY List the three kinds of seismic waves in the order they arrive at a station, and name the fastest.
4. MEDIUM A seismogram shows the P wave arriving at 10:15:00 and the S wave at 10:15:40. Using the rule of about 8 km per second of S minus P time, how far away was the earthquake?
5. MEDIUM Why can one seismograph station tell the distance to an earthquake but not its direction? How many stations are needed to find the epicenter?
6. MEDIUM Data reading. A table shows S minus P times measured at stations at known distances from an earthquake: 100 km, 12 s; 200 km, 24 s; 300 km, 36 s; 400 km, 48 s. Which statement is supported? (a) The S minus P time doubles when distance doubles. (b) The S minus P time stays the same at all distances. (c) The S minus P time falls as distance increases. (d) The P wave is slower than the S wave.
7. MEDIUM Data reading. A student's cardboard seismograph gave these average amplitudes: book dropped from 10 cm, 4 mm; from 20 cm, 9 mm; from 40 cm, 18 mm. With the empty cup instead of the weighted cup, the 20 cm drop gave 9 mm but the baseline wobbled by 3 mm on its own. What two conclusions does the data support, and what is one limit of the experiment?
8. HARD Experiment design. You want to test whether the length of the string affects how well your seismograph records a shake. Describe your plan: what you will change, what you will measure, what you will keep the same, and how you will make the shake the same each time.
9. HARD An earthquake warning system detects the P wave at a station 20 km from the epicenter and sends a radio alert at once. A city 100 km from the epicenter receives the alert almost instantly. If S waves travel at 3.5 km/s, about how many seconds of warning does the city get before the strong S wave shaking arrives? (Use P = 6 km/s to find when the alert was sent.)
10. CHALLENGE Zhang Heng's seismoscope and Milne's seismograph both used a hanging mass. Explain in a short paragraph what each could tell you and why Milne's was the

greater step for science.

COMMON MISTAKES

- Thinking the pen moves and draws the shaking. It is the other way around: the pen and mass hang still, and the ground, frame and paper move underneath them.
- Believing a seismograph predicts earthquakes. It records them after they begin; the few seconds of warning come from the P wave arriving before the S wave, not from any prediction.
- Reading the biggest wiggle as the first arrival. The first wiggle is the small P wave; the biggest wiggles are the surface waves that come last.

> **Make it a game · Find the Epicenter.** Draw a simple map on a large sheet of paper with three "stations" marked and a hidden epicenter you choose in secret. Measure the distance from each station to your epicenter and convert each to an S minus P time (about 1 s for every 8 km, using any scale you like, such as 1 cm = 40 km). Give your family only the three times. They must convert them back to distances, draw the three circles with a compass and mark where the circles cross. If they land within 1 cm of your secret point, they win the round and become the next earthquake.

> **Scripture.** "He looketh on the earth, and it trembleth: he toucheth the hills, and they smoke." (Psalm 104:32, KJV)

A seismograph can feel a trembling that no person feels. The psalmist reminds us whose earth is trembling, and that the instrument reads a world that answers to its Maker.

Practice answers

1. A seismograph is the instrument that records ground shaking. A seismogram is the record it makes, a wiggly line of ground motion against time.
2. The frame and drum move with the ground. The heavy hanging mass (and its pen) stays nearly still because of inertia: a mass resists changes in its motion, so it lags behind the sudden jerks of the ground.
3. P wave (primary) first, S wave (secondary) second, surface waves last. The P wave is fastest, about 6 km/s in the crust.
4. S minus P = 40 s. 40 × 8 = about 320 km.
5. The S minus P time gives only how far the waves traveled, and the waves could have come from any direction, so the possible epicenters lie on a circle around the station. Three stations are needed: three circles cross at only one point.
6. (a). From 100 to 200 km the lag goes from 12 s to 24 s, and from 200 to 400 km it goes from 24 s to 48 s. The lag is directly proportional to distance, about 12 s per 100 km (or about 8.3 km per second). (d) is wrong: the lag exists because P is faster, not slower.
7. Conclusions: amplitude grows with the size of the shake (roughly doubling when the drop height doubles), and a heavier mass gives a steadier baseline (3 mm of wobble disappears with the weight) without changing the amplitude of the real shake. Limit: a dropped book is not a true earthquake, the paper was pulled by hand at an uneven speed, and only three

heights were tested; more trials and a motor-driven paper strip would make the results stronger.

8. Change: string length (for example 15 cm, 30 cm, 45 cm). Measure: the amplitude of the trace in millimeters, and how much the baseline wobbles on its own. Keep the same: the mass in the cup, the marker, the paper speed, the box, the floor. Make the shake the same each time by dropping the same book from the same height at the same spot beside the box, three trials per string length, and averaging.
9. The P wave reaches the station at $20 \div 6 \approx 3.3$ s after the earthquake, so the alert goes out at about 3.3 s. The S wave reaches the city at $100 \div 3.5 \approx 28.6$ s. Warning time $\approx 28.6 - 3.3 \approx 25$ s, enough to get under a desk or stop a train.
10. Zhang Heng’s instrument used a hanging mass to trip a lever and drop a ball, so it could tell that a distant earthquake had happened and roughly its direction, but it recorded nothing about how long or how hard the ground shook or when each wave arrived. Milne’s seismograph used the hanging mass to draw a continuous record on paper with time marks, so the arrival of P, S and surface waves, their size and their timing could all be measured. From such records seismologists could find distances, locate epicenters, compare earthquakes and, as Lehmann did, learn the structure of the earth’s interior. A record you can measure is worth far more than a single clang.

4.4 Tsunamis: The Harbor Wave

OBJECTIVES

- Explain how an undersea earthquake makes a tsunami and why a tsunami is low and fast in deep water but tall and slow near shore.
- Calculate tsunami speed from water depth and travel time from distance and speed.
- List the natural warning signs of a tsunami and the correct response, and describe how warning systems with seismographs and ocean buoys work today.

Warm-up. Fill a baking dish halfway with water and let it settle. Lay a flat lid or small plate on the bottom at one end and lift it quickly 2 cm. Watch the bump of water run to the other end. Now tilt a book into the far end to make a sloping “beach” and try again. Where does the wave get taller? Write one sentence about what you saw.

Video. Coming soon. How tsunamis form and travel, tsunami warning signs and safety, DART buoys and the Pacific Tsunami Warning Center, 2004 Indian Ocean tsunami and Tilly Smith; look for NOAA, NOAA SciJinks, USGS, Smithsonian, SciShow Kids, Science Max and Homeschool Pop (Alternate).

KEY TERMS

tsunami
A series of very long ocean waves made when an earthquake, landslide or eruption suddenly moves a large amount of seawater; from the Japanese words for “harbor wave.”

wavelength
The distance from one wave crest to the next; a tsunami’s wavelength in the open ocean can be more than 100 km.

shoaling
What happens as a wave enters shallow water: it slows down, its wavelength shrinks and its height grows.

drawback
The sea pulling back from the shore before a tsunami crest arrives, exposing the seafloor; a warning sign.

runup
The highest point above normal sea level that a tsunami reaches on land.

wave train
The series of waves in a tsunami, arriving minutes to an hour apart; the first is often not the largest.

CORE IDEAS

The story. On the morning of December 26, 2004, a ten-year-old English girl named Tilly Smith was on Maikhao Beach in Phuket, Thailand, with her parents. The sea frothed and bubbled, and then the water pulled back from the beach. Tilly knew what it meant. Two weeks earlier, in her geography class at home in Surrey, her teacher had shown a film of a tsunami and explained the signs: the water draws back, and then it comes. She told her parents, and the beach was cleared in minutes. The wave came, and no one on that beach died. The earthquake that sent it had struck at 7:58 that morning, local time, under the sea off the north end of Sumatra, Indonesia. It was magnitude 9.1, tied with Japan's 2011 earthquake as the third largest ever recorded. A stretch of seafloor more than 1,000 km long lurched upward, lifting the whole ocean above it. Waves reached Sumatra within half an hour, Thailand and Sri Lanka in about two hours and Africa after about seven. About 230,000 people died in fourteen countries. There was no warning system in the Indian Ocean.

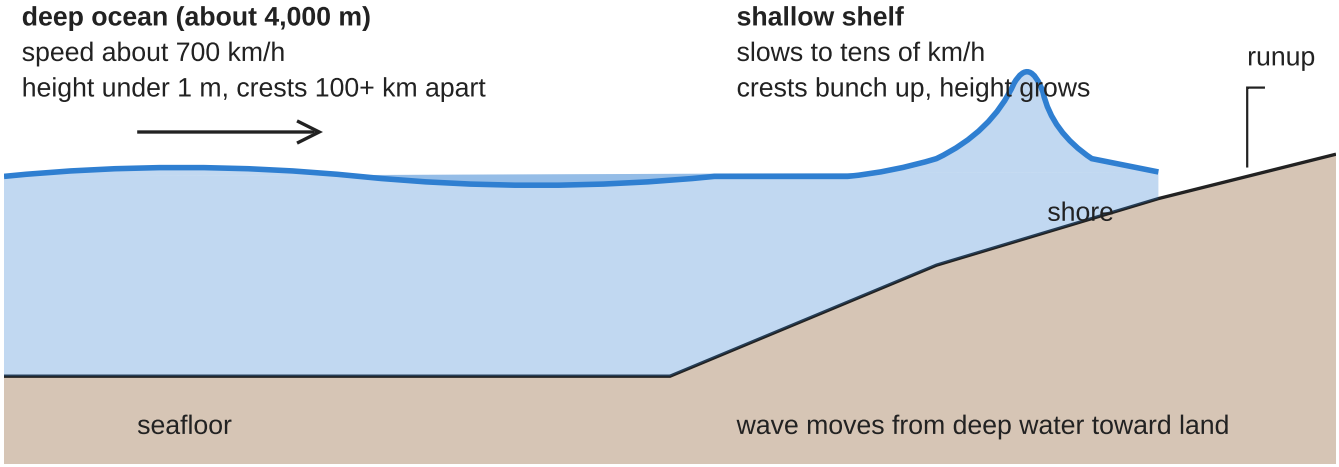
How they figured it out. A tsunami is not a big surfing wave. It is the whole depth of the ocean moving. When the seafloor jumps up, the water above it, perhaps 4,000 m deep, is lifted and spreads outward in every direction. The speed of such a wave depends only on the depth of the water: speed equals the square root of the depth in meters times the pull of gravity (9.8 m/s^2). In water 4,000 m deep the wave travels about 200 m/s, more than 700 km/h. Yet in the open ocean its height may be less than a meter, and its **wavelength**, the distance between crests, is 100 km or more, so a ship passing over it feels nothing. As the wave reaches the continental shelf and the water gets shallow, it slows to the speed of a car, the crests bunch up, and the energy that was spread through kilometers of deep water is squeezed into a wall. This is **shoaling**. A wave half a meter high at sea can arrive at the shore 10 m high or more, and it keeps coming for minutes, because the whole wavelength has to pour onto the land. After the Japan earthquake of 2011, the sea ran up nearly 40 m above sea level at one place on the coast of Iwate.

The big idea. Most tsunamis come from undersea earthquakes at plate boundaries where one plate dives under another (Unit 2); undersea landslides and eruptions like Krakatoa in 1883 (Lesson 3.2) make them too. Every tsunami is a **wave train**, a series of crests arriving minutes to an hour apart, and the first crest is often not the largest. Sometimes a trough arrives first and the sea draws back: that **drawback** is what Tilly Smith saw and what Lisbon saw in 1755. The natural warnings are three: strong or long shaking at the coast, the sea pulling back or rising strangely, and a roar like a train. Any one means go at once to high ground or far inland, and stay for hours. The **runup** of a big tsunami can reach several kilometers inland on flat coasts. Along the coast of Japan, old stone markers on hillsides warn people not to build below that line; in 2011 the village of Aneyoshi had obeyed, and the wave stopped short of its houses.

In the world today. On April 1, 1946, a tsunami from an earthquake in Alaska's Aleutian Islands crossed the Pacific unseen and killed more than 150 people in Hilo, Hawaii, five hours later. In 1949 the United States set up the Pacific Tsunami Warning Center in Hawaii, which NOAA runs today. When seismographs report a large undersea earthquake, the center calculates where waves could go and how soon. To know whether a wave is really coming,

NOAA uses DART buoys (Deep-ocean Assessment and Reporting of Tsunamis): a seafloor pressure sensor feels a tsunami only 1 cm high passing overhead and reports by buoy and satellite to the center. But warnings take minutes, and a tsunami from a nearby earthquake can arrive in ten. For people on the shore, the shaking itself is the warning.

God's handiwork. The psalmist wrote, "The LORD on high is mightier than the noise of many waters, yea, than the mighty waves of the sea." God set the sea its bounds (Job 38:11), and He also gave people minds to understand its motions and build buoys that hear a wave coming across an ocean. Tilly Smith saved a beach full of strangers because she had paid attention in class and was brave enough to speak. Knowledge, humility before the sea and care for one's neighbor belong together.



Shoaling. In deep water a tsunami is fast, long and low. Over the shallow shelf it slows, bunches up and grows tall before running up onto the land.

PICTURE STUDY



Under the Wave off Kanagawa (The Great Wave), Katsushika Hokusai, about 1830–1832 · Woodblock print, ink and color on paper · The Metropolitan Museum of Art, New York (one of many impressions)

Hokusai was about seventy when he designed this print for his series *Thirty-six Views of Mount Fuji*. It became the most famous Japanese picture in the world. Three fishing boats race home toward Edo (now Tokyo) while a great wave rears over them, its foam breaking into fingers. Far away, small and still, sits Mount Fuji.

Many people call this a picture of a tsunami. It is not. Hokusai drew a storm wave, a huge wind-driven breaker of the kind sailors feared in the open bay. A real tsunami in the open sea is low and almost invisible, and at the shore it comes not as a curling breaker but as a fast-rising flood that keeps coming. Knowing the difference is part of knowing the sea.

Look closely

- Find the three boats and the men bending low in them. How big is the wave compared with the boats?
- Look at the foam at the top of the wave. What does it remind you of?
- Find Mount Fuji. Why do you think Hokusai made the mountain so small and the wave so large?
- Look at the shape of the wave: steep, curling, breaking. Compare it with the tsunami diagram in this lesson. Which part of the ocean, deep or shallow, is Hokusai showing, and how can you tell?

Talk about it

1. Hokusai’s wave is a wind wave. In what ways is a tsunami different from a wind wave in cause, in wavelength and in how it arrives at the shore?

2. The Japanese have lived with tsunamis for centuries and gave the world the word. Why might a country with that history also produce the most famous picture of a wave?
3. If you saw the sea pull far back from the beach, what would you do, and how quickly?

> **Safety first.** This project uses water on a floor or counter. Work over a tray or in a bathtub with an adult nearby, mop spills at once so no one slips, and keep electrical devices well away from the water.

EXPERIMENT: THE WAVE TANK: DOES DEPTH CHANGE WAVE SPEED?

Seismologists say a tsunami's speed depends only on how deep the water is. You will test that claim in a bathtub or a long plastic storage box, timing a wave across a measured distance at three different depths. Then you will add a sloping beach and watch shoaling happen.

Question: Does a wave travel faster in deeper water? Prediction: write it down with your reason.

You will need

- A bathtub or a long clear plastic storage box (at least 60 cm long; longer is better)
- A ruler or tape measure, a stopwatch or phone timer, masking tape
- A flat paddle: a plastic cutting board, a book in a plastic bag, or a stiff lid
- A wooden board or baking sheet to prop up as a sloping beach, and towels
- Your notebook with a table ready: Depth (cm), Length (cm), Time for 10 crossings (s), Speed (cm/s)

Steps

1. Measure the inside length of the tub in centimeters and mark both ends with tape. Fill to a depth of 3 cm (measure with the ruler held upright) and let the water go still.
2. Hold the paddle upright at one end and give it one quick push forward of about 5 cm, then hold it still. One wave crest will run to the far end, bounce back, and continue bouncing. Start the timer at the push.
3. Count the crest passing the far end, then the near end, and so on. Stop the timer after 10 crossings (5 round trips). Record the time. Repeat three times and average.
4. Speed = (10 × length) ÷ time. Calculate it in cm/s and record.
5. Change only the depth: repeat at 6 cm and at 12 cm. Keep the same paddle, the same push and the same tub.
6. Compare with the rule: predicted speed in cm/s = the square root of (980 × depth in cm). For 3 cm that is about 54 cm/s; for 6 cm about 77 cm/s; for 12 cm about 108 cm/s. How close did you come?
7. Now prop the board as a sloping beach at the far end and send one wave at the deepest setting. Watch what happens to the wave's height and speed as it climbs the slope. Draw it. Mark on the board how far up the wave ran: that is its runup.

Tips

- Push the paddle the same small distance every time. A bigger push makes a taller wave but should not change its speed much; try it and see.
- If the crossings are too fast to count at 12 cm, count only 6 crossings and adjust the formula.
- Draw a graph of speed against depth. The line should curve, rising fast at first and then more slowly, because speed grows with the square root of depth.

Check your work

- I changed only the depth and kept the push, paddle and tub the same.
- I timed 10 crossings three times at each depth and averaged.
- I can explain why a tsunami is fast and low at sea but slow and tall at the shore.

FIELD NOTEBOOK

1. Draw the shoaling diagram from memory: deep ocean on the left with a long low wave, a rising seafloor, and a tall wave at the shore. Label speed and height at each end.
2. Make a warning poster titled “Three Signs, One Action” with the three natural tsunami signs and the one thing to do.
3. Draw a DART buoy system: the pressure sensor on the seafloor, the buoy on the surface, the satellite, and the warning center on land, with arrows for the signal.

> **From history.** After the 2011 tsunami, people in Japan noticed that the old stone warning markers on the coast of Iwate had been right. The marker at Aneyoshi, set up by survivors of the 1933 tsunami, told later generations to remember the great tsunamis and not to build below that point. The village had kept the rule. The 2011 wave ran up the valley to within a short walk of the stone and stopped, and every house above it was spared.

WORKED EXAMPLES

Example 1. A tsunami crosses an ocean basin 4,000 m deep. Find its speed in m/s and km/h. (Speed = square root of gravity × depth; gravity = 9.8 m/s².)

1. Multiply: 9.8 × 4,000 = 39,200.
2. Take the square root: √39,200 ≈ 198 m/s.
3. Change to km/h: 198 m/s × 3,600 s/h = 712,800 m/h ≈ 713 km/h.

Answer: About 200 m/s, or roughly 700 km/h, as fast as a jet airliner.

Example 2. In 2004 the tsunami traveled roughly 1,600 km from the earthquake off Sumatra to the east coast of Sri Lanka in about 2 hours. What was its average speed? Then find how fast the same wave moves when it reaches water only 10 m deep near the beach, and compare.

1. Average speed across the Bay of Bengal: 1,600 km ÷ 2 h = 800 km/h (the water there is mostly very deep).
2. Near the beach: 9.8 × 10 = 98, and √98 ≈ 9.9 m/s.
3. Change to km/h: 9.9 × 3.6 ≈ 36 km/h.
4. Compare: 800 ÷ 36 ≈ 22. The wave near shore is about 20 times slower than in the deep ocean.

Answer: About 800 km/h across the deep bay, but only about 36 km/h in 10 m of water. The slowing is what makes the wave pile up and grow tall.

Example 3. A DART buoy 600 km from a coastal city detects a tsunami in water 3,000 m deep. About how many minutes will the wave take to reach the city if the water stays deep most of the way?

1. Speed in 3,000 m of water: 9.8 × 3,000 = 29,400; √29,400 ≈ 171 m/s, which is about 617 km/h.
2. Time = distance ÷ speed = 600 km ÷ 617 km/h ≈ 0.97 h.
3. Change to minutes: 0.97 × 60 ≈ 58 minutes.

Answer: About 1 hour. The wave slows in the shallows near the coast, so the real time is a little longer, which is why warning centers use detailed maps of the seafloor.

PRACTICE

1. EASY What does the word tsunami mean, and from what language does it come?
2. EASY Name the three natural warning signs of a tsunami and the one action to take.
3. EASY Why can a ship in the open ocean pass over a tsunami without noticing it?
4. MEDIUM Find the speed of a tsunami in water 1,000 m deep, in m/s and km/h.
5. MEDIUM A tsunami travels at an average of 600 km/h across 1,800 km of ocean. How long until it reaches the far coast? If the earthquake happened at 2:00 p.m., when does the wave arrive?
6. MEDIUM Data reading. A table of tsunami speed against depth: 10 m, 36 km/h; 100 m, 113 km/h; 1,000 m, 356 km/h; 4,000 m, 713 km/h. Which statement is supported? (a) Speed doubles when depth doubles. (b) Speed grows with depth but more slowly than depth does: multiplying depth by 10 makes speed about 3 times greater. (c) Speed does not depend on depth. (d) Speed is greatest in shallow water.

7. MEDIUM Data reading. A tide gauge in a harbor recorded a tsunami wave train: wave 1 arrived at 3:10 p.m. with height 1.2 m; wave 2 at 3:35 p.m., 2.8 m; wave 3 at 4:05 p.m., 2.1 m; wave 4 at 4:40 p.m., 1.0 m. Which wave was largest? How far apart in time were the waves? A family returned to the beach at 3:30 p.m. after the first wave passed. Why was that a mistake?
8. HARD Experiment design. You want to test whether the slope of a beach changes how high a wave runs up. Using your wave tank, describe the plan: independent variable, dependent variable, three things kept the same, and how you will measure runup.
9. HARD Explain in three or four sentences why a tsunami that is only 0.5 m high in the deep ocean can arrive at the shore more than 10 m high. Use the words speed, wavelength and energy.
10. CHALLENGE A DART buoy can detect a tsunami only 1 cm high in 4,000 m of water. The buoy is 900 km from a city, and a seismograph network reported the earthquake 10 minutes before the buoy felt the wave. About how much time does the city have after the buoy's report, and why do warning centers want both seismographs and buoys?

COMMON MISTAKES

- Calling a tsunami a "tidal wave." Tides have nothing to do with it; tsunamis are made by earthquakes, landslides and eruptions that move the seafloor or the water.
- Picturing a tsunami as one giant curling surf wave like Hokusai's. At the shore it arrives as a fast-rising flood that keeps pouring in for minutes, and it is a series of waves, not one.
- Thinking the danger is over after the first wave. Later waves are often larger and can arrive an hour apart; stay on high ground until officials say it is safe.

> **Make it a game · High Ground.** Choose a "beach" at one end of the yard or room and "high ground" at the other. One player is the sea and stands at the beach with their back turned, calling out ordinary beach events ("a gull lands," "a boat goes by"). Everyone else plays on the beach. Whenever the sea calls out a real warning sign ("the water pulls back," "the ground shakes hard," "you hear a roar"), everyone must drop what they are doing and walk fast, not run, to high ground within ten seconds. Anyone who stays to look, or who leaves for a false sign, is out. Last player standing becomes the sea.

> **Scripture.** "The LORD on high is mightier than the noise of many waters, yea, than the mighty waves of the sea." (Psalm 93:4, KJV)

A tsunami is the mightiest wave on earth, and the psalm says plainly that God is mightier still. That is a reason for humility before the sea and for trust in the One who rules it.

Practice answers

1. "Harbor wave," from Japanese (tsu, harbor; nami, wave). Fishermen at sea felt nothing but came home to find their harbors wrecked.

2. Strong or long shaking at the coast; the sea pulling back (drawback) or rising strangely; a roar like a train. Action: go at once to high ground or far inland and stay there for hours.
3. In deep water the tsunami is less than a meter high and its crests are 100 km or more apart, so the ship rises and falls very gently over many minutes.
4. 9.8 × 1,000 = 9,800; √9,800 ≈ 99 m/s; 99 × 3.6 ≈ 356 km/h (about 360 km/h).
5. 1,800 ÷ 600 = 3 hours. It arrives at about 5:00 p.m.
6. (b). From 10 m to 100 m the speed goes from 36 to 113 km/h, about 3.1 times; from 100 m to 1,000 m, from 113 to 356, again about 3.1 times. Ten times the depth gives about √10 ≈ 3.2 times the speed.
7. Wave 2 (2.8 m) was largest. The waves came 25 to 35 minutes apart. Returning at 3:30 p.m. put the family on the beach five minutes before the biggest wave; the first wave in a tsunami is often not the largest, and people must stay on high ground for hours until officials say it is safe.
8. Independent variable: the slope of the board (for example, gentle, medium and steep, set by how high you prop one end, measured in cm). Dependent variable: runup, the highest point the water reaches up the board, measured with a ruler along the board or marked with tape. Keep the same: water depth, the paddle and the size of the push, the tub, the position of the board’s bottom edge. Run three trials at each slope and average the runup.
9. In deep water the wave moves very fast and its energy is spread through a wavelength of 100 km or more and the whole depth of the sea, so the surface rises only a little. As the wave enters shallow water its speed drops sharply, so the back of the wave catches up with the front and the wavelength shrinks. The energy that was spread over a long, deep wave is squeezed into a short, shallow one, and the only place for the water to go is up. The wave grows into a tall, fast-rising flood that keeps coming for many minutes.
10. Speed in 4,000 m of water is about 713 km/h, so the wave needs 900 ÷ 713 ≈ 1.26 h ≈ 76 minutes to reach the city after passing the buoy (a little more as it slows near shore). Seismographs give the earliest alarm (an earthquake has happened; a tsunami is possible) within minutes, but not every undersea earthquake makes a tsunami. The buoy confirms whether a wave is really traveling and how big it is, so the center can warn confidently and avoid false alarms that make people stop listening.

Unit 4 review

Answer each question. Show your work for calculations, use complete sentences for explanations, and label every part of your diagram. The test is worth 60 points.

1. (4 pts) Multiple choice. The Lisbon earthquake struck on (a) April 18, 1906; (b) November 1, 1755; (c) May 22, 1960; (d) December 26, 2004. Which disaster came last that day: the shaking, the sea wave or the fires?
2. (4 pts) Multiple choice. Each whole-number increase in magnitude makes the seismogram wiggle (a) 2 times taller; (b) 10 times taller; (c) 32 times taller; (d) 100 times taller. About how many times more energy is released per whole step?
3. (5 pts) Explain the difference between magnitude and intensity. Give one example of a sentence that describes intensity.
4. (6 pts) A magnitude 8.0 earthquake and a magnitude 6.0 earthquake are recorded at the same distance. How many times taller is the 8.0’s wiggle? About how many times more energy did it release? Show your steps.
5. (6 pts) Diagram. Draw a seismogram with a time axis in seconds. Mark and label the P wave arrival, the S wave arrival and the surface waves, showing which wiggles are smallest and which are largest. Mark the S minus P time. If the S minus P time on your drawing is 20 seconds, about how far away was the earthquake (use about 8 km per second)?
6. (5 pts) Why does the heavy mass in a seismograph stay nearly still while the ground shakes? What word names this idea, and what would happen to the record if the mass were very light?
7. (6 pts) A tsunami crosses water 1,000 m deep. Find its speed in m/s and in km/h (speed = square root of 9.8 × depth). Then explain in one sentence what happens to the wave’s speed and height when it reaches water 10 m deep.
8. (6 pts) Name the three natural warning signs of a tsunami, state the one correct action, and explain why it is a mistake to return to the beach after the first wave passes.
9. (6 pts) Describe Pombal’s survey of 1756: who was asked, two of the questions, and why it was the first step toward earthquake science.
10. (6 pts) Data reading. Three stations record one earthquake. Station A: S minus P time 25 s. Station B: 50 s. Station C: 10 s. (a) Find each station’s distance using about 8 km per second. (b) Which station is closest? (c) Explain how to use the three distances to find the epicenter.
11. (6 pts) Written explanation. Using elastic rebound, explain in four or five sentences how one slip on a fault under the sea can produce shaking on land, a tsunami and fires in a city. Then write one sentence on what Psalm 46:2–3 says to people who live through such a day.

Unit project: my earthquake station report

Put together a seismologist’s report for an imaginary coastal town. Include: your best seismograph trace from Lesson 4.3 with the P, S and surface waves labeled and the S minus

P time turned into a distance; a map on which you locate an epicenter from three stations by triangulation; a magnitude poster showing the ×10 wiggle and ×32 energy steps with two real earthquakes compared; your intensity map from Lesson 4.2; and a one-page tsunami plan for the town with the three natural warning signs, an evacuation route to high ground, and a sentence explaining how a DART buoy and a seismograph network would warn the town.

Finish with a short paragraph telling what Lisbon in 1755 taught the world, and what Psalm 46 teaches you about living on a shaking earth.

- **Accuracy**: Wave arrivals, distances, magnitude ratios and tsunami facts are correct and the calculations are shown.
- **Records**: The seismograph trace, intensity map and data tables are the student's own, labeled, dated and complete.
- **Explanation**: The tsunami plan and the closing paragraph explain the science clearly and connect it to Lisbon and to Psalm 46.
- **Care**: The report is neat, the diagrams are labeled and easy to read, and the map has a scale.

Answer key

1. (b) November 1, 1755. The fires came last, after the shaking and the sea wave, and burned for days.
2. (b) 10 times taller. About 32 times more energy per whole step.
3. Magnitude is a single number for the whole earthquake, measuring the energy released at the source. Intensity is how strong the shaking was at one particular place, judged by what people felt and what was damaged, and it changes from town to town (Modified Mercalli I to XII). Example: "In Oakdale, chimneys fell and plaster cracked" describes intensity (about VIII).
4. Difference = 2 steps. Wiggle: 10 × 10 = 100 times taller. Energy: 32 × 32 ≈ 1,000 times more.
5. The drawing should show a flat line, then small P wiggles, then larger S wiggles, then the largest surface waves, with a bracket between the P and S arrivals labeled S minus P. For 20 s: 20 × 8 = about 160 km (accept 160 to 170 km).
6. A mass resists changes in its motion, so when the ground and frame jerk, the hanging mass lags behind and stays nearly still; the pen records the difference. The word is inertia. A very light mass would be dragged along with the frame and would also swing on its own, so the record would be small, noisy and hard to read.
7. 9.8 × 1,000 = 9,800; √9,800 ≈ 99 m/s; 99 × 3.6 ≈ 356 km/h (about 360 km/h). In 10 m of water it slows to about 36 km/h, the crests bunch up, and the wave grows much taller (shoaling).
8. Signs: strong or long shaking at the coast; the sea pulling back (drawback) or rising strangely; a roar like a train. Action: go at once to high ground or far inland and stay for hours. A tsunami is a wave train; later waves, arriving minutes to an hour apart, are often larger than the first.
9. Pombal sent a list of questions to every parish priest in Portugal. Questions included: at what time did the earthquake begin and how long did it last; did the shaking seem to come from

one direction; did the sea rise first or fall first, and how many times; how many houses fell; were there aftershocks. It was the first organized collection of earthquake observations from a whole country, giving a data set from which patterns (such as where shaking was strongest) could be mapped, which is how science begins.

10. (a) A: 25 × 8 = 200 km; B: 50 × 8 = 400 km; C: 10 × 8 = 80 km. (b) Station C. (c) Draw a circle around each station with radius equal to its distance (to the map scale); the single point where all three circles cross is the epicenter (triangulation).
11. Plates push slowly on the rock along a fault, but friction holds it, so the rock bends and stores energy. When the stored force beats the friction the rock snaps back (elastic rebound), sending seismic waves through the crust at several km/s that shake the city within a minute and topple buildings. The same slip lifts the seafloor and the water above it, which spreads out as a tsunami and reaches the coast within an hour. The shaking knocks over lamps, candles and stoves, and fires spread through the ruins. Psalm 46 says that even when the earth is removed and the waters roar, God is our refuge, so we need not fear.

UNIT 5

Mountains

Mountains look like the most permanent things on earth, but they are crust that has been squeezed, bent, broken and lifted, and they are still moving. In this unit you will learn to read that movement the way geologists do: in the folds and faults of a road cut, in a fresh scarp at the foot of a range, in GPS stations that record India pushing into Asia a few centimeters a year, and in the gray limestone full of sea creatures at the summit of Mount Everest.

You will meet Grove Karl Gilbert reading the little cliffs at the foot of the Wasatch Range in 1883 and warning Salt Lake City; the highway crews who cut through Sideling Hill in Maryland and exposed a syncline 100 meters deep; Radhanath Sikdar, who worked out in 1852 that Peak XV was the highest mountain on earth; and Nicolas Steno, who laid a shark’s tooth beside a tongue stone in 1666 and founded the science of rock layers. You will fold clay, bend candy bars, build a collision in a box, and bury shells in a jar, measuring and graphing as you go.

Two lessons carry a Thinking About Time box, because bent layers and seashells on mountaintops are places where the age question comes up. You will learn to state what the museum sign says, what is actually observed, and how Christians who hold to a recent creation and the Flood read the same rock, remembering Psalm 104:8: “They go up by the mountains; they go down by the valleys unto the place which thou hast founded for them.”

BEFORE YOU BEGIN

- Knows that the earth’s crust is broken into plates that move at convergent, divergent and transform boundaries (Unit 2).
- Knows what a fault is and how stored energy in rock is released as an earthquake (Unit 4).
- Can find percents and averages, convert between millimeters, centimeters, meters and kilometers, and work a simple proportion.
- Can read a data table and draw a bar graph or line graph from measurements.

MASTERY CHECKLIST

- I can name the three kinds of stress and tell which makes folds, normal faults, reverse faults and strike-slip faults, and I can label an anticline, a syncline, a hanging wall and a footwall.
- I can explain why mountains rise in jerks along faults and name the main kinds of mountains: folded, fault-block, upwarped and volcanic.
- I can explain brittle and ductile behavior and the four things that decide whether rock bends or breaks, and I can measure the shortening of a folded layer as a percent.
- I can state the mainstream reading and the Flood reading of bent layers without cracks and of seashells on mountaintops, and say what each one assumes about time.

- I can explain how the Himalaya are built by the collision of India with Asia and use rates in cm per year and mm per year to describe the motion.
- I can tell how Steno compared a shark's tooth with a tongue stone and explain why a fossil shows that its layer was once soft.

OPTIONAL BOOKS AND RESOURCES

- **USGS, This Dynamic Earth: The Story of Plate Tectonics (online book)** (https://pubs.usgs.gov/gip/dynamic/dynamic.html): Free. The section on the Himalaya and the India-Asia collision has a clear map and cross-section. Read it with Lesson 5.3 and have your student find the sentence about how fast India is moving.
- **NASA Earth Observatory** (https://earthobservatory.nasa.gov/): Free. Search for images of the Himalaya, Tibet, the Appalachians and folded rock seen from space. Good for seeing that mountain belts are long bands of folded crust, not single peaks.
- **Smithsonian National Museum of Natural History** (https://naturalhistory.si.edu/): Free. The museum's online collections include fossil crinoids, brachiopods and shark teeth to compare with Lesson 5.4. Remember to read any dates on the pages as the museum's claim and talk through the Thinking About Time box.

5.1 Folding and Faulting: How Rock Bends and Breaks ★

OBJECTIVES

- Explain the three kinds of stress (compression, tension and shear) and tell which kind makes folds, normal faults, reverse faults and strike-slip faults.
- Draw and label an anticline, a syncline, and the hanging wall and footwall of a fault, and name the main kinds of mountains (folded, fault-block, upwarped and volcanic).
- Tell how G. K. Gilbert read the fault scarps at the foot of the Wasatch Range in 1883 and explain why a mountain range can rise in jerks.

Warm-up. Lay a dish towel flat on the table and put your hands on its two ends. Push them slowly toward each other. Count the ridges and troughs that form. Now take a dry cracker and push on its two ends the same way. What happened instead? Write one sentence: the towel _____ but the cracker _____. The earth's rocks do both.

Video. Coming soon. Folds and faults (anticline, syncline, normal, reverse and strike-slip faults) and the Wasatch fault; look for USGS, Utah Geological Survey, Smithsonian, SciShow Kids, Homeschool Pop (Alternate) and classroom demonstrations with clay layers or foam blocks.

KEY TERMS

stress
A force pushing, pulling or shearing rock. Compression squeezes, tension pulls apart, and shear slides one part past another.

fold
A bend in rock layers made by slow squeezing. An upward arch is an anticline; a downward trough is a syncline.

fault
A break in the crust along which blocks of rock have slipped past each other.

hanging wall and footwall
The two blocks on either side of a sloping fault. The hanging wall is the block above the fault surface; the footwall is the block below it.

normal, reverse and strike-slip faults
In a normal fault the hanging wall drops (tension). In a reverse or thrust fault the hanging wall rises (compression). In a strike-slip fault the blocks slide sideways (shear).

fault scarp
A small cliff at the surface made where one side of a fault has moved up or down.

CORE IDEAS

The story. In 1883 a geologist named Grove Karl Gilbert was walking along the foot of the Wasatch Range, the wall of mountains that stands east of Salt Lake City, Utah. The peaks rise more than 2,000 meters above the valley floor. Gilbert noticed something small at the base of that wall: fresh little cliffs, a few meters high, running for kilometers along the mountain front. They cut right across the fans of gravel that mountain streams had spread out at the canyon mouths. The gravel fans were young, and the little cliffs cut them, so the cliffs were younger still. Gilbert reasoned that the ground along a great crack had jerked: the mountain side up, the valley side down. Each jerk was an earthquake, and the cliff, which geologists call a fault scarp, was the earthquake's footprint. He wrote an open letter to a Salt Lake City newspaper that year warning that the fault would move again and that the city should build for it. The Wasatch fault is about 380 km long and is still active; on March 18, 2020, a magnitude 5.7 earthquake at Magna, just west of the city, reminded Utah that Gilbert had been right.

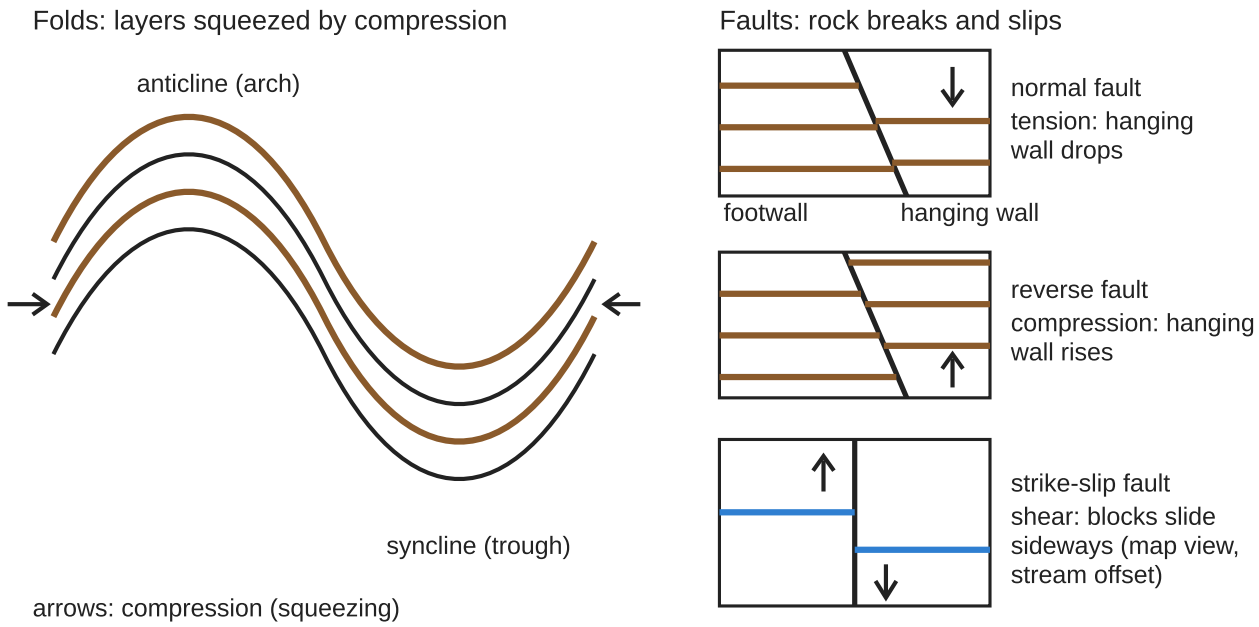
How they figured it out. The key was a rule stated by Nicolas Steno in 1669: sand and mud settle out of water in flat, level layers. So wherever layers are tilted, arched or broken, something moved them after they formed. Geologists sorted the moving forces, called **stress**, into three kinds. **Compression** squeezes rock from two sides. **Tension** pulls it apart. **Shear** slides one part past another, like a deck of cards pushed sideways. Rock that is squeezed slowly, like your dish towel, bends into **folds**: an upward arch is an **anticline**, a downward trough is a **syncline**. Rock that breaks, like your cracker, slips along a **fault**. Miners gave the two sides of a sloping fault their names: the block above the fault surface, which hung over their heads as they followed an ore vein, is the **hanging wall**; the block under their boots is the **footwall**. When tension pulls the crust apart, the hanging wall slides down: a **normal fault**, like the Wasatch. When compression squeezes, the hanging wall is shoved up and over: a **reverse fault**, or a **thrust fault** if the slope is gentle. When shear slides blocks sideways, with little up or down, it is a **strike-slip fault**, like the San Andreas fault in California.

The big idea. Mountains are not piles of rock dumped on the land. They are crust that has been squeezed, broken, bent and lifted. Where plates push together (Unit 2), the crust shortens and thickens into **folded mountains**: the Appalachians, the Alps and the Himalaya (Lesson 5.3) are mostly folds and thrust faults stacked on one another. Where the crust is stretched, it breaks into long blocks that tilt like a row of fallen books, and the high edges become **fault-block mountains**: the Wasatch Range, the Sierra Nevada and the Tetons. Where something pushes up from below without breaking the surface, the layers arch into a dome, an **upwarped mountain** such as the Black Hills of South Dakota. And volcanoes (Unit 3) build mountains by adding new rock on top. Every mountain is a contest: uplift raises it, and rain, ice and rivers wear it down. The shape you see is uplift minus erosion.

Try it and see. Make four flat sheets of play dough in different colors and stack them. Hold the stack between two books and push the books slowly together. Watch the anticlines and synclines grow and measure how much shorter the stack became. Now have a parent cut a fresh stack on a slant with a table knife, and slide the top piece up the slope: a reverse fault.

Slide it down the slope: a normal fault. Look at the cut face. Each colored layer is offset across the break by the same amount, and that offset is exactly what a geologist measures in a road cut or a trench to learn how far a fault has slipped.

God's handiwork. The forces that fold and break the crust are enormous, yet they are orderly, and a careful observer with a notebook and a tape measure can read them. Gilbert read a few meters of gravel cliff and warned a city. The prophet Nahum wrote that "the mountains quake at him, and the hills melt" (Nahum 1:5). The mountains are not permanent; only their Maker is. Psalm 90:2 says that before the mountains were brought forth, God was God, from everlasting to everlasting. Learning how mountains are built is one way to see His power; using that knowledge to build safely, as Gilbert urged, is one way to love our neighbors.



Folds come from slow squeezing. Faults come from breaking: normal (pulled apart), reverse (squeezed) and strike-slip (sheared sideways).

PICTURE STUDY



Mountain of the Holy Cross, Thomas Moran, 1875 · Oil on canvas · Autry Museum of the American West, Los Angeles

In 1873 the photographer William Henry Jackson, working for the Hayden Survey of the territories, climbed a neighboring ridge in Colorado and took the first photograph of a peak that trappers had talked about for years: a mountain with a cross of snow on its face. Thomas Moran went out the next summer to see it for himself, and in 1875 he painted this picture. It was shown at the Centennial Exhibition in Philadelphia in 1876 and became one of the most famous mountain paintings in America.

The peak, in the Sawatch Range, stands about 4,270 meters high. The upright of the cross is a deep fracture in the granite, a crack that runs hundreds of meters down the face and holds snow all summer; the crossbar is a ledge. The mountain is a block of very hard granite and gneiss lifted high with the rest of the Rocky Mountains and carved sharp by ice and water. Moran moved the stream and the rocks around to make his picture, as painters do, but the cross is real.

Look closely

- Find the cross. Which part of it is a crack in the rock and which part is a ledge? Why would snow last longest in those two places?
- Follow the skyline of the peak. Is it smooth and rounded or broken and jagged? What does that tell you about the rock?
- Look at the foreground: boulders, a waterfall, broken rock. Where did all that loose rock come from, and where is the water taking it?
- Moran painted from a sketch and a photograph, not from one spot. Can you find a place where he may have moved the scene around to fit it into a tall picture?

Talk about it

1. A fracture that does not slip is called a joint; a fracture that slips is a fault. Which word fits the crack that makes the upright of the cross? How could you tell the difference if you were standing on the mountain?
2. Uplift raised this peak and erosion is wearing it down. Name two things in the painting that show erosion at work.
3. Why do you think so many Americans in 1876 wanted to see this painting?

> **Safety first.** A parent should do any cutting of clay stacks with the table knife. Keep play dough away from small children and off the carpet.

EXPERIMENT: CLAY MOUNTAINS: DOES THE NUMBER OF LAYERS CHANGE THE FOLD?

Geologists cannot squeeze a mountain range in the laboratory, so they build small models and measure them. You will build stacks of play dough layers, squeeze them the same distance each time, and measure the folds that form. Then you will change one thing, the number of layers, and see whether thicker stacks fold the same way as thin ones.

Question: Does a stack with more layers fold into taller, fewer folds than a stack with fewer layers? Prediction: write yours before you squeeze anything.

You will need

- Play dough or modeling clay in three or four colors (homemade flour-and-salt dough works well)
- A rolling pin or a smooth jar, and a ruler (30 cm)
- Two hardcover books or two small boards to push with
- A sheet of waxed paper or a smooth tray to work on
- Notebook and pencil; a camera or phone to photograph each fold from the side

Steps

1. Roll each color into a sheet about 0.5 cm thick, and cut all sheets to the same size, about 15 cm long and 6 cm wide. Record the thickness and length.
2. Build Stack A with 2 layers. Lay it on the waxed paper between the two books, with the books touching the ends. Measure and record the starting length (15 cm).
3. Push the books slowly and evenly toward each other until the stack is 10 cm long (5 cm of shortening). Stop. Count the anticlines and synclines and measure the height of the tallest fold from the table to its crest. Photograph the side view. Record everything in a table: Stack, Layers, Start length, End length, Number of folds, Tallest fold (cm).
4. Build Stack B with 4 layers and Stack C with 6 layers, same sheet size, same 5 cm of shortening, same slow pushing. Record the same measurements.
5. Work out the shortening for each stack as a percent: shortening ÷ start length × 100. (It should be about 33% every time; if not, you pushed a different distance.)

6. Make a bar graph: stacks on the bottom, tallest fold height up the side. Make a second bar graph for number of folds.
7. Now take any stack, have a parent cut it on a slant, and slide the upper piece 2 cm up the slope. Measure how far each colored layer is offset across the cut. Is it the same for every layer? Photograph it and label the hanging wall and footwall.
8. Write your conclusion in three sentences: what you changed, what you measured, and whether your prediction was right.

Tips

- Push slowly. Fast pushing makes a mess of the layers and does not model the slow squeeze of the crust.
- If the layers slide on the waxed paper instead of folding, press the bottom layer down lightly so there is some friction, as there is under real rock.
- Chill the dough for 20 minutes and try one stack again. Does cold dough fold or crack? Keep that observation for Lesson 5.2.

Check your work

- I kept the sheet size, the shortening distance and the pushing speed the same, and changed only the number of layers.
- I measured fold height and counted folds for three stacks and graphed them.
- I can point to the hanging wall and footwall on my cut stack and say whether it is a normal or a reverse fault.

FIELD NOTEBOOK

1. Draw a cross-section with four layers folded into one anticline and one syncline. Label both, and add arrows showing the direction of compression.
2. Draw the three fault types as block diagrams. On each, label the hanging wall and footwall (or, for strike-slip, the two sides) and the kind of stress that made it.
3. Sketch the Wasatch front as Gilbert saw it: the mountain wall, a gravel fan at a canyon mouth, and a fault scarp cutting across the fan. Write one sentence explaining how he knew the scarp was younger than the fan.

> **From history.** Gilbert’s eye for small cliffs served him in another way. On the same Utah trips he traced old shorelines, like bathtub rings, high on the mountainsides around the Great Salt Lake, and showed that the lake had once been a vast inland sea, which he named Lake Bonneville. His 1890 report on it is still read today, and the shoreline benches are easy to spot from Salt Lake City. The Wasatch fault cuts those shorelines too, one more sign that the mountains have moved since the lake was high.

WORKED EXAMPLES

Example 1. Trenches dug across the Wasatch fault show that a single large earthquake typically lifts the mountain side about 2 m relative to the valley side. If the mountain front now stands 2,000 m above the valley floor, at least how many such earthquakes would it take to make that difference?

1. Divide the total offset by the offset per earthquake: 2,000 m ÷ 2 m = 1,000.
2. This is a minimum. Erosion has carried rock off the mountains and filled the valley with sediment, so the real total offset along the fault is greater than the height you see today.

Answer: At least 1,000 earthquakes of about 2 m each. Mountains like the Wasatch rise in small jerks, not all at once.

Example 2. A normal fault slopes at an angle such that for every 5 m the hanging wall slides along the fault surface, it drops 4 m straight down. How far does it also move sideways (horizontally)? Check your answer with the Pythagorean theorem.

1. The slip along the fault is the long side (hypotenuse) of a right triangle; the vertical drop (geologists call it the throw) is one short side.
2. A 3-4-5 right triangle has sides 3, 4 and 5. With hypotenuse 5 m and one side 4 m, the other side is 3 m.
3. Check: $3^2 + 4^2 = 9 + 16 = 25 = 5^2$. It works.

Answer: The hanging wall moves 3 m sideways (the heave) while dropping 4 m (the throw) along 5 m of fault slip.

Example 3. In a photograph of a road cut, a geologist standing beside the rock appears 3 cm tall, and an anticline in the layers behind her appears 24 cm wide from one limb to the other. The geologist is really 1.5 m tall. How wide is the real anticline?

1. Find the scale of the photo: 3 cm in the picture = 1.5 m in real life, so 1 cm = 0.5 m.
2. Multiply: 24 cm × 0.5 m per cm = 12 m.

Answer: About 12 m wide. Putting a person, a hammer or a coin in a rock photograph is how geologists record scale.

PRACTICE

1. EASY Name the three kinds of stress and say what each does to rock.
2. EASY What is the difference between an anticline and a syncline?

3. EASY In a normal fault, which block moves down, the hanging wall or the footwall? Which kind of stress makes a normal fault?
4. MEDIUM Gilbert found fault scarps cutting across young gravel fans at the foot of the Wasatch Range. Explain in two sentences how that told him the fault had moved recently.
5. MEDIUM Match each mountain range to its main type: folded, fault-block or upwarped (dome). (a) Appalachians (b) Tetons (c) Black Hills (d) Alps
6. MEDIUM Data reading. A geologist dug four trenches across one fault and measured the offset made by the most recent earthquake at each: Trench 1, 1.8 m; Trench 2, 2.2 m; Trench 3, 1.9 m; Trench 4, 2.1 m. (a) What is the average offset? (b) Which statement does the data best support? (i) The earthquake moved the fault the same amount everywhere. (ii) The earthquake moved the fault about 2 m along this stretch, with small differences from place to place. (iii) The fault did not move in this earthquake. (iv) The offset grows larger toward Trench 4.
7. MEDIUM Data reading. In a clay-fold experiment, stacks were shortened by the same 5 cm. Results: 2 layers, 6 folds, tallest fold 1.5 cm; 4 layers, 4 folds, tallest fold 2.4 cm; 6 layers, 3 folds, tallest fold 3.1 cm. Describe the pattern, and predict the number of folds and tallest fold for an 8-layer stack.
8. HARD Experiment design. You want to find out whether pushing speed changes how clay layers fold. Name the independent variable, the dependent variable, three things to keep the same, and tell why you would repeat each trial more than once.
9. HARD A reverse fault lifts the hanging wall 6 m straight up while the hanging wall slides 10 m along the fault surface. Is this fault steep or gently sloping? Explain using the two numbers.
10. CHALLENGE Explain in four or five sentences why a mountain range’s height is “uplift minus erosion,” using the Wasatch Range as your example.

COMMON MISTAKES

- Thinking an anticline is always a hill and a syncline always a valley. Folds are shapes in the rock layers underground; erosion can carve a valley right through the top of an anticline.
- Picturing a fault as an open chasm. A fault is a break where rock has slipped, and the two sides are usually pressed tightly together; the slip, not a gap, is what matters.
- Thinking mountains are piles of rock stacked on the land. Most mountains are the crust itself, squeezed into folds, broken into blocks and lifted, with erosion carving the shapes we see.

Make it a game · Stress Call. Stand facing a parent with your hands flat together in front of you. The parent calls a stress: “compression,” “tension” or “shear.” You must move your hands the right way at once (push together, pull apart, slide past) and shout the structure it makes: “fold!” or “normal fault!” or “strike-slip!” For bonus points, when the parent calls “fold,” name both the arch and the trough. Each correct call in under two seconds scores a point. Play to ten, then switch roles.

> **Scripture.** “The mountains quake at him, and the hills melt, and the earth is burned at his presence, yea, the world, and all that dwell therein.” (Nahum 1:5, KJV)

The prophet knew that mountains, which seem the most solid things on earth, quake and give way before God. Faults that lift mountains in jerks remind us that the earth is a made thing and that only its Maker is unshakable.

Practice answers

1. Compression squeezes rock together; tension pulls it apart; shear slides one part past another.
2. An anticline is an upward arch of folded layers; a syncline is a downward trough.
3. The hanging wall moves down. Tension (pulling apart).
4. The gravel fans were young, laid down by streams in recent times. Because the scarps cut across the fans, the fault movement had to be younger than the fans, so the fault had moved recently and could move again.
5. (a) folded; (b) fault-block; (c) upwarped (dome); (d) folded.
6. (a) (1.8 + 2.2 + 1.9 + 2.1) ÷ 4 = 8.0 ÷ 4 = 2.0 m. (b) (ii). The values differ slightly, so (i) is wrong; they do not rise steadily from Trench 1 to 4 (1.8, 2.2, 1.9, 2.1), so (iv) is wrong.
7. As the number of layers increases, the number of folds goes down and the folds get taller. A reasonable prediction for 8 layers: about 2 folds, tallest fold about 3.5 to 4 cm (any answer that continues the trend is acceptable).
8. Independent variable: pushing speed (slow, medium, fast). Dependent variable: the fold height or number of folds (one measurable result). Keep the same: the number and thickness of layers, the sheet size, the shortening distance, the dough temperature. Repeat trials so one lumpy stack does not decide the answer; average the results.
9. Gently sloping. The block slid 10 m along the fault but rose only 6 m, so most of the motion was sideways; using the 3-4-5 pattern doubled (6-8-10), it moved 8 m horizontally. A steep fault would rise almost as far as it slides. A gently sloping reverse fault is called a thrust fault.
10. The Wasatch fault lifts the mountain block a couple of meters in each large earthquake, so uplift adds height over many earthquakes. At the same time rain, snow, ice and streams break rock off the peaks and carry it down the canyons, spreading it in gravel fans on the valley floor. The gravel in the valley is mountain that has been removed. So the height we see is the total uplift minus everything erosion has taken away. If the fault stopped moving, erosion would slowly lower the range.

5.2 Bent Rock Layers Without Cracking: The Sideling Hill Syncline ★

OBJECTIVES

- Explain the difference between brittle and ductile behavior and name the four things that decide whether rock bends or breaks: temperature, pressure, speed of the push, and how wet or soft the material is.
- Describe the folded layers in the Sideling Hill road cut and measure the shortening of a bent layer as a percent.
- State the mainstream reading and the Flood reading of folded rock that shows no cracks, and tell what each one assumes about time.

Warm-up. Take a stick of chewing gum, a piece of chalk and a wax crayon. Try slowly to bend each one into a U. Which one bends, which one snaps, and which one depends on how fast you go? Now hold the crayon in your fist for one minute to warm it and try again. Write down what changed.

Video. Coming soon. Folded rock layers, ductile versus brittle deformation, and the Sideling Hill road cut in Maryland; look for USGS, Maryland Geological Survey, Smithsonian, Science Max, SciShow Kids, and classroom demonstrations with candy bars, Silly Putty or clay at different temperatures.

KEY TERMS

brittle
Breaking into pieces when stressed, like glass or cold chalk. Brittle rock makes faults and cracks.

ductile
Bending or flowing without breaking when stressed, like warm wax or wet clay. Ductile rock makes folds.

confining pressure
The squeeze from all sides that rock feels when it is buried under a great weight of other rock. It helps hold rock together so it bends instead of cracking.

strain rate
How fast a material is being bent or stretched. The same material may bend when pushed slowly and snap when pushed fast.

soft-sediment deformation
Bending or folding of layers that happened while they were still wet and unhardened, before they turned to stone.

hinge and limbs

The hinge is the line of sharpest bending in a fold; the limbs are the two sloping sides on either side of it.

CORE IDEAS

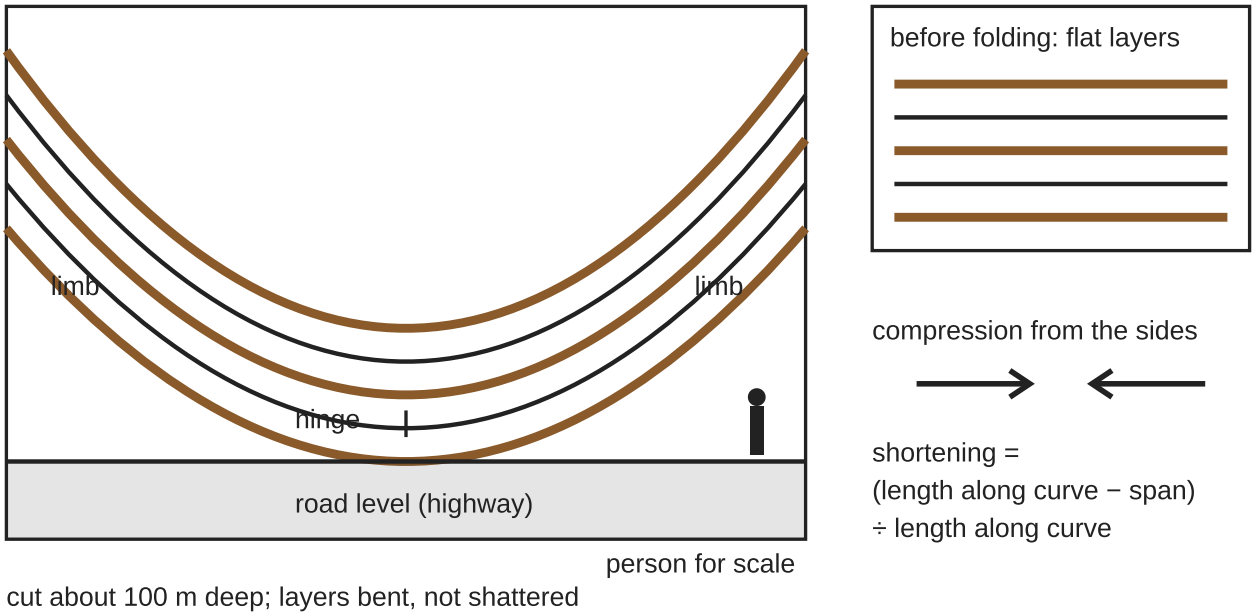
The story. In the early 1980s, highway crews in western Maryland began blasting a notch through a long forested ridge called Sideling Hill so that Interstate 68 could run straight through instead of winding over the top. By 1985 the cut was finished, about 100 meters deep, and when the dust settled, drivers coming around the bend saw something that made them pull over. The whole wall of rock, sandstone and shale in stripes of gray, tan and red, was bent into a giant U. The layers dip down from the left, flatten at the bottom and rise again on the right: a syncline, cut cleanly in half so you can see straight into it. Geologists already knew the ridge was folded, but no one had ever seen the fold so plainly. Maryland built a parking area and an exhibit so travelers could stop and look. What strikes nearly everyone is the same thing: the layers are bent, not shattered. They curve through the hinge at the bottom of the U like the pages of a bent paperback, and you can follow one layer with your eye all the way around.

How they figured it out. How does solid rock bend? Engineers and geologists worked on that question in the laboratory. Around 1900, Frank Dawson Adams at McGill University in Montreal sealed small columns of marble inside thick steel jackets and squeezed them slowly for weeks. The marble shortened and bulged without breaking, like a bar of cold butter pressed under a plate. The steel jacket supplied **confining pressure**, the squeeze from all sides that rock feels when buried under kilometers of other rock. Experiments since then have sorted out four things that decide whether a material is **brittle** (it breaks) or **ductile** (it bends): temperature, because warm things bend more easily than cold ones; confining pressure, because a squeeze from all sides keeps cracks from opening; **strain rate**, because a slow push lets a material flow while a fast push snaps it; and the material itself, because wet clay bends where dry sandstone cracks. You already know all four from the kitchen. A cold chocolate bar snaps and a warm one droops. Silly Putty pulled slowly stretches into a long thread, and the same putty yanked fast breaks with a clean edge.

The big idea. Folds and faults (Lesson 5.1) are the same rock answering the same push in two different ways. Near the surface, where rock is cold and nothing presses on it from the sides, it behaves brittlely and faults. Deep down, warm and squeezed on all sides, it behaves ductilely and folds. There is also a third possibility: layers that have not yet hardened into rock at all. Wet sand and mud fold easily, as anyone who has pushed on a sandcastle knows, and geologists call bending that happened before the sediment turned to stone **soft-sediment deformation**. So when you stand in front of a fold like Sideling Hill, there are two questions to ask, and they are both fair questions. First, what do we see? Second, what was the rock like when it bent: deep, warm and hard, or shallow, wet and soft? The answer to the second question is an interpretation, and it is tied up with how much time passed between the laying down of the layers and their folding. That is why this lesson has a Thinking About Time box.

Try it and see. Here is the measurement geologists make at every fold. Lay a piece of string along one layer of a folded model, following every curve, and measure the string: that is the layer's original length, because the layer was laid flat. Then measure straight across from one end of the layer to the other: that is its length now. The difference, divided by the original length, is the **shortening**. A layer that was 12 cm long and now spans 9 cm has been shortened 3 cm, or 25 percent. Folded mountain belts have been shortened by that much and more; the crust that is "missing" sideways has gone up into the folds.

God's handiwork. A layer of rock bent into a U is a kind of record: the layer was laid flat, as Steno said, and then something pushed. Psalm 104 describes the waters of the Flood standing above the mountains and then fleeing at God's rebuke, and in verse 8 it says the mountains went up and the valleys went down as the waters drained to the place He had made for them. Christians who read the folded layers as Flood sediments, still soft when the mountains rose, see in Sideling Hill the fingerprint of that verse. Whatever one concludes about the timing, the fold itself was made by a real push on a real day, under the hand of the One who "weighed the mountains in scales" (Isaiah 40:12). The job of a young scientist is to look first, measure carefully, and name an interpretation as an interpretation.



The Sideling Hill syncline, as a driver sees it: layers that were laid flat (inset) are now bent into a U. The hinge is the line of sharpest bending; the limbs rise on either side.

⏳ Thinking About Time

What the sign says. The exhibit at the Sideling Hill cut and the textbooks say that these sand and mud layers were laid down about 350 million years ago in rivers and shallow seas, hardened into sandstone and shale, were buried under kilometers of later rock, and then were squeezed into this fold tens of millions of years later when the Appalachian Mountains were pushed up. Buried that deep, the textbooks say, warm rock under

confining pressure creeps a little at a time, so solid stone can bend over millions of years without breaking.

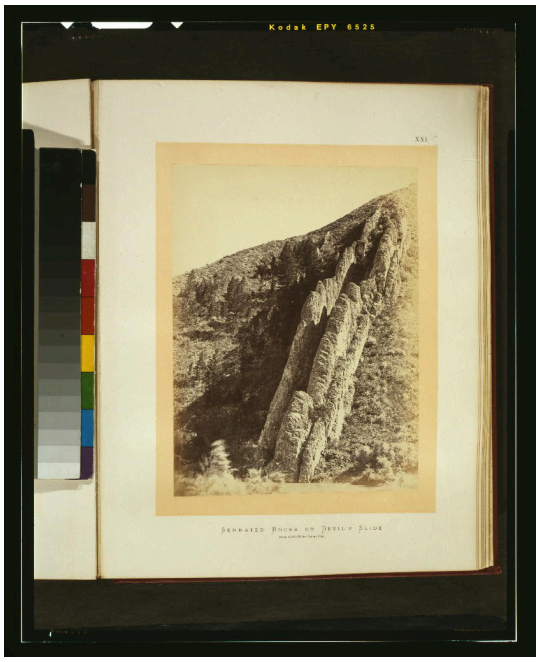
What we observe. We observe layers of sandstone and shale about 100 meters thick bent into a sharp U, following the curve through the hinge without a broken-up zone, with some layers slightly thicker at the hinge and thinner on the limbs. We observe in the laboratory that rock under high confining pressure can be bent slowly (Adams's marble experiments, around 1900), and also that wet, unhardened sand and mud fold easily with no pressure at all. Everyone agrees on the first fact: the layers were flat when they were laid down and were bent afterward.

How Christians read it. Many Christian geologists read folds like this one as soft-sediment deformation. In their reading the layers were laid down quickly during the Flood year (Genesis 7–8), and they were still wet and unhardened when the mountains rose and the waters drained (Psalm 104:8), so they bent like layers of damp sand instead of cracking like stone. They point out that the mainstream reading needs the rock to have been hardened, then buried deep and kept warm for a very long time, and then bent without the cracks that cold, hard rock makes; the mainstream reading answers that deep burial supplies the warmth and pressure, and that other folds do show cracks and mineral veins. Both readings agree on what is seen in the cut; they differ on how much time passed between the laying down and the folding, and that is the question to keep in view whenever you read a sign.

Try it. Put one chocolate bar in the refrigerator and leave another in a warm pocket for ten minutes, then bend both slowly. Which one is "deep, warm and squeezed," and which is "cold and shallow"? Which one does a fresh, damp layer of sand act like?

Psalm 104:8

PICTURE STUDY



Devil's Slide, Weber Canyon, Utah, Andrew J. Russell, photographer for the Union Pacific Railroad, 1868 · Albumen print from a glass negative · Library of Congress, Prints and Photographs Division; published as plate XXI of Sun Pictures of Rocky Mountain Scenery (1870)

When the Union Pacific built its line through Weber Canyon in 1868 and 1869, the railroad hired Andrew J. Russell to photograph the work and the scenery, and the pictures were sold to travelers. One of the most popular showed the Devil's Slide: two parallel walls of limestone, each about 12 meters high and standing about 8 meters apart, running some 60 meters down the mountainside. Travelers thought it looked like a giant's slide.

The walls are rock layers. They were laid down flat on an old seafloor, and the whole stack was later tilted until the layers stood nearly on end, as one limb of a great fold. Two hard limestone layers now stand up like fins because the softer rock between and around them has worn away faster. Russell's camera recorded tilted strata before most people had heard the word.

Look closely

- Find the two walls. Are they the same thickness? Do they stay parallel all the way down the slope?
- The space between the walls was once filled with a softer layer. What happened to it, and where did it go?
- The layers were once flat. Turn your head so that the walls look horizontal. Now imagine the whole hillside bent back the way it was laid down. How far did it tilt?
- Look for the railroad or the river at the bottom of the canyon, if the print shows them. Why would a railroad photographer want this scene?

Talk about it

1. The limestone layers were tilted nearly straight up without shattering into blocks. Which of the four things in the lesson (temperature, pressure, speed, softness) could explain that? Which cannot be known from the photograph alone?
2. What measurement could you make at the Devil's Slide that a drawing could not give you as reliably?
3. Why is a photograph a better record for a scientist than a painting? Is there anything a painting can do that a photograph cannot?

> **Safety first.** Use warm tap water, never boiling water, to warm candy for the bend test. A parent should handle any knife used to cut candy bars to equal lengths.

EXPERIMENT: BEND OR BREAK? TESTING TEMPERATURE AND SPEED ON A CANDY BAR

Rock in the laboratory bends or breaks depending on temperature, pressure, speed and what it is made of. You cannot squeeze marble in a steel jacket at home, but you can test two of those four things on a chewy candy bar: temperature and speed. You will bend candy bars slowly at three temperatures and measure the angle each one reaches before it cracks. Then you will test speed.

Question: Does a warmer bar bend farther before cracking, and does a slow bend go farther than a fast one? Prediction: write both of your predictions before you begin.

You will need

- Nine chewy candy bars of the same kind and size (Tootsie Rolls or similar caramel-style bars work well), unwrapped only at test time
- A refrigerator, a bowl of room-temperature water and a bowl of warm tap water (about 40 °C)
- A kitchen thermometer, a protractor, a ruler and a clock with a second hand
- Notebook and pencil; paper towels

Steps

1. Measure and record the three temperatures: inside the refrigerator (about 4 °C), the room-temperature water (about 20 °C) and the warm water (about 40 °C). Place three bars in each condition for 15 minutes, keeping them in their wrappers in the water.
2. Take one cold bar. Hold its two ends and bend it slowly and steadily, taking about 30 seconds to reach a right angle if it gets that far. The moment you see a crack, stop and hold the shape. Use the protractor to measure the bend angle (0° is straight; 180° is folded flat). If no crack appears at 180°, record "180°, no crack."
3. Repeat with the other two cold bars, then the three room-temperature bars, then the three warm bars. Record every angle in a table: Temperature, Trial 1, Trial 2, Trial 3, Average.
4. Draw a bar graph: temperature on the bottom, average bend angle before cracking up the side.

5. Now test speed. Take two more room-temperature bars. Bend one slowly, 30 seconds to a right angle, and the other as fast as you can, under one second. Record the angle at which each cracks. Repeat if you have extra bars.
6. Write your conclusion: which of your predictions was right, and which of the four factors from the lesson did your experiment test? Which two did it not test, and why would those be hard to test at home?
7. Finish by relating your results to Sideling Hill. Write two sentences, one for each reading in the Thinking About Time box, telling what each reading would say the candy bar shows.

Tips

- Keep the bars in their wrappers in the water so they do not get soggy; it is the temperature you are testing, not the wetness.
- Bend every bar with the same grip at the same places, about 1 cm from each end.
- Your averages matter more than any single trial. One bar with an air bubble inside can crack early.

Check your work

- I tested three temperatures with three trials each and kept the bending speed the same.
- I tested two speeds at the same temperature.
- I can name the two factors I tested and the two I did not, and I can state both readings of a fold without cracks.

FIELD NOTEBOOK

1. Draw the Sideling Hill syncline as a driver sees it, with at least five layers, the road at the bottom, and labels for hinge and limbs. Add a small person for scale and estimate the height of the cut from your scale.
2. Make a two-column chart: Brittle and Ductile. Under each, list three household things and the conditions (cold, warm, fast, slow) that make them act that way.
3. Copy the Thinking About Time box into your notebook in your own words, one short paragraph for each of the three headings.

> **From history.** Frank Dawson Adams’s marble experiments at McGill were done with steel jackets and a screw press, and some of the squeezes went on for weeks. He and his colleague John Nicolson read them to the Royal Society of London in 1900 and published them in 1901 under the plain title “An experimental investigation into the flow of marble.” The marble columns came out shorter, fatter and still whole, with their crystals bent and slid past one another, and the pictures of those squashed columns have been printed in geology textbooks ever since.

WORKED EXAMPLES

Example 1. A string laid along one folded layer at Sideling Hill, following every curve from one side of the cut to the other, measures 120 m. The straight-line distance between the two ends of that layer is 90 m. By how much has the layer been shortened, and what percent is that?

1. The layer was laid down flat, so its original length is the length along the curve: 120 m.
2. Shortening = original length − present span = 120 m − 90 m = 30 m.
3. Percent shortening = 30 ÷ 120 × 100 = 25%.

Answer: The layer has been shortened by 30 m, or 25 percent. The missing width went up into the fold.

Example 2. In a candy-bar test, bars cracked at these average angles: 4 °C, 10°; 20 °C, 40°; 40 °C, 180° (no crack). How many times farther did the 20 °C bar bend than the 4 °C bar? Between 4 °C and 20 °C, how many degrees of extra bend did each 1 °C of warming give, on average?

1. Ratio: 40° ÷ 10° = 4, so the room-temperature bar bent four times as far.
2. Change in bend: 40° − 10° = 30°. Change in temperature: 20 °C − 4 °C = 16 °C.
3. Rate: 30° ÷ 16 °C ≈ 1.9° of extra bend per 1 °C of warming.

Answer: Four times as far; about 1.9° of bend per degree Celsius. Temperature changes brittle behavior into ductile behavior a little at a time.

Example 3. One bar was bent slowly, reaching 90° in 45 s before cracking. Another was bent fast and cracked at 30° after only 1 s. Find each bar’s bending rate in degrees per second and compare them.

1. Slow bar: 90° ÷ 45 s = 2° per second.
2. Fast bar: 30° ÷ 1 s = 30° per second.
3. Compare: 30 ÷ 2 = 15, so the fast bend was 15 times faster, and it cracked after only one third as much bending.

Answer: 2°/s and 30°/s; the fast bend was 15 times faster and cracked sooner. Strain rate matters: the same material is ductile when pushed slowly and brittle when pushed fast.

PRACTICE

1. EASY What does brittle mean, and what does ductile mean? Give one household example of each.

2. EASY Name the four things that decide whether rock bends or breaks.
3. EASY In a fold, what is the hinge and what are the limbs?
4. MEDIUM Silly Putty pulled slowly stretches into a long thread, but the same putty yanked fast snaps. Which of the four factors does this show? Explain in one sentence.
5. MEDIUM A folded layer measures 80 cm along its curve and 60 cm straight across between its ends. Find the shortening in centimeters and as a percent.
6. MEDIUM Data reading. A student bent candy bars at four temperatures and recorded the average angle before cracking: 5 °C, 12°; 15 °C, 30°; 25 °C, 75°; 35 °C, 160°. (a) Between which two temperatures did the bend angle increase the most? (b) Which conclusion does the data best support? (i) Temperature has no effect on bending. (ii) Warmer bars bend farther before cracking, and the effect gets larger at higher temperatures. (iii) Bars bend the same amount at every temperature above 15 °C. (iv) Colder bars bend farther.
7. MEDIUM Data reading. Four pieces of the same clay were pulled apart at different speeds. Results: pulled over 60 s, stretched 15 cm before breaking; over 20 s, stretched 9 cm; over 5 s, stretched 4 cm; over 1 s, stretched 1 cm. Describe the pattern in one sentence and predict what would happen if a piece were pulled over 120 s.
8. HARD Experiment design. You want to test whether wet sand layers fold more easily than dry sand layers. Describe what you would change, what you would keep the same, what you would measure, and how you would make the comparison fair.
9. HARD State the mainstream reading and the Flood reading of the Sideling Hill fold in two sentences each. Then write one sentence telling what observation both readings agree on.
10. CHALLENGE A geologist finds two folds in the same mountain range. Fold A has smooth, unbroken layers with no cracks. Fold B has the same layers bent the same amount, but with many small cracks filled with white mineral veins. Using the four factors, suggest a reason the two folds look different, and tell what you would want to measure to test your idea.

COMMON MISTAKES

- Thinking rock is always brittle because it is hard at the surface. Under enough warmth, confining pressure or a slow enough push, solid rock bends; and sediment that has not yet hardened bends very easily.
- Treating the time between laying down and folding as something you can see in the rock. You can see the bend and measure it; how long the layers waited before bending is an interpretation that depends on assumptions.
- Measuring shortening with the present span as the original length. The original length is the length along the curve, because the layer was laid down flat.

> **Make it a game · Bend or Break Lightning Round.** A parent names a material and a condition, such as “chocolate, freezer,” “Silly Putty, yanked,” “wet sand, pushed slowly,” “glass, warm room,” “marble, buried 10 km and squeezed for a very long time.” You call “bend!” or “break!” and name the factor that decides it (temperature, pressure, speed or

softness). One point for the right call, one for the right factor. Lose a point if you say “bend” for cold chalk. Play to twelve.

Scripture. “They go up by the mountains; they go down by the valleys unto the place which thou hast founded for them.” (Psalm 104:8, KJV)

The psalm describes the waters of the Flood draining away as mountains rose and valleys sank. Christians who read folded layers as still-soft Flood sediments bent during that rising see this verse in the rock. Whatever the timing, the fold is a record of a real push by the hand of the One who founded the earth.

Practice answers

1. Brittle means breaking into pieces when stressed (chalk, glass, a cold chocolate bar). Ductile means bending or flowing without breaking (warm wax, wet clay, chewing gum).
2. Temperature, confining pressure, strain rate (how fast the push is), and the material itself (including how wet or soft it is).
3. The hinge is the line of sharpest bending; the limbs are the sloping sides on either side of the hinge.
4. Strain rate. The same material at the same temperature is ductile when stretched slowly and brittle when stretched fast.
5. 80 − 60 = 20 cm; 20 ÷ 80 × 100 = 25%.
6. (a) Between 25 °C and 35 °C (an increase of 85°; the other steps were 18° and 45°). (b) (ii).
7. The slower the pull, the farther the clay stretches before breaking (ductile when slow, brittle when fast). Pulled over 120 s it should stretch farther than 15 cm, perhaps 20 cm or more, before breaking.
8. Change only the water content: one tray of dry sand layers and one of damp sand layers (same sand, same layer thickness, same tray). Keep the same: the number of layers, the push distance, the pushing speed and the board used to push. Measure the same thing in both, such as the height of the tallest fold or whether the layers crack and slump instead of folding. Repeat each condition several times and average. The comparison is fair because only one factor differs.
9. Mainstream reading: the layers hardened into rock, were buried kilometers deep where they were warm and under confining pressure, and were bent slowly over a very long time (the textbook says millions of years) without breaking. Flood reading: the layers were laid down quickly during the Flood year and were still wet and soft when the mountains rose as the waters drained, so they bent like damp sand without cracking. Both agree that the layers were laid down flat and were bent afterward by a push from the sides.
10. Possible reasons: Fold B bent faster (higher strain rate), or colder and shallower (less temperature and confining pressure), or after the layers had hardened, while Fold A bent slowly, deeper, or while the sediment was still soft. To test: compare the layers under a microscope to see whether grains in Fold A are whole or crushed, measure the depth of burial from the rocks above each fold, and look for signs of soft-sediment deformation such as layers thickening smoothly at the hinge. Any answer that names a factor and a matching measurement is acceptable.

5.3 The Himalaya: Where India Pushes into Asia

OBJECTIVES

- Explain how the Himalaya are being built by the collision of India with Asia, using the words convergent boundary, thrust fault, folding and crustal thickening.
- Tell how Peak XV was measured in 1852 and how its height has been remeasured since, and convert the 1856 figure in feet to meters.
- Use rates (centimeters per year, millimeters per year) and scale to describe how fast the mountains move and how small they are compared with the whole earth.

Warm-up. Put two thick folded bath towels on the table with their ends touching. Push them slowly toward each other. Watch what rises where they meet. Measure the height of the pile with a ruler, then push 5 cm more and measure again. Now imagine the towels are continents. Which part of the earth does the pile stand for?

Video. Coming soon. How the Himalaya and Mount Everest formed from the India-Asia collision, GPS measurement of plate motion, and the 2020 remeasurement of Everest; look for USGS, NASA, Smithsonian, SciShow Kids, Homeschool Pop (Alternate), and mountaineering or nature footage of Everest and Kangchenjunga.

KEY TERMS

convergent boundary
A place where two plates move toward each other. When two continents meet, neither sinks easily, so the crust crumples and thickens into mountains.

thrust fault
A gently sloping reverse fault along which one great slab of rock is pushed up and over another. The Himalaya are built on stacked thrust faults.

crustal thickening
The piling up of crust by folding and thrusting, so that it becomes much thicker than normal. Under Tibet the crust is about twice its usual thickness.

uplift
The raising of rock to a higher elevation. Uplift is measured today in millimeters per year.

plateau
A high, broad, fairly flat region. The Tibetan Plateau north of the Himalaya averages more than 4,500 m above sea level.

survey
Careful measurement of positions, distances and heights on the earth, done with instruments such as theodolites and, today, GPS receivers.

CORE IDEAS

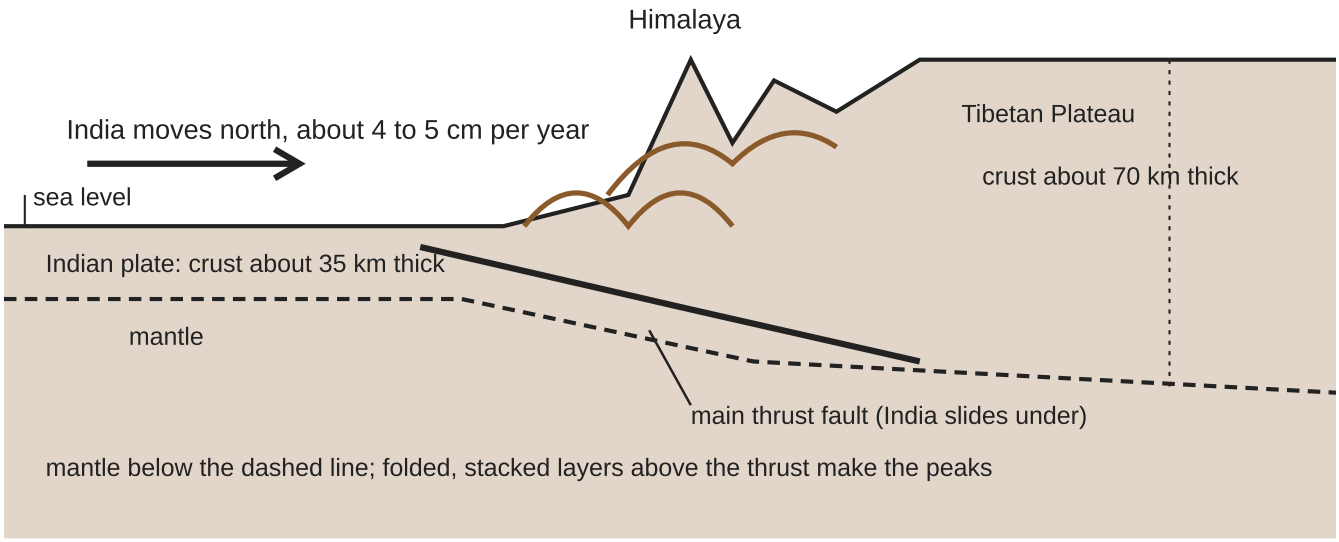
The story. In 1852, in the office of the Great Trigonometrical Survey of India, a mathematician named Radhanath Sikdar was working through a stack of angle measurements taken from the plains of northern India toward the snow peaks on the horizon, more than 150 km away. The surveyors could not enter Nepal, so they had sighted the peaks from six stations and measured the angles with a theodolite, then used trigonometry to find each peak's height. One peak, known only as Peak XV, came out highest. Andrew Waugh, the head of the survey, spent four more years checking the numbers for errors from the bending of light in the air before he announced the result in 1856: 29,002 feet, or about 8,840 meters, the highest mountain on earth. In 1865 the peak was named Mount Everest after Waugh's predecessor, Sir George Everest, though the people who live near it had long called it Chomolungma and Sagarmatha. The mountain has been remeasured many times since. In 2020 Nepal and China, using GPS receivers carried to the summit, agreed on an official height of 8,848.86 meters. The Victorian surveyors, working from 150 km away, had come within about 9 meters.

How they figured it out. Why is the highest mountain there at all? The answer came from plate tectonics (Unit 2). India is a plate of its own, and it is moving north into Asia at a **convergent boundary**. When ocean crust meets a continent, the heavy ocean plate sinks beneath it. But India is a continent, light and thick, and when two continents meet, neither one sinks easily. Instead the crust between them crumples. Layers that were laid down flat on a seafloor are folded (Lesson 5.1), broken along **thrust faults**, and pushed up and over one another in great slabs, each slab stacking on the next like shingles. The result is **crustal thickening**: under the Tibetan Plateau the crust is about 70 km thick, roughly twice the thickness of ordinary continental crust, and the Himalaya stand along the southern edge of that pile. The push has not stopped. GPS stations bolted to bedrock across India, Nepal and Tibet show India still moving north at about 4 to 5 cm per year, and the Himalaya still rising by a few millimeters a year. The push is also why the region shakes. On April 25, 2015, a magnitude 7.8 earthquake on the great thrust fault under Nepal lifted the land near Kathmandu and took nearly 9,000 lives, and the stress is already building toward the next one.

The big idea. The Himalaya are a textbook of everything in this unit. They run about 2,400 km from west to east, hold ten of the fourteen peaks on earth above 8,000 m, and are made of folded, faulted, thickened crust. They are also a textbook of erosion. Their height blocks the wet summer winds from the Indian Ocean, so the southern slopes get some of the heaviest rain on earth while Tibet, behind them, is a dry, cold desert. That rain, with glaciers and landslides, strips rock from the mountains as fast as they rise, and the rivers that drain them, the Indus, the Ganges and the Brahmaputra, carry the sediment to the sea and spread it on the ocean floor in fans thousands of meters thick. Measure the summit of Everest and you find gray limestone full of sea creatures (Lesson 5.4); measure the Bay of Bengal and you find the ground-up Himalaya. The mountains are a conveyor: crust pushed up by the collision, rock carried back down by water.

Try it and see. Build the collision in a box. Spread a layer of flour in a shallow tray, dust it with cocoa, add another flour layer, and repeat for four or five layers. Stand a stiff card at one end and push it slowly toward the other end. Watch the layers fold, break and climb over one another in front of the card. Measure the height of the pile after every 2 cm of pushing and graph it. You will find the pile grows quickly at first and then more slowly as it spreads, just as a real mountain belt widens as well as rises. Look at the side of the pile against the tray wall: you will see folds and little thrust faults, miniature Himalaya.

God’s handiwork. The surveyors of 1852 worked from the plains, patiently measuring angles, because they wanted the truth about a mountain they could not reach. That is good science: measure what you can, check for error, and report honestly. Psalm 95:4 says that “the strength of the hills is his also.” The push that lifts the highest mountains on earth, measured today in centimeters per year, and the rain that carries them to the sea, are both in His hand. The Himalaya are not a disaster or an accident; they are part of a made and ordered world, and the people who live among them, as in every mountain country, need good measurements so that they can build wisely for the next earthquake.



India pushes north into Asia. Crust folds, stacks along thrust faults and thickens to about 70 km under Tibet. The Himalaya rise along the front of the pile.

PICTURE STUDY



Kangchenjunga from Darjeeling, Edward Lear, 1879 · Oil on canvas · Yale Center for British Art, New Haven

Edward Lear is best remembered for his nonsense rhymes, but he earned his living as a landscape painter and traveled through India in 1873 and 1874. At Darjeeling, in January 1874, he saw Kangchenjunga, the third highest mountain on earth at 8,586 m, standing about 70 km away across the foothills. He wrote in his diary that it was so far off and so stupendous that it was hard to take in. He made sketches on the spot and painted several large versions afterward; this is one of them, finished in 1879.

Notice how Lear solves a problem every mountain painter faces: how to show something so big. He fills the bottom of the picture with dark trees, a path and tiny people, so that the pale peaks, lit by the sun and floating above the morning mist, seem to belong to another world. In truth they are the same crust as the foothills, pushed up higher by the same collision.

Look closely

- Find the people and the small building in the foreground. How tall would a person be beside the mountain, if the painting were to scale?
- The peaks are lit and the valleys are dark. What time of day is it, and from which direction is the sun coming?
- Trace the skyline of the range. Count how many separate summits you can see.
- Look at where the snow begins. Why is there snow on the peaks and forest on the hills, when they are only 70 km apart?

Talk about it

1. Lear painted from sketches made in 1874, five years before he finished this canvas. What could a surveyor’s theodolite record in 1874 that Lear’s sketchbook could not?

2. The painter makes the mountain look impossibly far away and high. Using the lesson, explain why Kangchenjunga really is that high.
3. Why do you think Lear, who loved to make people laugh, was so moved by this view that he painted it again and again?

EXPERIMENT: COLLISION IN A BOX: DOES MORE PUSH MAKE A TALLER MOUNTAIN?

Geologists build “sandbox” models of mountain belts to see how layers fold and stack when they are pushed. You will build one with flour and cocoa, push it a measured distance at a time, and graph how the mountain grows. Then you will look at the side of your model for folds and thrust faults.

Question: As the push distance increases, does the height of the pile increase steadily, or does it grow more slowly as it goes? Prediction: sketch the graph you expect before you start.

You will need

- A shallow baking tray or clear plastic storage box (a clear side lets you see the layers)
- About 4 cups of flour and a few spoonfuls of cocoa powder (or colored sand)
- A stiff card or a small board that fits the width of the tray, to push with
- A ruler, a notebook, a pencil and a camera
- A sieve or a spoon for making even layers

Steps

1. Spread a flour layer about 1 cm thick across the tray and smooth it. Dust it with a thin, even coat of cocoa. Add another 1 cm of flour, more cocoa, and so on until you have four or five flour layers separated by cocoa lines. Record the total thickness.
2. Stand the card upright against one end wall of the tray so it reaches the bottom. Mark the starting position on the tray edge with tape.
3. Push the card 2 cm into the layers, slowly and steadily. Stop. Measure the height of the highest point of the pile above the original layer surface. Record: Push distance 2 cm, height ___ cm.
4. Push another 2 cm (4 cm total) and measure again. Continue in 2 cm steps to 12 cm or until the pile reaches the far wall. Photograph the side view at each step if your box is clear.
5. Make a line graph: push distance on the bottom (0 to 12 cm), pile height up the side. Draw the line through your points.
6. Study the side view. Find at least one fold and one place where a layer has been pushed up and over another (a thrust). Draw what you see and label it.
7. Measure the width of the pile at the end. Did the mountain grow only up, or out as well? Write a sentence comparing your graph to your prediction.
8. Repeat the whole experiment with eight thinner layers, keeping everything else the same. Does the thickness of the layers change the shape of the pile or the number of folds?

Tips

- Push slowly. A fast push throws flour instead of folding it.
- Keep the card pressed to the bottom of the tray so the layers are shoved forward, not slid under.
- If the layers only slide as a block, press the first flour layer down firmly so it grips the tray, as rock grips the crust beneath it.

Check your work

- I pushed in equal steps and measured the height at every step.
- I graphed height against push distance and described the shape of the line.
- I found and labeled a fold and a thrust in my model.

FIELD NOTEBOOK

1. Draw a cross-section of the India-Asia collision from memory: India on the left, Asia on the right, the thrust fault between, the Himalaya on top, and the thick crust under Tibet. Add an arrow with India's speed.
2. Make a timeline strip for the measurement of Everest: 1852 (Sikdar's calculation), 1856 (29,002 ft announced), 1865 (named), 1953 (first climbed by Hillary and Tenzing), 2020 (8,848.86 m). Write one sentence under each.
3. Draw the water cycle over the Himalaya: wet winds from the ocean, rain on the southern slopes, dry Tibet behind, and rivers carrying sediment to the sea.

> **From history.** Sir George Everest, the surveyor the mountain was named for, never saw it, and he objected to the honor. He pointed out that his name could not be written in Hindi and that local people could not pronounce it. The Royal Geographical Society named the peak after him anyway in 1865. On May 29, 1953, Edmund Hillary of New Zealand and Tenzing Norgay, a Sherpa of Nepal, became the first people to stand on the summit that Sikdar had computed a century before.

WORKED EXAMPLES

Example 1. The 1856 announcement gave the height of Peak XV as 29,002 feet. Convert this to meters (1 foot = 0.3048 m) and compare it with the 2020 figure of 8,848.86 m. By how many meters did the Victorian surveyors miss, and what percent of the mountain's height is that?

1. 29,002 ft × 0.3048 m/ft = 8,839.8 m, about 8,840 m.
2. Difference: 8,848.86 − 8,839.8 ≈ 9 m.
3. Percent: 9 ÷ 8,849 × 100 ≈ 0.1%.

Answer: About 8,840 m; the 1856 figure was low by about 9 m, roughly one tenth of one percent, measured from 150 km away. (Some of the difference is also snow depth and later changes in how sea level is defined.)

Example 2. GPS shows India moving north toward Asia at about 5 cm per year. How far has it moved since the 1852 survey (take 174 years)? How far would it move in a grandparent's lifetime of 80 years?

1. Since 1852: 5 cm/yr × 174 yr = 870 cm = 8.7 m.
2. In 80 years: 5 cm/yr × 80 yr = 400 cm = 4 m.
3. Most of that motion goes into squeezing the crust (folds and thrusts), not into lifting the summit straight up; Everest rises only a few millimeters a year.

Answer: About 8.7 m since 1852 and about 4 m in 80 years. The motion is slow but measurable, and it adds up.

Example 3. The earth's diameter is about 12,742 km and Everest is about 8.85 km high. On a globe 1 m (100 cm) across, how high would Everest be?

1. Find the scale: 100 cm on the globe stands for 12,742 km, so 1 km is 100 ÷ 12,742 cm ≈ 0.00785 cm.
2. Multiply: 8.85 km × 0.00785 cm/km ≈ 0.069 cm.
3. Convert: 0.069 cm ≈ 0.7 mm.

Answer: About 0.7 mm, less than the thickness of a coin. The highest mountain on earth is a scratch on a 1 m globe; the earth is very nearly a smooth sphere.

PRACTICE

1. EASY What kind of plate boundary is building the Himalaya, and which two pieces of crust are meeting there?

2. EASY Who worked out in 1852 that Peak XV was the highest mountain, and what height was announced in 1856?
3. EASY About how thick is the crust under the Tibetan Plateau, and how does that compare with ordinary continental crust?
4. MEDIUM Why does ocean crust sink under a continent at a convergent boundary, but one continent does not sink under another? What happens instead?
5. MEDIUM If Everest rises about 4 mm per year, how much would it rise in 250 years? Express your answer in meters.
6. MEDIUM Data reading. Official or widely used heights for Everest: 1856, 8,840 m (29,002 ft, by theodolite from the plains); 1955, 8,848 m (Indian survey); 1999, 8,850 m (American GPS survey, snow surface); 2005, 8,844.43 m (Chinese survey, rock surface without snow); 2020, 8,848.86 m (Nepal and China, GPS). (a) What is the range of the five values? (b) Which is the best explanation of the differences? (i) Everest grew 10 m between 1856 and 1999. (ii) The differences come mostly from different instruments and from measuring the rock top versus the snow top; a few millimeters of uplift per year adds less than 1 m over this time. (iii) The mountain shrank between 1999 and 2005. (iv) The surveys were careless.
7. MEDIUM Data reading. Suppose four GPS stations record these northward speeds relative to the far interior of Asia: Station A (southern India), 4.5 cm/yr; Station B (plains of Nepal), 3.5 cm/yr; Station C (southern Tibet, just north of the Himalaya), 1.5 cm/yr; Station D (northern Tibet), 0.3 cm/yr. Between which two stations is the crust being squeezed (shortened) the most? Explain how you know.
8. HARD Experiment design. Using the flour-and-cocoa collision box, design an experiment to find out whether damp layers fold differently from dry layers. State the question, the independent and dependent variables, two things to keep the same and what you will measure.
9. HARD The summit of Everest is limestone that formed under the sea, and the Bay of Bengal floor is covered with sediment thousands of meters thick. Explain in three or four sentences how these two facts fit together.
10. CHALLENGE Waugh waited four years before announcing the height of Peak XV because light bends as it passes through the air, which makes distant peaks look slightly higher than they are. Explain why measuring the same peak from six different stations helped the surveyors trust their answer, and name one other source of error they had to think about.

COMMON MISTAKES

- Thinking Everest grew by meters between surveys. The differences between measured heights come mainly from instruments and from snow versus rock; uplift is only a few millimeters a year.
- Picturing India sinking under Asia like an ocean plate. Both are continents; neither sinks easily, so the crust crumples and thickens instead.
- Thinking the highest mountains are huge compared with the earth. On a 1 m globe Everest would be less than 1 mm high; the earth is almost perfectly smooth at that

scale.

Make it a game · Surveyor's Chain. Choose a tall object outside, such as a tree or a pole, and do not go near it. From three different spots, each a measured number of paces away, hold a ruler at arm's length and record how many centimeters tall the object appears and how many paces away you stood. Multiply apparent height by paces for each spot; if the three products come out close together, your "survey" is consistent, as Waugh's six stations were. The player whose three products agree most closely wins the round. Then pace to the object and find its real height with a tape measure and a parent's help.

Scripture. "In his hand are the deep places of the earth: the strength of the hills is his also." (Psalm 95:4, KJV)

From the deep sediment of the Bay of Bengal to the summit of Everest, the whole conveyor of uplift and erosion is in God's hand. The strength that lifts the highest mountains belongs to Him.

Practice answers

1. A convergent boundary where two continents meet: India (moving north) and Asia.
2. Radhanath Sikdar, a mathematician of the Great Trigonometrical Survey of India; 29,002 feet (about 8,840 m).
3. About 70 km, roughly twice the normal thickness of about 35 km.
4. Ocean crust is thin and dense, so it sinks. Continental crust is thick and light, so when two continents meet neither sinks easily; the crust between them crumples, folds, breaks along thrust faults, and thickens into mountains.
5. 4 mm × 250 = 1,000 mm = 1 m.
6. (a) 8,850 − 8,840 = 10 m. (b) (ii). At a few mm per year, uplift since 1856 is well under 1 m, far less than the 10 m range, and the 2005 figure is lower because it left off the snow cap.
7. Between B and C: the speed drops by 2.0 cm/yr across that stretch (3.5 to 1.5), more than between A and B (1.0) or C and D (1.2). Where the ground on the south side moves faster than the ground on the north side, the crust between them is being shortened, and the biggest drop lies across the Himalaya.
8. Question: Do damp flour layers make taller or fewer folds than dry layers when pushed the same distance? Independent variable: dampness of the layers (dry versus lightly misted). Dependent variable: pile height at a fixed push distance (or number of folds). Keep the same: number and thickness of layers, push distance, pushing speed, tray and card. Measure the pile height after each 2 cm step and count folds in the side view; repeat each condition at least twice.
9. Layers that formed on a seafloor were folded, thrust and lifted by the collision of India with Asia until some of them stand at the summit of Everest. Heavy rain, glaciers and landslides break rock from the rising mountains, and the Ganges and Brahmaputra carry the sediment to the Bay of Bengal. The thick sediment on the bay floor is the ground-up Himalaya. The mountains are a conveyor: uplift raises seafloor rock, and erosion carries it back to the sea.
10. Each station gave an independent height; if all six agreed closely after correcting for the bending of light, the surveyors could be confident that no single mistake or bad day of air was

fooling them, and the average was more reliable than any one measurement. Other sources of error: the exact distance to the peak, the height of the survey station above sea level, the depth of snow on the summit, and the pull of the mountains’ own mass on the surveyors’ plumb lines.

5.4 Fossil Seashells on Mountaintops (Psalm 104:8)

OBJECTIVES

- Tell how Nicolas Steno compared a shark's teeth with tongue stones in 1666 and concluded that fossils are the remains of living things buried in layers that were once soft.
- Describe the marine fossils found in limestone at the summit of Mount Everest and on other high mountains, and explain what both the mainstream reading and the Flood reading say about how they got there.
- Count and compare fossils in a sample, use a proportion to estimate size from a tooth, and read Psalm 104:6–9 as a description of waters standing above the mountains and then draining away.

Warm-up. Hold a seashell, or look at a picture of one, and then look at the highest hill you can see from your window. Write two sentences: one giving your best guess of how a shell could end up buried in rock at the top of a mountain, and one naming what you would want to measure or look at to test your guess. Keep the page; you will come back to it at the end of the lesson.

Video. Coming soon. Marine fossils on mountaintops, the limestone at the summit of Everest, Nicolas Steno and the shark's teeth (glossopetrae), and how fossils form in layers; look for Smithsonian, USGS, National Park Service Grand Canyon fossil pages, SciShow Kids, Homeschool Pop (Alternate) and Moody Science classics.

KEY TERMS

fossil
The remains or traces of a living thing preserved in rock: a shell, a bone, a tooth, a footprint or a leaf print.

marine fossil
A fossil of something that lived in the sea, such as a clam, a coral, a sea lily or a shark.

limestone
A sedimentary rock made mostly of calcium carbonate, often built from shells, corals and other sea-creature remains.

crinoid
A sea lily: a sea animal related to starfish, with a stalk made of stacked button-like pieces. Crinoid pieces are among the most common fossils in limestone.

brachiopod
A sea animal with two shells, like a clam but built differently, very common as a fossil in limestone.

tongue stones (glossopetrae)

Triangular stones found in the rocks of Malta and Italy that people once thought fell from the sky or grew in the ground. Steno showed they are fossil shark teeth.

CORE IDEAS

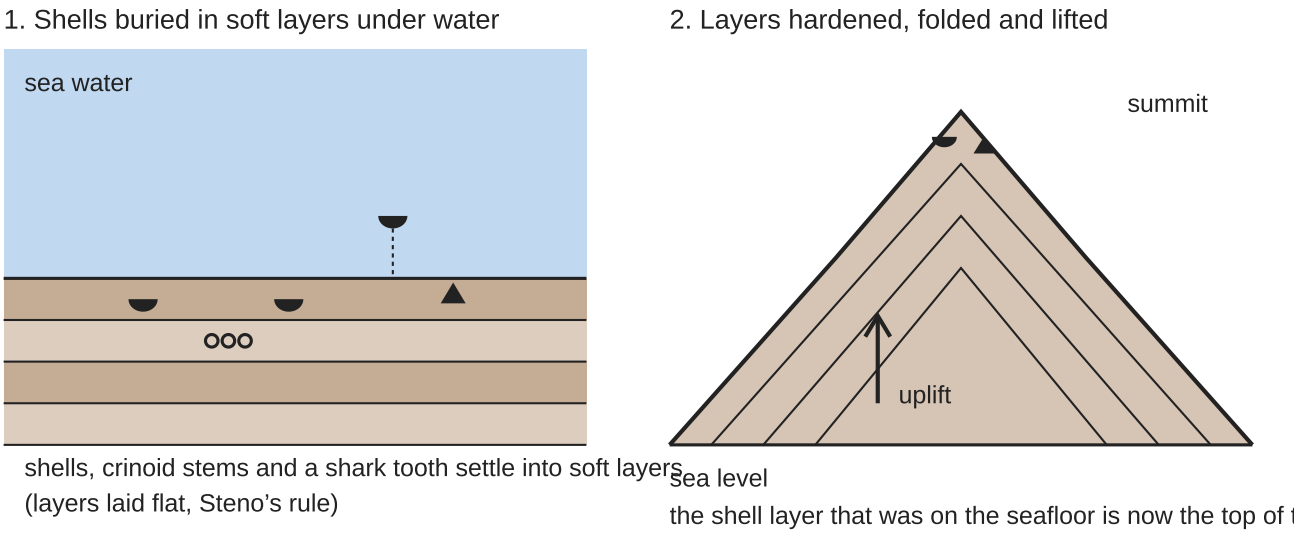
The story. In October 1666, fishermen near Livorno on the coast of Tuscany caught an enormous shark. The Grand Duke of Tuscany, Ferdinando II, ordered its head sent to Florence, to a young Danish doctor at his court named Nicolas Steno, who was known for his skill with the dissecting knife. Steno opened the great mouth and studied the rows of triangular teeth. He had seen that shape before. All over Malta and Italy, people dug up triangular stones from the rock and called them **glossopetrae**, tongue stones. Some said they fell from the sky during eclipses; others said they grew in the ground; many carried them as charms against poison. Steno laid a tongue stone beside a tooth from the shark. Same shape, same serrated edge, same root. He concluded that tongue stones were shark teeth, turned to stone, and that the rock they lay in had once been soft mud on a seafloor. He published the comparison in 1667 with an engraving of the shark's head. Then he asked the next question. If sea creatures lie buried in the hills of Tuscany, far from the sea and high above it, how did they get there?

How they figured it out. Steno's answer, published in 1669, was the foundation of the science of rock layers. A tooth or shell inside solid rock, he argued, must have been there before the rock hardened, because a hard shell cannot push its way into stone. So the layer was soft when the shell was buried, and it was laid down flat under water. Later it hardened, and later still something lifted or tilted it. That is Steno's rule from Lesson 5.1 applied to fossils. Later naturalists found marine fossils almost everywhere they looked on high ground. In 1835 Charles Darwin found fossil seashells high in the Andes of South America. The rim of the Grand Canyon, more than 2,000 m above sea level, is limestone full of brachiopods, crinoids and sponges. And at the top of the world, the gray band of rock at the summit of Mount Everest is limestone; climbers have carried pieces down, and under the microscope it holds stacked **crinoid** stems, bits of trilobites and small shells. The highest point on earth is made of seafloor.

The big idea. Everyone who has studied the question agrees on three things. The shells are real animals, not stones that happen to look like shells. The layers that hold them were laid down under water, flat and soft. And the layers were raised to their present height afterward, by the folding, faulting and crustal thickening you studied in Lessons 5.1 to 5.3. The disagreement is about how long each step took, and that question is handled in the Thinking About Time box. Textbooks say the Everest limestone formed on a shallow seafloor and was raised by the slow collision of India with Asia over a very long time. Many Christian geologists read the same rock in the light of Genesis 7 and Psalm 104: the waters of the Flood "prevailed exceedingly" and covered the high hills, laying down sea-creature layers across the continents, and then the mountains rose and the valleys sank as the waters drained to the place God had set for them. Psalm 104:8 in the King James Version reads, "They go up by the mountains; they go down by the valleys," and these readers take it as the plainest description in Scripture of how seafloor became summit.

Try it and see. A fossil is a buried thing, and burial is something you can watch. Fill a tall jar one third full with sand, mud and fine gravel, drop in a few small shells, add water to the top, cap it and shake it hard. Set it down and watch. The coarse grains settle first, then the sand, then the mud, in flat layers, and the shells are buried inside them within minutes. Steno would have recognized every step. Then make a fossil of your own: press a shell into a flat pad of clay, lift it out, and you have a mold; fill the mold with plaster and you have a cast. Most fossil shells in limestone are molds and casts like these, where the original shell dissolved and left its shape behind.

God's handiwork. Steno was a careful observer and a devout Christian; he became a bishop later in life, and he once wrote that what we see is beautiful, what we know is more beautiful, and what we do not yet know is most beautiful of all. He saw no contest between the Bible and the shark's tooth. The tooth said: this rock was once soft mud under the sea. The Scriptures said: "the waters stood above the mountains" and then "they go up by the mountains; they go down by the valleys." Go back to the sentences you wrote in the warm-up. You guessed, and then you named something to measure. That is exactly what Steno did in 1666, and it is what a Christian naturalist still does: look closely at the made world, measure honestly, and read the Maker's Word with the same care.



Seafloor to summit. Shells are buried in soft layers under water (left); the hardened layers are later folded, faulted and lifted (right). Both readings in the Thinking About Time box agree on these two steps and differ on the time between them.

⏳ Thinking About Time

What the sign says. The textbook says the gray limestone at the summit of Everest formed on a warm, shallow seafloor about 470 million years ago, in the period museums call the Ordovician, long before there were fish on land or trees, and that it was carried to the top of the world over the last 50 million years as India pushed slowly into Asia at a few centimeters per year. Museum signs beside Grand Canyon rim fossils give similar numbers, around 270 million years, for the Kaibab Limestone.

What we observe. We observe limestone at 8,849 m holding crinoid stems, trilobite pieces and small shells of sea animals, with the layers lying in order and bent. We observe sea-creature limestone on the rim of the Grand Canyon, in the Alps, in the Andes and in the Appalachians. We measure, with GPS, India moving north about 4 to 5 cm a year and the Himalaya rising a few millimeters a year. We do not observe the time between the burial of the shells and the raising of the rock; that is calculated from assumptions about rates and starting conditions.

How Christians read it. Christians who hold to a recent creation read these layers as laid down during the Flood year, when “all the high hills, that were under the whole heaven, were covered” (Genesis 7:19), burying sea creatures by the billions in sediment spread across the continents. They read Psalm 104:8 as the mountains rising and the valleys sinking while the waters drained, with the movement of the plates far faster during the Flood than the few centimeters a year we measure today (Lesson 2.4). In their reading the slow rates measured now are the tail end of a catastrophe, not the whole story. The mainstream reading stretches today’s rates back over a very long time. Both readings start from the same tooth, shell and layer; they differ on the time, and a careful student can state both without mocking either.

Try it. Shake a jar of sand, mud, gravel and small shells with water and time how long it takes for the shells to be buried in flat layers. Then write down one thing the jar can show you and one thing it cannot.

Psalm 104:8

PICTURE STUDY



Head of a Shark, with Its Teeth and Two Tongue Stones (plate from Canis carchariae dissectum caput), Engraver unknown, for Nicolas Steno, 1667 (this copy from a 1669 printing) · Engraving on paper, printed in Florence · Published in Steno's Elementorum myologiae specimen; this copy in the Biblioteca Europea di Informazione e Cultura, Milan; other copies in major libraries

This is the picture Steno published with his report on the shark of 1666. The head fills the plate, its mouth open so that the reader can count the rows of teeth. Below it the engraver drew two teeth by themselves, large, exactly the shape of the tongue stones that people dug from the rocks of Malta.

The engraving is an argument. Steno did not have to write a long chapter; he put the living tooth and the stone tooth on one page and let the reader compare them. Scientific drawings since then have done the same work: showing, side by side, the things that the scientist wants you to compare for yourself.

Look closely

- Count how many rows of teeth you can see in the shark's mouth. Sharks grow new teeth from behind and shed old ones, which is why so many fossil shark teeth are found.
- Look at the two teeth drawn below. Find the serrated edge and the root. Are the two teeth the same size and shape?
- The engraver drew the head from the front rather than the side. What does that view show that a side view would hide?
- Is there anything in the picture that shows how big the shark really was? What could the engraver have added for scale?

Talk about it

1. Steno compared shape, edge and root. Why is comparing several features better evidence than comparing just one?
2. People had called tongue stones charms, sky stones and things that grew in the ground. What single observation made those ideas hard to keep?
3. What question did the shark's tooth answer, and what new question did it raise about the hills of Tuscany?

> **Safety first.** If you make a plaster cast, mix plaster outdoors or over newspaper, do not put your hands into setting plaster (it gets hot as it hardens), and never pour leftover plaster down a drain.

EXPERIMENT: BURIED IN LAYERS: DOES SHELL SIZE CHANGE WHERE A SHELL IS BURIED?

Fossils are buried things, and burial can be watched in a jar. You will shake sand, mud, gravel and shells of two sizes in water, let everything settle, and record where the shells come to rest in the layers. Then you will make a mold and cast of a shell to see how a fossil shape is preserved after the shell itself is gone.

Question: When sediment and shells settle out of water together, do large shells end up in a different layer from small shells? Prediction: write yours before you shake the jar.

You will need

- A tall clear jar with a tight lid (a 1 L canning jar or a clean pasta-sauce jar)
- A cup each of coarse sand, fine sand or potting soil (for mud) and small aquarium gravel
- Six small shells (about 1 cm) and six larger shells (about 3 cm), or pasta shells of two sizes
- Water, a ruler, a stopwatch, a notebook and a pencil
- For the cast: modeling clay, a small cup of plaster of Paris, water and a disposable cup and spoon

Steps

1. Put the gravel, sand and soil into the jar in any order, about one third full in all. Add the twelve shells. Fill the jar with water to about 3 cm from the top and cap it tightly.
2. Shake the jar hard for 20 seconds, set it on the table and start the stopwatch. Do not touch it. Watch and write down the time when the gravel has settled, the time when the sand has settled, and the time when the water above is clear enough to see through.
3. When the water is clear, measure the thickness of each layer from the bottom with the ruler. Draw the jar in your notebook with the layers to scale and label them.
4. Find every shell you can see through the glass. For each, record its size (small or large) and the height of its resting place above the bottom of the jar. Make a table: Shell, Size, Height (cm), Layer.

5. Repeat the shake and settle two more times, recording the same things. Compute the average resting height for small shells and for large shells across all three trials.
6. Write your conclusion: Did size change where the shells were buried? Were the shells buried in minutes or hours? How is this like, and unlike, the burial of a shell on a real seafloor or in a flood?
7. Now make a fossil mold: flatten a pad of clay about 2 cm thick, press a shell firmly into it, and lift the shell straight out. Mix plaster in the disposable cup until it is like pancake batter, pour it into the mold and let it set for an hour. Peel off the clay. Compare your cast with the real shell and with a photograph of a fossil brachiopod or clam.

Tips

- Hold the jar still after shaking; even a bump will blur the layers.
- If the water stays cloudy a long time, that is the finest mud still settling. Note the time; fine mud takes the longest.
- For the mold, dust the clay lightly with flour so the shell lifts out cleanly.

Check your work

- I timed the settling, measured the layers and drew the jar to scale.
- I recorded the resting height of every shell for three trials and compared small and large.
- I made a mold and a cast and can explain which one a fossil hunter usually finds.

FIELD NOTEBOOK

1. Draw a shark’s tooth and a tongue stone side by side, as Steno did, and label the three features he compared: shape, serrated edge and root.
2. Draw a cross-section from seafloor to summit in two panels: flat soft layers with shells under water, then the same layers bent and lifted into a mountain with the shell layer on top.
3. Copy Psalm 104:6–9 into your notebook and underline every word that describes water moving or land rising or sinking.

> **From history.** Steno’s 1669 book was only meant to be a preview, which is why its title begins with the word Prodromus, meaning a forerunner. He never wrote the full book. In 1675 he was ordained a priest, and in 1677 a bishop, and he spent the rest of his short life serving poor congregations in northern Germany, giving away nearly everything he owned. The three rules of rock layers in his little preview, that layers are laid down in order, laid flat, and spread out sideways until something stops them, are still the first things every geology student learns.

WORKED EXAMPLES

Example 1. Suppose the shark Steno dissected was about 3 m long and its largest teeth were 4 cm tall. A tongue stone dug from the rock is 10 cm tall. If a shark's length is in proportion to its tooth height, about how long was the shark that shed the tongue stone?

1. Find the ratio of the tooth heights: 10 cm ÷ 4 cm = 2.5.
2. Multiply the known shark's length by that ratio: 3 m × 2.5 = 7.5 m.
3. This is an estimate. It assumes the fossil shark was built in the same proportions as the living one, which is the same kind of assumption scientists make when they estimate a dinosaur's length from one bone.

Answer: About 7.5 m long, two and a half times the length of the shark from Livorno.

Example 2. A slab of rim limestone 20 cm by 10 cm holds 30 fossil fragments (brachiopods and crinoid pieces). How many fossils is that per square centimeter? About how many would you expect in a 1 m by 1 m patch of the same layer?

1. Area of the slab: 20 cm × 10 cm = 200 cm^2.
2. Fossils per cm^2: 30 ÷ 200 = 0.15 per cm^2.
3. A 1 m by 1 m patch is 100 cm × 100 cm = 10,000 cm^2. Multiply: 0.15 × 10,000 = 1,500.

Answer: 0.15 fossils per cm^2, or about 1,500 in a square meter of the layer, if the slab is typical. Counting a small sample and scaling up is how geologists estimate how many creatures a layer holds.

Example 3. Suppose a mountain summit is being lifted at 10 mm per year while weather and ice remove rock from the top at 6 mm per year. What is the net rise per year? How much net rise is that in 500 years, in meters?

1. Net rise = uplift − erosion = 10 mm − 6 mm = 4 mm per year.
2. In 500 years: 4 mm × 500 = 2,000 mm.
3. Convert: 2,000 mm = 2 m.

Answer: A net rise of 4 mm per year, or 2 m in 500 years. Today's rates are small; the Thinking About Time box explains why the two readings disagree about whether they were always this small.

PRACTICE

1. EASY What are tongue stones, and what did Steno show them to be?

2. EASY Name two kinds of marine fossils found in the limestone at the summit of Everest.
3. EASY Why did Steno conclude that a layer holding a shell must have been soft when the shell was buried?
4. MEDIUM List the three things that both the mainstream reading and the Flood reading agree on about seashells on mountaintops. Then state in one sentence what they disagree about.
5. MEDIUM A fossil shark tooth is 6 cm tall. A living shark 2 m long has teeth 2 cm tall. Using a proportion, estimate the length of the fossil shark.
6. MEDIUM Data reading. A student compared fossil counts from three limestone samples of equal size: Sample A, Grand Canyon rim at 2,100 m: 18 brachiopods, 12 crinoid pieces, 5 sponges. Sample B, Himalayan ridge at 5,000 m: 20 crinoid pieces, 3 trilobite pieces, 6 brachiopods. Sample C, Everest summit at 8,849 m: 7 crinoid pieces, 4 shell fragments, 0 sponges. Which conclusion is best supported? (a) Marine fossils are found only below 3,000 m. (b) Higher samples have more fossils. (c) Marine fossils occur in limestone at all three elevations, so elevation alone does not decide whether sea fossils are present. (d) Crinoids live only on mountains.
7. MEDIUM Data reading. In a settling-jar experiment, a student recorded the resting heights of shells above the jar bottom. Small shells: 2.1, 2.4, 1.9, 2.3 cm. Large shells: 1.2, 1.5, 1.1, 1.4 cm. The gravel layer runs 0 to 1.6 cm and the sand layer 1.6 to 3.0 cm. (a) Find the average height for each size. (b) In which layer did each size come to rest? (c) Suggest a reason.
8. HARD Experiment design. You want to find out whether shells settle in a different layer when the sediment is mostly mud instead of mostly sand. Describe the independent and dependent variables, what you would keep the same, how many trials you would run, and one thing a jar cannot tell you about a real seafloor.
9. HARD Read Psalm 104:6–9. Write one sentence for each verse telling what the water or the land is doing, in your own words.
10. CHALLENGE Explain in five or six sentences how a crinoid that lived in the sea could now be part of the rock at the summit of Everest, giving the steps that all geologists agree on and then the point where the two readings part ways.

COMMON MISTAKES

- Thinking fossil shells on a mountain mean the animals lived on the mountain. The animals lived in the sea; the seafloor layers were raised afterward.
- Thinking a fossil is the original shell unchanged. Most fossil shells are molds, casts or shells replaced by minerals; the shape is preserved, not the living material.
- Treating the time between burial and uplift as something you can read off the rock. Burial and uplift are observed in the layers; the time between them is an interpretation that depends on assumptions about rates.

> **Make it a game · Steno's Table.** A parent lays out six objects, some natural and some made: a seashell, a pebble, a chicken bone, a bottle cap, a leaf, a tooth-shaped triangle cut from cardboard. You have one minute to sort them into "was once part of a living

thing” and “never alive,” and for each one say the single feature that gave it away, as Steno named the root and serrated edge. One point per correct sort, one per good feature. Then switch: you set the table and the parent sorts. Play three rounds.

Scripture. “Thou coveredst it with the deep as with a garment: the waters stood above the mountains. At thy rebuke they fled; at the voice of thy thunder they hasted away. They go up by the mountains; they go down by the valleys unto the place which thou hast founded for them. Thou hast set a bound that they may not pass over; that they turn not again to cover the earth.” (Psalm 104:6–9, KJV)

The psalm describes waters standing above the mountains, then fleeing as mountains rise and valleys sink, and a promise that the earth will not be covered again (compare Genesis 9:11). Christians who read the seashell layers as Flood deposits see in these verses the raising of seafloor to summit by the hand of God.

Practice answers

1. Triangular stones dug from the rocks of Malta and Italy; Steno showed they are fossil shark teeth.
2. Any two of: crinoid (sea lily) stems, trilobite pieces, small shells (such as brachiopods).
3. A hard shell cannot push its way into solid rock, so the shell must have been there before the layer hardened; the layer was soft sediment when the shell was buried.
4. Both agree that the shells are real animals, that the layers were laid down flat and soft under water, and that the layers were raised to their present height afterward. They disagree about how much time each step took.
5. 6 ÷ 2 = 3; 2 m × 3 = 6 m.
6. (c). All three samples hold marine fossils. (a) is contradicted by B and C; (b) is wrong because Sample C has the fewest; (d) confuses where fossils are found with where the animals lived (in the sea).
7. (a) Small: (2.1 + 2.4 + 1.9 + 2.3) ÷ 4 = 2.2 cm. Large: (1.2 + 1.5 + 1.1 + 1.4) ÷ 4 = 1.3 cm. (b) Large shells rested in the gravel layer; small shells in the sand layer. (c) Heavier, larger shells sink faster and settle with the gravel; small, light shells settle later with the sand.
8. Independent variable: the kind of sediment (mostly mud versus mostly sand). Dependent variable: the resting height or layer of the shells. Keep the same: the jar, amount of water, number and size of shells, shaking time, settling time. Run at least three trials of each and average. A jar cannot show the effect of currents, the size of a real sea, or how long real layers waited before hardening.
9. Verse 6: God covered the earth with the deep, and the waters stood above the mountains. Verse 7: at God’s rebuke and the voice of His thunder the waters fled and hurried away. Verse 8: the mountains went up and the valleys went down to the place God founded for the waters. Verse 9: God set a boundary the waters may not pass, so they will not again cover the earth.
10. The crinoid died and its stem pieces were buried in soft lime mud on a seafloor, along with shells and trilobite pieces. The mud hardened into limestone with the fossils inside, as Steno showed must happen after burial. The push of India into Asia folded, faulted and thickened the crust, and thrust faults carried the limestone layers upward until some of them stand at the summit, 8,849 m above the sea. Everyone agrees on burial, hardening and uplift. The readings part ways on time: textbooks say the burial happened about 470 million years ago

and the uplift took tens of millions of years at today’s slow rates, while Flood geologists say the burial happened in the Flood year, when the waters covered the high hills, and the uplift happened rapidly as the waters drained, with today’s rates being only the slow tail end.

Unit 5 review

Answer each question. Show your work for calculations, use complete sentences for explanations, and label every part of your diagram. The test is worth 60 points.

1. (4 pts) Multiple choice. Which kind of stress makes a normal fault? (a) compression (b) tension (c) shear (d) heat. In a normal fault, which block moves down?
2. (4 pts) Multiple choice. The Wasatch Range, the Sierra Nevada and the Tetons are mainly (a) volcanic mountains (b) folded mountains (c) fault-block mountains (d) upwarped domes. Name one range that is mainly folded.
3. (6 pts) Diagram. Draw a cross-section with four rock layers folded into one anticline and one syncline, and cut by one normal fault. Label the anticline, the syncline, the hanging wall and the footwall, and draw arrows showing which way the hanging wall moved.
4. (5 pts) Explain in two or three sentences how G. K. Gilbert knew in 1883 that the Wasatch fault had moved recently, and what he told the people of Salt Lake City.
5. (5 pts) Name the four things that decide whether rock bends or breaks, and for each one say which direction (more or less) makes rock more likely to bend.
6. (6 pts) A folded layer measures 150 m along its curve and the straight-line distance between its ends is 120 m. Find the shortening in meters and as a percent. Then explain why the length along the curve is used as the original length.
7. (6 pts) The layers at Sideling Hill are bent into a U without a crumbled zone. State what the textbook says about when and how the layers bent, and what many Christian geologists say. Then write one sentence on what both readings agree about.
8. (5 pts) Multiple choice. The Himalaya are being built at (a) a divergent boundary where plates pull apart (b) a transform boundary where plates slide past (c) a convergent boundary where two continents collide (d) a hot spot. About how thick is the crust under Tibet, and why?
9. (6 pts) India moves north at about 5 cm per year. (a) How far does it move in 60 years, in meters? (b) The 1856 height of Everest was 29,002 feet. Convert it to meters (1 ft = 0.3048 m) and compare it with 8,848.86 m.
10. (5 pts) Data reading. Heights measured for Everest: 1856, 8,840 m; 1955, 8,848 m; 1999, 8,850 m (snow top); 2005, 8,844 m (rock top); 2020, 8,849 m. A student says the mountain grew 10 m between 1856 and 1999. Using the fact that uplift is a few millimeters a year, explain whether the data support that claim.
11. (4 pts) What did Steno compare in 1666, and what did he conclude about tongue stones and about the rock that held them?
12. (4 pts) Written explanation. Marine fossils are found in limestone at the summit of Everest. Write three or four sentences explaining the steps all geologists agree on, the point where the mainstream and Flood readings differ, and what Psalm 104:8 says.

Unit project: my mountain builder’s field book

Put together a field book that shows how mountains are made and how you measured it. Include: photographs or drawings of your clay folds and cut fault from Lesson 5.1 with the

hanging wall, footwall, anticline and syncline labeled and the shortening worked out as a percent; your candy-bar data table and bar graph from Lesson 5.2 with a paragraph on the four factors; your collision-box graph of pile height against push distance from Lesson 5.3 with a labeled drawing of a fold and a thrust in the model; and your settling-jar table and your plaster cast from Lesson 5.4 with a drawing of Steno's tooth comparison.

Finish with a one-page Thinking About Time summary in your own words for seashells on mountaintops: what the sign says, what we observe, and how Christians read it, with Psalm 104:6–9 copied out and one sentence on what the Himalaya teach you about the strength of the hills being God's.

- **Accuracy**: Folds, faults, stresses, rates and conversions are correct, and every diagram is labeled with the right terms.
- **Records**: Data tables and graphs from all four experiments are the student's own, complete, dated and averaged where needed.
- **Explanation**: The Thinking About Time summary states the museum claim fairly, names what is observed, and gives the creation reading clearly without mocking either side.
- **Care**: The field book is neat, the drawings are clear, and the cast and photographs are mounted or described so a reader can follow the work.

Answer key

1. (b) tension. The hanging wall moves down.
2. (c) fault-block mountains. Folded: the Appalachians, the Alps or the Himalaya.
3. The drawing should show layers arched up (anticline) and down (syncline), a sloping fault cutting them with the layers offset across it, the block above the fault surface labeled hanging wall with an arrow pointing down, and the block below labeled footwall.
4. He found fresh fault scarps a few meters high cutting across young gravel fans at the foot of the range; because the scarps cut the fans, the fault movement had to be younger than the fans, so it was recent. He warned the city in an open letter that the fault would move again and that they should build for earthquakes.
5. Temperature (warmer bends more), confining pressure (more pressure bends more), strain rate (slower pushing bends more), and the material or its softness (wetter, softer or unhardened sediment bends more).
6. 150 − 120 = 30 m; 30 ÷ 150 × 100 = 20%. The layer was laid down flat, so its original length is its full length, which is now the length along the curve.
7. Textbook: the layers hardened into rock, were buried deep where they were warm and under confining pressure, and were bent slowly over a very long time (the textbook gives millions of years) without breaking. Christian geologists who hold to the Flood: the layers were laid down quickly in the Flood year and were still wet and soft when the mountains rose as the waters drained, so they bent like damp sand. Both agree the layers were laid down flat and were bent afterward by compression.
8. (c). About 70 km, roughly twice normal, because the crust has been folded, thrust and stacked (crustal thickening) as India pushes into Asia.
9. (a) 5 × 60 = 300 cm = 3 m. (b) 29,002 × 0.3048 ≈ 8,840 m, about 9 m less than the 2020 figure.

10. No. At a few mm per year, uplift over 143 years is well under 1 m, so the 10 m difference must come mostly from better instruments and from measuring snow versus rock. The 2005 rock-top figure being lower than the 1999 snow-top figure shows this.
11. He compared the teeth of a freshly caught shark with tongue stones dug from rock (same shape, serrated edge and root). He concluded that tongue stones are fossil shark teeth and that the rock holding them was soft seafloor mud when the teeth were buried.
12. All agree the shells are real sea animals buried in soft layers under water, that the layers hardened, and that they were lifted afterward by folding, faulting and crustal thickening. The readings differ on time: the textbook says burial happened hundreds of millions of years ago and uplift took tens of millions of years at today’s rates, while Flood geologists say the burial happened in the Flood year and the uplift was rapid as the waters drained. Psalm 104:8 says, “They go up by the mountains; they go down by the valleys unto the place which thou hast founded for them,” which these readers take as the mountains rising and valleys sinking as the Flood waters drained.

UNIT 6

Erosion and Deposition

Water, wind and ice are always at work on the land, wearing rock away in one place and laying it down in another. In this unit you will learn to read that work the way geologists do: as a rate, something measured in meters per year or cubic meters per second, and then to ask the harder question of whether the rate you measured today was the same in the past. You will see a waterfall walk upstream, a delta build out into the sea, a dune march across the desert, and canyons cut in days and years rather than ages.

You will meet Charles Lyell and James Hall surveying the crest of Niagara Falls in 1841 and 1842; Herodotus reading the black mud of the Nile around 450 B.C. and naming the first delta; Ralph Bagnold driving a Ford across the Libyan Desert and then measuring hopping sand grains in a wind tunnel in London; and the geologists who surveyed Canyon Lake Gorge in Texas after a six-week flood in 2002 cut a bedrock canyon 2.2 km long. You will build a model waterfall with a hard cap, a delta in a tray, a wind tunnel in a box and a flood on a sand slope, and you will measure, graph and record every one.

Two lessons carry a Thinking About Time box, at Niagara and at the rapid canyons. Erosion is where ages are most often read from rates, so this is the unit where you learn the habit for life: state what the sign says, state what has actually been observed, and give the reading of Christians who hold to a recent creation and the Flood, remembering that every age built on a rate rests on an assumption about the past.

BEFORE YOU BEGIN

- Knows the difference between weathering, erosion and deposition and can name water, wind and ice as agents of erosion.
- Knows the rock cycle well enough to recognize sedimentary layers and understand that sediment hardens into rock (Unit 5).
- Can divide to find a rate, convert among millimeters, centimeters, meters and kilometers, and work with large numbers such as millions of cubic meters.
- Can read a data table and draw a line graph or bar graph from measurements, and can name independent and dependent variables in a simple experiment.

MASTERY CHECKLIST

- I can explain how a hard cap rock over soft rock makes a waterfall keep its height and retreat upstream, and I can compute a retreat rate from survey data.
- I can explain how a delta forms, name its topset, foreset and bottomset beds and its distributaries, and explain sorting of gravel, sand, silt and clay.
- I can describe saltation, suspension and creep, sketch a dune with its windward slope and slip face, and use the cube rule to compare how much sand a gale moves against a breeze.

- I can tell how Canyon Lake Gorge was cut in days and the Mount St. Helens canyons in a few years, name plucking, abrasion and hydraulic action, and explain why a canyon's depth does not by itself tell its age.
- I can compute an erosion or deposition rate and then state clearly the assumptions behind any age built from it.
- I can state what a sign says about the age of a gorge or canyon, what is actually observed, and how Christians who hold to a recent creation read it, without mocking either side.

OPTIONAL BOOKS AND RESOURCES

- **U.S. Geological Survey (USGS)** (https://www.usgs.gov/): Free. Search the site for Mount St. Helens 1980 and for the Cascades Volcano Observatory photo archive to see the debris avalanche, the pumice plain and the channels cut in 1982. The USGS Water Science School pages on sediment and streamflow fit Lessons 6.2 and 6.4.
- **NASA Earth Observatory** (https://earthobservatory.nasa.gov/): Free. Search for the Nile Delta, the Mississippi River Delta, the Wax Lake Delta and sand dunes to see from space the shapes you draw in Lessons 6.2 and 6.3. Read any dates on the pages as the source's claim and talk through the Thinking About Time boxes.
- **Herodotus, *An Account of Egypt* (Project Gutenberg)** (https://www.gutenberg.org/): Free. Search Project Gutenberg for Herodotus and open the Macaulay translation of Book II, An Account of Egypt. A parent can read aloud the short passages near the beginning where Herodotus reasons that the Delta is the river's deposit (Lesson 6.2).

6.1 Niagara Falls Retreats: Lyell and Hall Measure a Waterfall, 1841–1842 ★

OBJECTIVES

- Describe how a hard cap rock over soft rock makes a waterfall keep its height and retreat upstream, using Niagara's dolostone and shale as the example.
- Compute an erosion rate from survey data (distance divided by time) and use it to estimate how long a gorge took to form, stating the assumptions.
- Explain why the retreat rate at Niagara has not stayed constant and what that means for any age built on a rate.

Warm-up. Stand a hard cracker on two sugar cubes like a little table. With a spoon, drip water onto one cube, a few drops at a time, until it crumbles. What happens to the cracker above it? Write one sentence predicting how this might be like a waterfall whose top layer is hard rock and whose bottom layer is soft.

Video. Coming soon. Niagara Falls erosion and retreat, cap rock and undercutting, the 1969 dewatering of the American Falls, how waterfalls form; search USGS, Niagara Parks, Smithsonian, PBS and nature-documentary channels, SciShow Kids and Homeschool Pop (Alternate).

KEY TERMS

erosion
The wearing away and carrying off of rock and soil by moving water, wind or ice.

deposition
The laying down of eroded material in a new place when the water, wind or ice that carried it slows down.

cap rock
A hard layer of rock lying on top of softer layers. At Niagara the cap is dolostone and the softer layers are shale and sandstone.

undercutting
The eating away of soft rock at the base of a cliff so that the harder rock above is left hanging and eventually breaks off.

plunge pool
The deep basin at the foot of a waterfall, drilled by the falling water and the stones it churns.

gorge
A deep, steep-walled valley cut by a river. The Niagara Gorge is the 11 km trench the falls left behind as they retreated.

CORE IDEAS

The story. In the summer of 1841 Charles Lyell, the best-known geologist in Britain, came to Niagara Falls with James Hall, the state geologist of New York. Travelers had been writing about the falls for a century and a half, but Lyell had come to ask a question the travelers had not: how fast was the falls moving? For the falls does move. Every old resident Lyell talked with said the same thing: within living memory the brink had crept upstream. One told him that in forty years the Horseshoe Falls had retreated about 45 m, more than a meter a year. Lyell wrote the figure down, but he did not trust a memory to carry a measurement. The next year, 1842, Hall did what no one had done before. He surveyed the crest line of both falls with instruments and set fixed marks on the shore, so that anyone who came after could survey again and compare. That survey was the first step in turning a traveler's wonder into a measured rate.

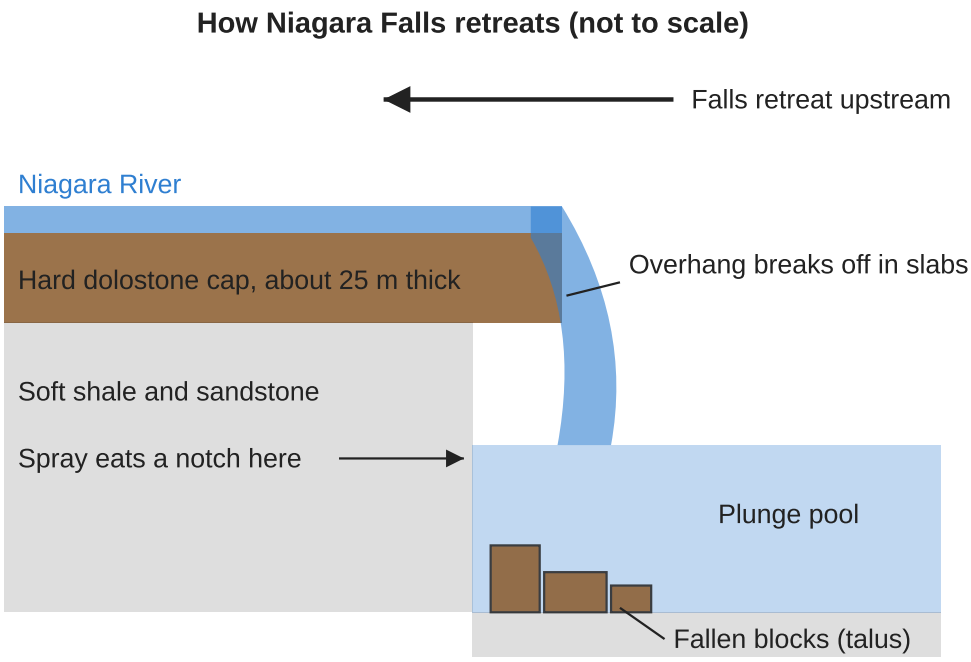
How they figured it out. The Niagara River carries the water of four Great Lakes from Lake Erie to Lake Ontario, dropping about 99 m in 58 km, and more than half of that drop happens at the falls. The Horseshoe Falls, on the Canadian side, is about 57 m high and roughly 670 m along its curving crest and takes about nine tenths of the water; the American Falls is narrower and takes the rest. The cliff the river pours over is a sandwich. On top lies a hard gray layer of **dolostone**, the Lockport, about 25 m thick. Beneath it lie softer shales and sandstones that crumble when they are wet. The falling water and the endless spray eat away these soft lower layers and hollow a cave at the base of the cliff. The hard cap is left hanging over empty air. When the overhang grows too long it breaks off in great slabs, which pile up at the foot of the falls and are slowly ground away in the plunge pool, a basin nearly as deep as the falls is high. Then the whole process begins again a few meters upstream. This is **undercutting**, and it is why a waterfall does not wear down into a gentle slope but keeps its height and walks backward. Downstream the river runs through the gorge the falls have left behind: 11 km of steep walls back to the Niagara Escarpment at Lewiston and Queenston, where the falls must once have stood.

The big idea. Erosion is the carrying away of rock and soil by moving water, wind or ice; **deposition** is the laying down of that material somewhere else. The key to studying either one is a rate: how much, in how long. When later surveyors repeated Hall's measurement, the rate came out. Between 1842 and 1905 the Horseshoe Falls retreated roughly 1.3 m a year on average, a figure the geologist G. K. Gilbert worked out for the U.S. Geological Survey in 1907. The American Falls, with a tenth of the water, retreated only a few centimeters a year. Nature had run a comparison for us: same rock, same climate, different flow, and the falls with more water retreats more than ten times faster. Falls do not retreat smoothly, either. Table Rock, a famous ledge on the Canadian side, crashed down in 1850. A huge slab fell from Prospect Point at the American Falls in 1954. Years of quiet are broken by a single night's collapse, so a yearly rate is really an average of long pauses and sudden jumps.

In the world today. Since the Niagara Diversion Treaty of 1950, Canada and the United States send much of the river through tunnels to power stations instead of over the falls. In the daylight hours of the tourist season at least 2,832 m^3 of water per second still go over

the brink, but at night and in winter only half as much, and the rest turns turbines. With less water pounding the shale, and with engineers having cemented and drained the weakest parts of the crest, the retreat has slowed to an estimated few tens of centimeters a year or less. In 1969 the U.S. Army Corps of Engineers even shut off the American Falls for five months with a temporary dam of rock, so that geologists could walk the dry riverbed, study the fallen blocks and the cracks in the cap, and bolt the loosest places. The dry falls drew crowds almost as large as the wet one.

God's handiwork. Psalm 46 speaks of waters that roar and are troubled and mountains that shake, and tells us not to fear, because God is our refuge. Standing in the spray at Niagara you can feel the ground tremble as the river throws more than an Olympic swimming pool of water over the edge every second. The falls are an enormous working model of how God's ordinary laws, water and gravity working on hard rock and soft, shape the land. They also taught geologists a lesson in humility that you will carry through this whole unit: a rate must be measured before it can be trusted, and even a measured rate may not hold for the past.



How Niagara Falls retreats. Spray and falling water undercut the soft shale, the hard dolostone cap overhangs and breaks off, and the brink moves upstream.

⏳ Thinking About Time

What the sign says. Textbooks and the park signs say the Niagara River began cutting its gorge about 12,000 years ago at Lewiston and Queenston, when the last great ice sheet melted back from the region at the end of what the signs call the Ice Age, and that the falls have retreated the 11 km to their present place since then.

What we observe. We observe an 11 km gorge, a measured retreat of roughly 1.3 m per year on the Horseshoe Falls between 1842 and 1905, a far slower rate on the American Falls with a tenth of the water, and a slower rate today after half the river was diverted.

Dividing 11,000 m by 1.3 m per year gives about 8,500 years; Lyell’s cautious 30 cm per year gave him 35,000 years; the old resident’s figure of more than a meter a year gives less than 10,000. No one has measured the rate in any century but the last two.

How Christians read it. Christians who hold to a recent creation read the Ice Age as a few centuries after the Flood of Genesis, while the earth was still cooling and draining. In that reading a much larger river of melting ice water poured over the escarpment and retreated far faster than the 1.3 m a year we have measured, so the gorge fits within the Bible’s thousands of years. Every age for the gorge, including the 12,000 years on the sign, is a rate multiplied by an assumption about the past. The skill is to name the assumption out loud.

Try it. Compute the gorge’s age at 0.3, 1.3 and 5 m per year, and beside each answer write the assumption it makes about the river’s past.

PICTURE STUDY



Niagara, Frederic Edwin Church, 1857 · Oil on canvas, about 1.0 by 2.3 m · National Gallery of Art, Washington, D.C. (Corcoran Collection)

Frederic Edwin Church traveled to Niagara several times in 1856, sketching from the Canadian shore in every kind of light. Back in his New York studio he painted this canvas more than two meters wide and did something no painter had dared. He left out the ground. There is no rock, no railing and no onlooker in the foreground; you stand at the lip of the Horseshoe Falls with the green water sliding past your feet toward the drop. When the picture went on show in New York in May 1857, people paid to see this one painting, and thousands came.

On the far side you can make out Terrapin Tower, a stone lookout built in 1833 on the rocks off Goat Island and torn down in 1873. A rainbow forms in the spray, and Church was careful

to paint it exactly as it appears in nature, with the sun behind the viewer.

Look closely

- Follow the water from the left edge of the picture to the brink. Where does it speed up? How does Church show speed with paint?
- Find the line where the green water turns to white mist. That curve is the crest Hall surveyed in 1842.
- Look at the far cliff beyond the tower. That is the cap rock and the soft rock beneath it. Can you tell which is which?
- Where is the viewer standing? What has Church taken away so that you feel the danger of the edge?

Talk about it

1. Church painted the brink in 1857. From the rate you learned, about how far upstream would the crest have moved by 1907, and would the picture still match?
2. Why do you think a painting with no foreground made people feel they were really there?
3. What can a painting record about Niagara that a survey cannot, and what can a survey record that a painting cannot?

> **Safety first.** This experiment uses several liters of water. Work outdoors or in a bathtub, keep towels ready, and mop any spills on hard floors at once.

EXPERIMENT: MODEL WATERFALL: DOES A HARD CAP MAKE A FALLS RETREAT?

Niagara keeps its height and walks upstream because a hard layer sits on a soft one. You will build two small cliffs of damp sand, cap one with a hard lid and leave the other bare, pour the same water over each, and measure how far each brink retreats.

Question: Does a hard cap over soft material make a model waterfall retreat as a steep step instead of wearing into a slope? Predict which cliff will move farther back after 3 L of water, and which will stay vertical.

You will need

- A long shallow plastic tub or large baking tray, at least 40 cm long
- Damp sand, about 6 cups, or a mix of sand and flour
- A flat, hard lid or thin tile about 10 cm across to serve as cap rock
- A jug or measuring cup marked at 500 mL, and a bucket of water
- A ruler, a pencil, a notebook and a stopwatch

Steps

1. At one end of the tub, pack damp sand into a block about 10 cm high, 15 cm wide and 15 cm deep, with a straight vertical face toward the empty end of the tub. Press the

hard lid onto the top so its edge lines up exactly with the face.
2. Mark the position of the brink on the side of the tub with the pencil. Record it as 0 cm.
3. Hold the jug 20 cm above the lid and pour 500 mL of water in a steady stream over the edge of the cap, aiming so the water lands at the foot of the face. Try to take about 10 seconds each time.
4. Measure how far the face under the cap has moved back from the pencil mark. Record it. Note whether the face is still vertical and whether the cap overhangs.
5. Repeat the pour five more times, measuring after each one, for 3 L in all. If the cap breaks loose, record the pour number when it fell and set it back on the new brink.
6. Empty the tub, rebuild an identical sand block with no cap, and repeat all six pours, measuring the retreat and sketching the shape of the face each time.
7. Make a table with three columns: Water poured (L), Retreat with cap (cm), Retreat without cap (cm). Graph both on one line graph. Write a conclusion: which cliff retreated farther, which kept a vertical face, and how this explains the Niagara Gorge.

Tips

- Keep the pour height, speed and aim the same every time. The pour is your river, and a river that changes is not a fair test.
- Watch the base of the capped face closely. The water should hollow a notch under the cap just as spray hollows the shale at Niagara.

Check your work

- I kept the sand, block size, water amount and pour height the same and changed only the cap.
- I measured retreat after every 500 mL and recorded it in a table and a graph.
- I can explain why the capped cliff kept its height and why the bare one turned into a slope.

FIELD NOTEBOOK

1. Draw a labeled cross-section of Niagara Falls showing the river, the dolostone cap, the soft shale, the undercut notch, the plunge pool and the fallen blocks, with an arrow showing which way the falls retreat.
2. Draw a simple map of the Niagara River from Lake Erie to Lake Ontario. Mark the falls, the 11 km gorge and the escarpment at Lewiston and Queenston, and add a scale bar.
3. Make a table titled “Three ages for one gorge.” In three rows write Lyell’s 35,000 years, the park sign’s 12,000 years and the 8,500 years from the measured rate, and beside each write the rate and assumption it rests on.

> **From history.** The first written description of Niagara Falls came from Father Louis Hennepin, a Franciscan priest traveling with the explorer La Salle, who saw the falls in December 1678. In the book he published in 1683 he guessed their height at more than

150 m, almost three times too tall, and the engraving made from his account spread the fame of the falls across Europe. Measuring, it turned out, was harder than marveling, and it was another 160 years before Hall surveyed the crest.

WORKED EXAMPLES

Example 1. Surveys found that a point on the crest of the Horseshoe Falls stood about 82 m farther upstream in 1905 than in Hall's survey of 1842. What was the average rate of retreat in meters per year, in centimeters per year and in centimeters per day?

(Use the map or drawing "Each collapse of the overhang moves the brink upstream." shown earlier in this lesson.)

1. Time between surveys: 1905 − 1842 = 63 years.
2. Rate = distance ÷ time = 82 m ÷ 63 years ≈ 1.3 m per year.
3. In centimeters: 1.3 m = 130 cm, so about 130 cm per year.
4. Per day: 130 cm ÷ 365 days ≈ 0.36 cm per day, about the thickness of two coins, though in reality the falls moved in sudden collapses with long pauses between.

Answer: About 1.3 m per year, or 130 cm per year, which averages to roughly 0.36 cm per day.

Example 2. The Niagara Gorge is about 11 km long. How long would the falls have taken to cut it (a) at Lyell's cautious 0.3 m per year, (b) at the measured 1.3 m per year and (c) at the old resident's figure of about 3 m per year? What must you assume to use any of these answers?

1. Convert the length: 11 km = 11,000 m.
2. (a) 11,000 m ÷ 0.3 m per year ≈ 37,000 years. Lyell used 7 miles for the gorge and got about 35,000 years.
3. (b) 11,000 m ÷ 1.3 m per year ≈ 8,500 years.
4. (c) 11,000 m ÷ 3 m per year ≈ 3,700 years.
5. Every answer assumes the rate never changed over the whole gorge. But the flow of the river, the thickness of the cap rock and the softness of the rock beneath all varied along the way, and today's rate was changed by engineers, so none of these numbers is a measurement of the past. Each is a rate times an assumption.

Answer: (a) about 37,000 years, (b) about 8,500 years, (c) about 3,700 years. All three assume a constant rate, which is the one thing we know was not true.

Example 3. In the daytime tourist season at least 2,832 m^3 of water per second go over Niagara Falls; at night it is 1,416 m^3 per second. An Olympic swimming pool holds about 2,500 m^3. (a) How many pools go over the falls each second by day? (b) How much water goes over in one daytime hour? (c) If the whole river carries about 6,000 m^3 per second on average, what fraction goes over the falls at night?

1. (a) 2,832 ÷ 2,500 ≈ 1.1 pools per second.
2. (b) 2,832 m^3 per second × 3,600 seconds = 10,195,200 m^3, about 10.2 million m^3 per hour, or roughly 4,100 swimming pools.
3. (c) 1,416 ÷ 6,000 ≈ 0.24, so about a quarter of the river goes over the falls at night and about three quarters goes through the power tunnels.

Answer: (a) About 1.1 Olympic pools every second. (b) About 10.2 million m^3 in an hour. (c) About one quarter of the river's flow at night.

PRACTICE

1. EASY Name the two kinds of rock in the Niagara cliff, say which one is on top, and explain why that order matters.
2. EASY Define erosion and deposition. Give one example of each that you could see at Niagara.
3. EASY Why did Charles Lyell write down the resident's figure but not use it as a measurement? What did James Hall do about the problem in 1842?
4. MEDIUM A waterfall's brink is measured 26 m farther upstream than it was 20 years earlier. Find the average retreat rate in meters per year and centimeters per year. At that rate, how far would it retreat in a century?
5. MEDIUM Data reading. A simplified record of the Horseshoe Falls crest, measured from Hall's 1842 marks:

   Year | Total retreat since 1842 (m)
   1842 | 0
   1875 | 43
   1905 | 82
   1927 | 103
   1950 | 118
   2000 | 130

   (a) Find the average rate from 1842 to 1905. (b) Find the average rate from 1950 to 2000. (c) What happened around 1950 that best explains the change?
6. MEDIUM Data reading. Two falls, one river (figures rounded):

   Falls | Share of river flow | Crest width | Retreat 1842–1905
   Horseshoe | about 90% | about 670 m | about 1.3 m per year

American | about 10% | about 260 m | about 0.1 m per year

(a) About how many times faster did the Horseshoe Falls retreat? (b) Which variable in the table best explains the difference? (c) What is held the same in this natural comparison that makes it a fair test?

7. MEDIUM In two or three sentences, explain why a retreat rate of “1.3 m per year” does not describe what a visitor would actually see in any one year. Use the Table Rock collapse of 1850 or the Prospect Point fall of 1954 in your answer.
8. HARD Experiment design. You want to know whether a thicker cap rock makes a model waterfall retreat more slowly. Name the independent variable, the dependent variable, at least three things you would keep the same, and how you would record the results.
9. HARD At night 1,416 m^3 of water per second go over Niagara Falls. How much water goes over in a 10-hour night? How many Olympic pools (2,500 m^3) is that? Why would you expect the falls to retreat more slowly at night than by day?
10. CHALLENGE Write a paragraph: Lyell figured about 35,000 years for the Niagara Gorge, the park sign says about 12,000 years, and the measured rate of the 1800s gives about 8,500 years. Explain why three careful people could get three different answers from the same gorge, and name the one thing you would need to know about the past to decide between them.

COMMON MISTAKES

- Thinking a waterfall wears its lip down into a gentle slope. Because the hard cap sits on soft rock, the falls keep their height and move upstream, leaving a gorge.
- Thinking the retreat rate measured in the 1800s has always been the same. The river’s flow, the rock being cut and even engineers have changed it, so an age built on one rate is an estimate resting on an assumption.
- Thinking erosion happens a little every day. At Niagara most retreat happens in sudden collapses after years of quiet undercutting.

> **Make it a game · Rate Relay.** Write ten cards, each with a distance and a time, such as “65 m in 50 years” or “3 km in 1,500 years.” Shuffle them. A parent flips a card and starts a 20-second timer; you compute the rate in meters per year and call it out. A correct rate scores a point, and a correct conversion to centimeters per year scores a bonus. For the last round, the parent gives a rate and a gorge length and you must say the age it implies and name the assumption in one breath. Play to ten points.

> **Scripture.** “Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah.” (Psalm 46:2–3, KJV)

The psalm pictures roaring waters and shaking ground, the very things you feel at the brink of Niagara, and answers them with trust in God, who is our refuge even when the earth itself is being worn away.

Practice answers

1. Hard dolostone (the Lockport) lies on top of softer shale and sandstone. Because the soft rock is underneath, spray and falling water hollow it out, the hard cap overhangs and breaks off, and the falls keep their height while retreating upstream. If the soft rock were on top, the falls would wear into a slope.
2. Erosion is the wearing away and carrying off of rock and soil by moving water, wind or ice; deposition is laying that material down in a new place. At Niagara, erosion is the undercutting of the shale and the wearing of the gorge; deposition is the pile of fallen blocks at the foot of the American Falls or the sand and gravel the river drops in Lake Ontario.
3. The resident's figure came from memory, not from a measurement, and could not be checked. Hall surveyed the crest with instruments and placed fixed marks so later surveyors could measure the change exactly.
4. 26 m ÷ 20 years = 1.3 m per year = 130 cm per year. In 100 years: 1.3 × 100 = 130 m, if the rate stayed the same.
5. (a) 82 m ÷ 63 years ≈ 1.3 m per year. (b) (130 − 118) m ÷ 50 years = 12 ÷ 50 = 0.24 m per year, about 24 cm per year. (c) The 1950 Niagara Diversion Treaty sent much of the river through power tunnels, so less water hit the shale, and engineers also strengthened parts of the crest. Less water means slower undercutting.
6. (a) 1.3 ÷ 0.1 = about 13 times faster. (b) The share of the river's flow: nine times more water pounds the shale beneath the Horseshoe Falls. (c) Both falls cut the same rock layers in the same climate, side by side, so rock type and weather are held the same. The widths also differ, so flow is not the only variable, but it is by far the largest difference.
7. The falls do not creep back a few millimeters a day. Spray hollows the shale quietly for years while nothing seems to change at the brink, and then an overhang such as Table Rock in 1850 or the Prospect Point slab in 1954 breaks off all at once and the crest jumps back several meters. The 1.3 m per year is an average of long pauses and sudden collapses.
8. Independent variable: the thickness of the cap (for example one, two and three stacked lids, or clay layers of 5 mm, 10 mm and 15 mm). Dependent variable: how far the brink retreats after a fixed amount of water, such as 3 L. Keep the same: the sand mix and dampness, the block's height and width, the pour height, speed and aim, the amount of water, and the person pouring. Record retreat after every 500 mL in a table for each thickness, repeat each thickness at least twice, and graph retreat against cap thickness.
9. 1,416 m^3/s × 36,000 s = 50,976,000 m^3, about 51 million m^3. 51,000,000 ÷ 2,500 ≈ 20,400 pools. With half the daytime flow, less water and spray attack the soft shale, so the undercutting that drives retreat is slower.
10. A strong answer says that all three used the same method, length divided by rate, but chose different rates: Lyell a cautious 30 cm per year, the measured surveys about 1.3 m per year, and the sign a model in which the rate varied as the lakes and the ice sheet changed. The gorge is the same; the assumption about the past differs. To decide, you would need to know how much water flowed over the escarpment in the centuries before anyone measured it, which no survey can tell you. That is why a rate measured today gives a range of possible ages, not a settled one, and why a Christian can read the gorge within the Bible's thousands of years while stating the sign's claim accurately.

6.2 Deltas: Herodotus Reads the Nile, about 450 B.C.

OBJECTIVES

- Explain how a delta forms where a river slows at a sea or lake, and name its topset, foreset and bottomset beds and its distributaries.
- Explain sorting: why coarse grains drop first and fine grains travel farthest, and predict where sand, silt and clay will settle.
- Compute a deposition rate from a table of delta measurements and state the assumptions behind any age built from it.

Warm-up. Fill a clear glass two thirds full of water. Stir in a spoonful of garden soil (not potting mix) and swirl hard for ten seconds. Set the glass down and watch for one minute. What lands first? What is still floating when the minute ends? Write down the order you saw and guess why.

Video. Coming soon. How river deltas form, Nile Delta and Mississippi bird’s-foot delta from space, Wax Lake Delta growth time-lapse, stream-table delta demonstration, sediment sorting; search NASA Earth Observatory, USGS, Smithsonian, SciShow Kids, Homeschool Pop (Alternate) and nature-documentary channels.

KEY TERMS

delta
A fan of sediment built where a river slows down and drops its load as it enters a sea or lake. Named by the Greeks for the triangle shape of the letter Δ.

sediment
Loose grains of rock and soil, from boulders down to clay, carried and laid down by water, wind or ice.

sediment load
The total amount of sediment a river carries, measured in tonnes per year.

distributary
A channel that splits off from the main river on a delta and carries part of its water to the sea. The opposite of a tributary, which joins a river.

sorting
The separating of grains by size as water slows. Coarse grains settle first, fine grains last, so each place on a delta gets its own grain size.

topset, foreset and bottomset beds
The three layers of a delta: flat coarse beds on top, sloping sandy beds in front, and thin flat beds of silt and clay spread out on the sea or lake floor.

CORE IDEAS

The story. About 450 B.C. a Greek traveler named Herodotus sailed up the Nile. He had come to Egypt to collect stories for his *Histories*, but he kept his eyes open, and the land itself puzzled him. The great river split into branches before it reached the sea, and between the branches lay a flat, black-soiled triangle of farmland more than 200 km across. Herodotus noticed three things. The soil was black river mud, nothing like the desert sand on either side. Seashells lay on the low hills and salt crusted the ground, as if the sea had once been there. And when sailors a full day's voyage from shore let down a sounding line, it came up with Nile mud from eleven fathoms of water. He put the clues together and wrote that the whole lower country was the river's own gift, built of mud the Nile had carried down and dropped. Because the land was shaped like the Greek letter Δ, the Greeks called it the Delta. Herodotus is the earliest writer whose use of the name has come down to us, and every delta on earth has carried that name since.

How they figured it out. Herodotus did more than describe. He reasoned about a rate. The priests at Memphis told him that long before, a flood of 8 cubits had covered the fields, while in his day the river had to rise 15 or 16 cubits to do the same, so the land must be building up. He then asked how long the river would need to fill a gulf as big as the Red Sea with mud, and guessed ten thousand or twenty thousand years. That guess was a rate multiplied by an assumption, the same move you studied at Niagara: he had no measured rate, he assumed the river had always behaved as it did in his lifetime, and he said plainly that it was a guess. Still, the method was sound. Find a process you can watch today, measure how fast it works, and reason carefully from there. In 1890 the American geologist Grove Karl Gilbert studied the dry deltas that streams had built into Lake Bonneville, the vanished lake whose shorelines ring the Great Salt Lake in Utah, and gave us the words for a delta's insides. Flat **topset beds** of gravel and coarse sand lie where the river still flows. Sloping **foreset beds** of sand build out in front like a ramp. Thin flat **bottomset beds** of silt and clay spread far out across the floor.

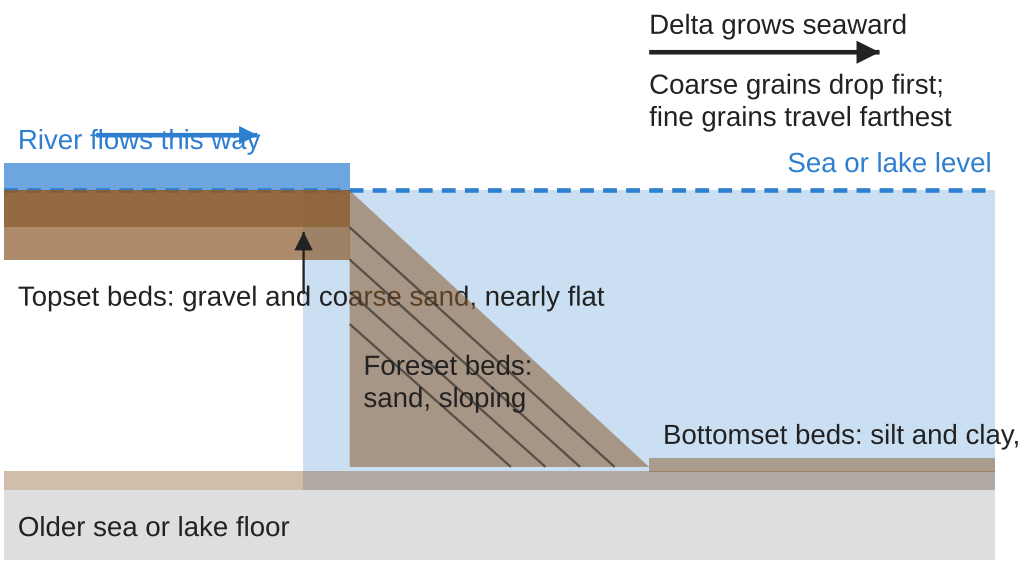
The big idea. A river can carry sediment only as long as it keeps moving. Where it meets the still water of a sea or lake it slows, loses its grip, and drops what it was carrying. The heaviest grains fall first, right at the mouth. Sand settles a little farther out. Silt drifts on for kilometers, and clay, which sinks so slowly that a grain can take a day to fall through a jar, can be carried far out to sea. This separating by size is called **sorting**, and it is why a delta is not a heap but a neat set of layers, coarse on top and near the land, fine at the bottom and far from it. As the pile grows, the river channel clogs with its own deposits and splits into **distributaries**, and the fan spreads. Different rivers build different shapes. The Nile's smooth arc is shaped by waves pushing the sediment along the coast. The Mississippi pokes long fingers into the quiet Gulf of Mexico, which geologists call a bird's-foot delta. Rivers entering a strong tidal sea build no fan at all and end in a wide estuary instead.

In the world today. Deltas are being measured right now. The Mississippi River carries roughly 150 million tonnes of sediment to the Gulf each year, less than half of what it carried before dams on its tributaries began trapping mud in the 1950s. In 1941 the U.S. Army Corps of Engineers dug a straight channel called the Wax Lake Outlet to carry Atchafalaya

River floodwater past Morgan City, Louisiana. After the great flood of 1973 a brand-new delta rose above the water at its mouth, and it has grown ever since by roughly a square kilometer a year, photographed from satellites, so for the first time we can watch a delta build from nothing with a stopwatch running. The Nile shows the opposite lesson. When the Aswan High Dam was completed in 1970 it trapped nearly all the river's mud in the lake behind it, and the Nile Delta, no longer fed, began to lose its coastline to the waves, in places by tens of meters a year. A delta is a balance: the river deposits, the sea takes away, and whichever is faster wins.

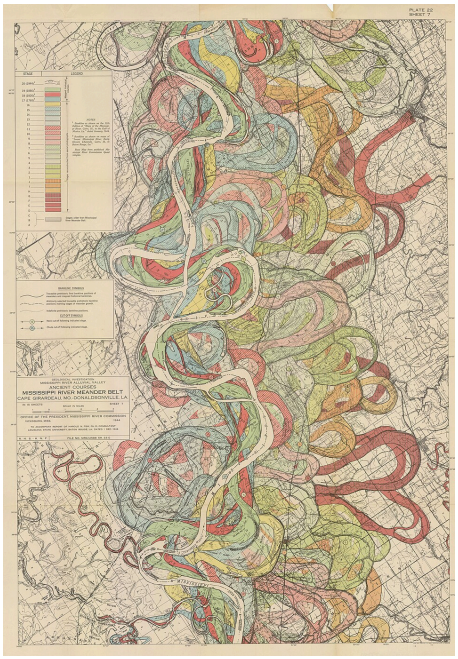
God's handiwork. Ecclesiastes says that all the rivers run into the sea, yet the sea is not full, and the waters return to the place from which they came. The delta is where that return is written in the ground. Soil carried off a thousand hillsides is gathered by the river and laid down in neat, sorted beds, and farmers have fed nations from it since the days of Joseph. The same ordinary law, that still water drops what moving water carries, works in a glass of muddy water on your table and in a delta two hundred kilometers wide. Learn to read it in the glass and you can read it anywhere.

A delta in cross-section (not to scale)



A delta in cross-section, with Gilbert's three kinds of beds. Coarse grains drop first and build the topset and foreset beds; silt and clay travel farthest and form the thin bottomset.

PICTURE STUDY



Ancient Courses, Mississippi River Meander Belt, Harold N. Fisk, for the Mississippi River Commission, U.S. Army Corps of Engineers, 1944 · Printed map in many colors, one sheet of a set · U.S. Army Corps of Engineers, Vicksburg, Mississippi; in the public domain and widely reproduced

In 1944 the geologist Harold Fisk finished a huge study of the lower Mississippi valley for the Army Corps of Engineers, who needed to know where the river had been before deciding where to build levees. He drilled thousands of holes, read the old sand and clay in each one, and drew every former channel he could trace on a set of long map sheets, giving each old course its own color.

The result looks like a painting, and people hang the sheets on their walls today. But it is a scientific record of deposition. Every colored ribbon is a channel the river once filled with sand and then abandoned, leaving the sand behind as a record. The delta you are studying in this lesson is the end of this river, where all of these courses have poured their load into the Gulf.

Look closely

- Find the present river, the narrowest line. How many older courses can you count crossing it in one place?
- Notice the shape of the loops. Why do you think a slow river on flat land swings in curves instead of running straight?
- Look for a place where a loop is cut off and left as a crescent. Rivers abandon such loops in floods. What happens to the water left in the cut-off loop?
- The colors overlap. Which must be older, a ribbon that is cut by another or the one that cuts it?

Talk about it

1. Fisk read the old channels from drill holes. What would a core of sand with a core of clay beside it tell him about where the channel and the floodplain had been?
2. A river that has wandered back and forth across its whole valley has spread its sediment over the whole valley floor. How does this help explain why delta and floodplain soils are so good for farming?
3. Why would engineers building a levee want to know where the river used to run?

> **Safety first.** This project uses a few liters of water and makes mud. Work outdoors or in a bathtub, keep towels ready, and wash hands when you are done. Do not pour sand down a sink drain.

EXPERIMENT: BUILD A DELTA: DOES THE SPEED OF THE RIVER CHANGE THE DELTA?

A river drops its load when it slows. You will pour muddy water down a short sand channel into a pool, measure the delta it builds, and find out whether a fast river or a slow river builds a bigger or a different delta from the same amount of sand and water.

Question: Does pouring the same mixture faster change the size, shape or sorting of the delta? Predict which flow, fast or slow, will carry sand farther into the pool, and where the finest grains will end up.

You will need

- A large shallow plastic tub or paint-roller tray at least 50 cm long
- Damp sand, about 8 cups, plus a cup of fine soil or silt-sized material such as sifted garden soil
- Two jugs or bottles: one with a wide mouth for fast pouring and one with a small spout or a hole punched in the cap for slow pouring
- A measuring cup marked at 250 mL, a bucket of water, a spoon
- A ruler, a pencil, a notebook and a stopwatch

Steps

1. Pack damp sand into the upper third of the tub to make a sloping land about 5 cm high, and cut a straight channel 2 cm wide down the middle of it. Pour clean water into the lower end of the tub to make a sea about 2 cm deep.
2. Mark the shoreline where the channel meets the sea with the pencil on the side of the tub. This is your zero line.
3. In the wide-mouthed jug, stir 2 heaping spoons of sand and 1 spoon of fine soil into 500 mL of water. Pour it all into the top of the channel in about 10 seconds. Time it.
4. Wait one minute for the water to clear. Measure how far the new delta reaches past the zero line, how wide it is, and sketch its shape from above. Note where the coarsest grains lie and how far the cloudy fine material spread. Record everything in a table.
5. Repeat the fast pour three more times with the same mixture, measuring after each, for 2 L in all.

6. Empty and rebuild the land, the channel and the sea exactly as before. Now mix the same amounts and pour them through the slow jug, taking about 60 seconds each time. Repeat four times, measuring after each pour.
7. Graph delta length against liters poured for both flows on one line graph. Write a conclusion: which flow built the longer delta, which built the steeper and narrower one, where the fine grains went, and how your delta compares to the Nile’s arc or the Mississippi’s bird’s-foot.

Tips

- Keep the sand, the slope, the sea depth and the mixture the same every time. Only the pouring speed changes.
- Look at the front of your delta from the side with a flashlight. You should see the sloping foreset beds Gilbert described.
- If you can, let the sea settle overnight and look at the thin film of fine mud across the bottom of the tub. That is your bottomset bed.

Check your work

- I changed only the pouring speed and kept everything else the same.
- I measured the delta after every pour and recorded length, width and a sketch in a table and a graph.
- I can point to the topset, foreset and bottomset beds in my model and explain where the coarse and fine grains went and why.

FIELD NOTEBOOK

1. Draw a labeled cross-section of a delta with the river, the sea, the topset, foreset and bottomset beds, and arrows showing which way the delta grows. Shade coarse grains dark and fine grains light.
2. Draw a map of the Nile Delta from Cairo to the sea with the two main branches, Rosetta on the west and Damietta on the east. Add a scale bar and draw the Greek letter Δ beside it.
3. Make a sorting chart from your warm-up glass: a column of the glass, with sand, silt and clay layers labeled in the order they settled and the time each took.

> **From history.** Grove Karl Gilbert, who measured Niagara’s retreat for the U.S. Geological Survey, had already studied deltas in the desert. In his 1890 monograph on Lake Bonneville he described the gravel deltas that mountain streams had built into the vanished lake, now standing high and dry above the Great Salt Lake, and named their topset, foreset and bottomset beds. Geologists still call a delta with this neat three-part structure a Gilbert delta.

WORKED EXAMPLES

Example 1. In a model delta, a student poured muddy water 500 mL at a time and measured how far the delta had grown past the shoreline: 0.5 L, 6 cm; 1.0 L, 9 cm; 1.5 L, 11 cm; 2.0 L, 12.5 cm. (a) What was the growth rate in cm per liter for the first pour and for the last? (b) Why does the delta grow more slowly even though every pour carries the same sand?

(Use the map or drawing "Every new load must build out a wider, deeper front." shown earlier in this lesson.)

1. (a) First pour: 6 cm ÷ 0.5 L = 12 cm per liter. Last pour: (12.5 − 11) cm ÷ 0.5 L = 1.5 cm ÷ 0.5 L = 3 cm per liter.
2. The rate fell to one quarter of what it was.
3. (b) Each pour brings the same amount of sand, but the delta is a fan. As it reaches farther out, the front is wider and the water in front of it is deeper, so the same sand must be spread over a larger area and a thicker pile to push the front out one more centimeter.
4. Lesson: a delta's length does not grow at a constant rate, so you cannot find its age by dividing its length by today's rate without knowing how the rate has changed.

Answer: (a) About 12 cm per liter at first, falling to 3 cm per liter. (b) Because a growing fan must spread the same sand over a wider, deeper front, so each liter pushes it less far.

Example 2. The Mississippi River delivers about 150 million tonnes of sediment to the Gulf of Mexico each year. Settled river mud has a density of about 1.5 tonnes per cubic meter. (a) What volume of sediment is that per year? (b) If it all settled evenly over a delta lobe of 100 km², how thick a layer would it make in one year? (c) Over the whole delta plain of about 10,000 km²?

1. (a) Volume = mass ÷ density = 150,000,000 t ÷ 1.5 t/m³ = 100,000,000 m³, that is 100 million cubic meters per year.
2. (b) 100 km² = 100 × 1,000,000 m² = 100,000,000 m². Thickness = volume ÷ area = 100,000,000 m³ ÷ 100,000,000 m² = 1 m per year.
3. (c) 10,000 km² = 10,000,000,000 m². Thickness = 100,000,000 ÷ 10,000,000,000 = 0.01 m = 1 cm per year.
4. In reality the sediment is not spread evenly: most drops near the active mouths, some is carried far out by currents, and before the 1950s the load was more than twice as large.

Answer: (a) About 100 million m³ a year. (b) About 1 m a year over 100 km². (c) About 1 cm a year over 10,000 km².

Example 3. Approximate settling speeds in still water: a 0.25 mm sand grain falls about 3 cm/s; a 0.02 mm silt grain about 0.03 cm/s; a 0.002 mm clay particle about 0.0004 cm/s. (a) How long does each take to fall 30 cm to the bottom of a jar? (b) A river 3 m deep flows at 0.5 m/s into a calm lake and the current keeps that speed for a while. About how far from the mouth would each grain travel before reaching the bottom, if the water did not stir it back up?

1. (a) Time = distance ÷ speed. Sand: 30 ÷ 3 = 10 s. Silt: 30 ÷ 0.03 = 1,000 s, about 17 minutes. Clay: 30 ÷ 0.0004 = 75,000 s, about 21 hours.
2. (b) Depth 3 m = 300 cm. Time to fall: sand 300 ÷ 3 = 100 s; silt 300 ÷ 0.03 = 10,000 s; clay 300 ÷ 0.0004 = 750,000 s.
3. Distance = speed × time at 0.5 m/s: sand 0.5 × 100 = 50 m; silt 0.5 × 10,000 = 5,000 m = 5 km; clay 0.5 × 750,000 = 375,000 m = 375 km.
4. Real currents swirl and lift grains, so these are rough minimums, but the pattern is exactly what Gilbert saw: sand at the mouth, silt beyond, clay far out on the bottomset.

Answer: (a) Sand about 10 s, silt about 17 min, clay about 21 h. (b) Sand about 50 m, silt about 5 km, clay hundreds of kilometers. That is sorting.

PRACTICE

1. EASY What is a delta, and why does a river drop its sediment there?
2. EASY Name the three clues Herodotus noticed in Egypt and tell what each one suggested to him.
3. EASY Put these grains in the order they settle in still water, first to last, and give the delta bed where you would expect to find most of each: clay, gravel, sand, silt.
4. MEDIUM What is the difference between a tributary and a distributary? Which does a delta have, and why?
5. MEDIUM A new delta was first seen above water in 1973. By 2013 it covered about 60 km². (a) What was its average growth rate in km² per year? (b) At that rate, how large would it be in 2053? (c) Give one reason the real answer might differ.
6. MEDIUM Data reading. Sediment reaching the Nile Delta coast and the shoreline near the Rosetta mouth (figures rounded, simplified from published studies):

   Period | Sediment reaching the coast (million tonnes per year) | Shoreline near Rosetta
   Before 1964 | about 120 | slowly advancing
   After 1970 | less than 5 | retreating tens of meters per year

   (a) What happened in Egypt between 1964 and 1970 that explains the change in sediment? (b) Explain, using the idea of a balance between river and sea, why the shoreline changed direction. (c) Does this table prove that waves became stronger? Explain.

7. MEDIUM Data reading. Samples taken from the floor of a lake at increasing distance from a river mouth:

   Distance from mouth (km) | Most common grain
   0 | gravel and coarse sand
   1 | medium sand
   3 | fine sand
   8 | silt
   20 | clay

   (a) Describe the pattern in one sentence. (b) A sample of medium sand is found 15 km from the present mouth. Give one reasonable explanation. (c) Which Gilbert bed would the 20 km sample belong to?
8. HARD Experiment design. You want to test whether a mixture with more fine silt builds a flatter, wider delta than a mixture of pure sand. Name the independent and dependent variables, list at least three things to keep the same, say how you would measure “flatter,” and explain why you would repeat each trial.
9. HARD Herodotus guessed that the Nile could fill a gulf the size of the Red Sea in 10,000 to 20,000 years. In two or three sentences, say what was good about his reasoning and what assumption he could not check. Then explain why the Wax Lake Delta is a better test of a delta’s growth rate than any ancient delta.
10. CHALLENGE Write a paragraph explaining how a single flood could lay down more sediment on a delta than many ordinary years, and why that matters for anyone who tries to tell how old a delta is by dividing its thickness by today’s yearly deposit. Use your Mississippi worked example or your own model in the explanation.

COMMON MISTAKES

- Thinking a delta is simply a pile the river dumps at its mouth. A delta is sorted and layered: coarse grains near the mouth and on top, fine grains far out and underneath.
- Mixing up tributaries and distributaries. Tributaries join a river upstream; distributaries split away from it on the delta.
- Thinking a delta grows at a steady rate forever. As the fan reaches deeper water and spreads wider, the same sediment pushes it out less far, and floods and dams change the supply.

Make it a game · Sort the Load. Cut twelve cards and write a grain on each: gravel, coarse sand, fine sand, silt or clay, plus a few surprise cards such as “flood year” or “dam built upstream.” Lay out a long strip of paper marked River mouth at one end and Deep water at the other. A parent flips a card and you have five seconds to place it on the strip where it would settle. A correct spot earns a point. A surprise card earns two points if you can say in one sentence how it changes the delta. Play to twelve.

Scripture. “All the rivers run into the sea; yet the sea is not full; unto the place from

> whence the rivers come, thither they return again.” (Ecclesiastes 1:7, KJV)

Solomon saw the water cycle long before anyone drew it: rivers pour into the sea, the sea sends its water back as rain, and the rivers run again. The delta is where the rivers leave their load behind at the end of the journey, sorted and laid down in order by the laws God set in the water.

Practice answers

1. A delta is a fan of sediment built where a river enters a sea or lake. The river slows in the still water, loses the energy that was carrying its load, and drops it.
2. Black river mud instead of desert sand (the land was built of river deposits); seashells and salt on the hills (the sea had once covered the land); and Nile mud brought up by sounding lines a day’s sail from shore (the river carries mud far out to sea).
3. Gravel, sand, silt, clay. Gravel and coarse sand in the topset beds near the mouth, sand in the foreset beds, silt and clay in the bottomset beds far out.
4. A tributary joins a river and adds water; a distributary branches off and carries water away. A delta has distributaries because the channel clogs with its own deposits and the water splits into new paths to reach the sea.
5. (a) 60 km^2 ÷ 40 years = 1.5 km^2 per year. (b) 60 + 1.5 × 40 = 120 km^2. (c) The river’s sediment load may change, a flood or hurricane may remove land, the water offshore gets deeper so growth slows, or the river may shift to a new mouth.
6. (a) The Aswan High Dam was built (completed 1970) and trapped the river’s mud in the lake behind it. (b) A delta coast is a balance between the sediment the river adds and the sediment the waves carry away. When the river stopped delivering, the waves kept removing, so the balance tipped and the shore retreated. (c) No. Nothing in the table measures the waves. The change is explained by the drop in sediment supply; the waves may be exactly as strong as before.
7. (a) Grain size gets smaller with distance from the mouth because finer grains settle more slowly and are carried farther. (b) The river mouth used to be nearer that spot, or a large flood once carried sand farther than usual, or a different stream enters nearby. (c) The bottomset beds.
8. Independent variable: the share of silt in the mixture (for example 0%, 25% and 50% silt by spoonfuls). Dependent variables: the delta’s width, its length and the slope of its front. Keep the same: total amount of sediment, amount of water, pouring speed and height, slope of the land, depth of the sea, and the tub. Measure flatness by the delta’s height at the shoreline divided by its length, or by measuring the angle of the front with a protractor against the tub wall. Repeat each mixture at least twice because small differences in pouring change the result; averaging shows the real effect.
9. Good: he started from things he could see (black mud, shells, mud far offshore, the rising flood level) and reasoned about a process that is still working today, and he admitted he was guessing. The assumption he could not check: that the river had always carried mud at the same rate, with no bigger floods or smaller ones in the past. The Wax Lake Delta began at a known date (1973) from a known cause, so its growth can be measured directly, year by year, with photographs, instead of being inferred from a rate assumed to be constant.
10. A strong answer notes that a river’s sediment load rises steeply with its flow: a great flood carries far more water and far faster water, picking up sand and gravel that a normal year never moves, and may deposit a layer in days that equals many years of ordinary mud. If a

delta’s beds were built mostly by such floods, then dividing total thickness by the small yearly deposit of a calm year gives an age much too large; the Mississippi example (1 m per year on a 100 km² lobe) would be very different in a flood year or a drought year. The thickness is a measurement; the age is a measurement divided by an assumed rate, and the assumption must be stated.

6.3 Wind and Sand: Ralph Bagnold in the Libyan Desert, 1929–1941

OBJECTIVES

- Describe how wind moves sand by saltation and creep and silt by suspension, and explain why wind sorts grains even more sharply than water does.
- Name and sketch the main dune shapes (barchan, transverse, longitudinal and star) and explain how the windward slope, the slip face and the angle of repose shape a dune.
- Compute a dune’s migration rate from two surveys and use the cube rule to compare how much sand a gale moves against a breeze.

Warm-up. Put a spoonful of dry sand or sugar at one end of a baking tray and a spoonful of flour beside it. Kneel so your eyes are level with the tray and blow once, gently, across both piles from 20 cm away. Which grains hopped? Which floated up as a cloud? Which did not move? Write one sentence on what size of grain the wind carries best.

Video. Coming soon. How wind moves sand, saltation slow-motion footage, barchan dune migration time-lapse, Sahara and White Sands dunes, Dust Bowl 1935 newsreel footage, Bagnold Dunes on Mars; search NASA, USGS, NOAA, Smithsonian, National Park Service, SciShow Kids, Homeschool Pop (Alternate) and nature-documentary channels.

KEY TERMS

saltation
The hopping of sand grains along the ground in the wind. A grain lifts, flies a short arc, lands and knocks other grains into the air. Most sand moves this way.

suspension
Fine silt and clay carried high in the air by the wind for long distances, as in a dust storm.

deflation
The lowering of a land surface as wind carries away its loose grains, often leaving a floor of stones called desert pavement.

abrasion
The sandblasting of rock and other objects by wind-driven grains, strongest within a meter of the ground.

dune
A mound or ridge of wind-blown sand with a gentle windward slope and a steep downwind slip face. Barchan dunes are crescents with horns pointing downwind.

angle of repose
The steepest slope a pile of loose grains can hold before it slides. For dry sand it is about 32 to 34 degrees, the angle of every dune’s slip face.

CORE IDEAS

The story. In the autumn of 1929 a young British army officer named Ralph Bagnold drove out of Cairo with a few friends in Ford Model A cars to see how far into the Libyan Desert a motor car could go. Over the next three years he and his companions crossed the Great Sand Sea, learned to let air out of their tires to float over soft sand and to lay steel channels under the wheels when they sank, and covered thousands of kilometers where no wheel had gone before. But what gripped Bagnold was the sand itself. Dune after dune rose in the same crescent shape, each with a gentle back and a steep front, marching slowly across the gravel. In a strong wind the whole desert floor seemed to smoke a few centimeters above the ground, yet above knee height the air was almost clear. Bagnold wanted to know why, and no book could tell him. So when he went home he built a wind tunnel in London, filled it with desert sand, and started measuring.

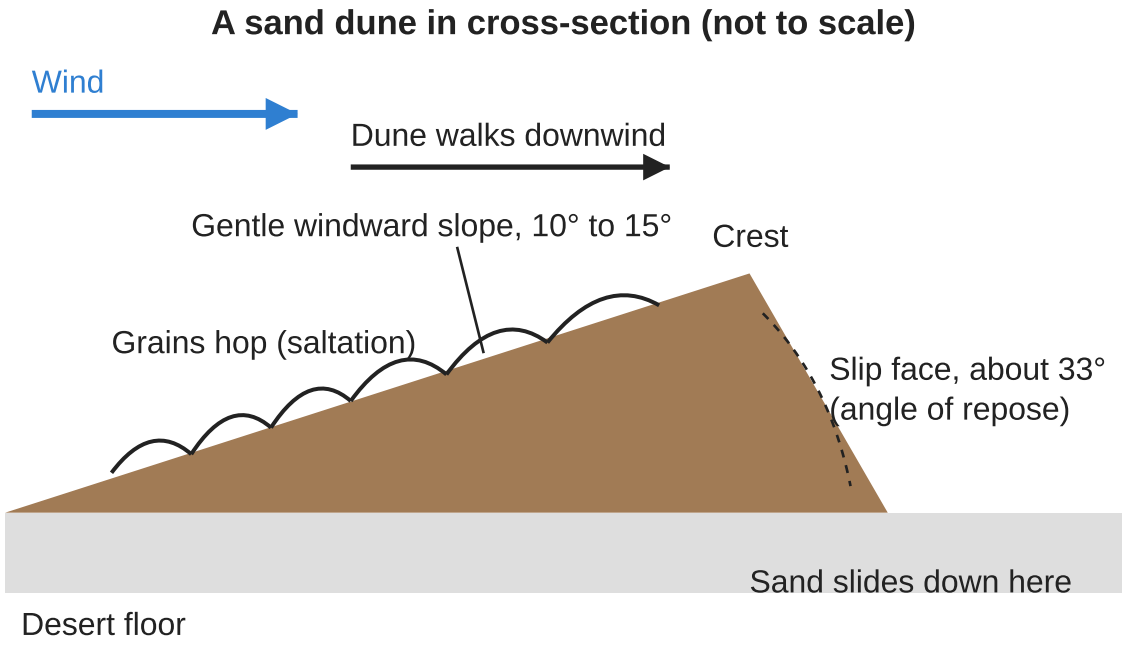
How they figured it out. In the tunnel Bagnold could set the wind to any speed and watch single grains. Below a certain speed nothing moved. For ordinary dune sand, grains about a quarter of a millimeter across, the wind had to reach roughly 4 to 5 m/s near the ground, a stiff breeze, before the first grains lifted. Once they lifted, they did not float. They flew in low arcs a few centimeters high, landed, and knocked two or three more grains into the air. He called this hopping **saltation**, from the Latin word for jumping, and showed that it is how most sand travels. Grains too big to fly are shoved along the ground by the landing grains, which he called **creep**. Dust and silt, much finer, are tossed up by the hopping grains and stay aloft in **suspension**, which is why the desert floor smokes while the air above is clear, and why a dust storm can carry silt across an ocean while the sand stays home. He also found that the amount of sand moved rises roughly with the **cube** of the wind speed: double the wind and you move about eight times the sand. In 1941 he published it all in *The Physics of Blown Sand and Desert Dunes*.

The big idea. Wind is a weak, choosy carrier. It cannot lift gravel and it leaves damp clay stuck to the ground, so it picks out sand and silt and sorts them more sharply than any river does. The sand piles up into **dunes**, and every dune has the same anatomy. The wind drives grains up a gentle windward slope of 10 to 15 degrees, over the crest, and drops them in the quiet air beyond, where they pile up until the slope reaches the **angle of repose**, about 32 to 34 degrees, and slide down in little avalanches. That steep face is the slip face. Because sand is taken from the back and added to the front, the whole dune walks downwind, and a small dune walks faster than a big one. Where sand is scarce and the wind blows from one direction the dunes are crescent-shaped **barchans** with horns pointing downwind. Plentiful sand joins into **transverse** ridges across the wind; winds from two directions build **longitudinal** ridges, and winds from many directions pile up **star dunes**. Wind also wears things away. **Deflation** strips loose grains from a surface until only stones are left, a desert pavement, and **abrasion** by flying grains sandblasts rocks and fence posts, but only near the ground, where saltating grains fly. The silt that wind carries off settles far away as a soft yellow soil called loess.

In the world today. The hardest lesson about wind and soil was learned on the American Great Plains. In the early 1930s a long drought followed years in which farmers had plowed

up the deep-rooted prairie grass to plant wheat, and with nothing to hold it the dry topsoil began to blow. On April 14, 1935, remembered as Black Sunday, a wall of dust rolled across Oklahoma, Kansas and the Texas Panhandle and turned noon to midnight. That spring Hugh Hammond Bennett, a soil scientist who had been warning about erosion for years, testified before Congress, and within weeks Congress created the Soil Conservation Service. Bennett's cures were practical: plow along the contour of a slope instead of up and down it, leave stubble on the field over winter, plant strips of soil-holding crops, and plant rows of trees as windbreaks. Between 1935 and 1942 more than 200 million trees were planted in shelterbelts from North Dakota to Texas. A windbreak works because it slows the wind at the ground below the speed Bagnold measured, and sand that cannot lift cannot leave.

God's handiwork. Jesus warned of a house built upon the sand, which fell when the winds blew and beat upon it. Anyone who has watched a dune slide knows what He meant: sand cannot hold a slope steeper than its angle of repose, the picture of a life with no foundation. Yet the same grains, in God's ordering, make the seashore and the desert, filter our drinking water in the ground and feed the wheat fields of the loess. Bagnold looked at something everyone had seen, asked how it worked, and measured until he knew. The laws he found turned out to hold even on Mars, where the dunes NASA named for him are built by a thinner wind out of darker sand, hopping in the same low arcs.



A dune in cross-section. Sand hops up the gentle windward slope by saltation, drops over the crest, and slides down the slip face at the angle of repose, so the dune walks downwind.

PICTURE STUDY



Dust Storm Approaching Stratford, Texas, April 18, 1935, Unknown photographer, from the George E. Marsh Album, 1935 · Black-and-white photograph · NOAA Photo Library (National Oceanic and Atmospheric Administration)

Four days after Black Sunday, someone in Stratford, a small town in the Texas Panhandle, stood still long enough to photograph the next dust storm coming. The picture is now kept by NOAA and has become the best-known image of the Dust Bowl. The dark wall is not a cloud of rain. It is topsoil from plowed fields, tens of kilometers of it, carried in suspension by a cold wind and rolling along the ground like a wave.

Storms like this one buried fences, filled ditches, killed cattle that breathed the dust, and sent thousands of families west. They also taught the nation, within a single decade, that soil is a gift that can blow away and that farming methods matter.

Look closely

- Compare the sunlit houses with the cloud. Where is the sun, and what will happen to the light in the town in the next few minutes?
- Look at the top edge of the dust. Is it a sharp line or a billowing one? What does that tell you about how the wind is moving?
- Find the bottom of the cloud where it meets the ground. Bagnold found that sand hops near the surface while silt rises high. Which is this cloud made of, and how do you know?
- Notice how little there is to stop the wind: no trees, no hills. How would a row of trees have changed this picture?

Talk about it

1. Why did the Plains blow in the 1930s and not in the 1830s, when the same winds blew over the same land?
2. What is the difference between the sand that builds a dune and the dust in this photograph? Which travels farther?
3. Hugh Bennett said the answer was in how farmers worked the land. Name two of his methods and explain how each one keeps the wind speed at the ground below the lifting speed.

> **Safety first.** Blowing sand can scratch eyes. Wear safety glasses or goggles, keep your face at least 50 cm from the tray, and work outdoors or in a garage. If you use an electric fan, keep it dry, keep fingers away from the blades, and have a parent handle the cord and switch. Do not breathe dust; use damp cloths to clean up.

EXPERIMENT: WIND TUNNEL IN A TRAY: DOES GRAIN SIZE CHANGE HOW FAR THE WIND CARRIES IT?

Bagnold's wind tunnel showed that wind is a choosy carrier. You will build a tray-sized tunnel with a fan or hair dryer on its cool setting, release grains of three sizes into the same wind, and measure how far each travels.

Question: Does the size of a grain change how far a steady wind carries it? Predict which of your three materials will travel farthest, which will hop, and which will not move at all.

You will need

- A long shallow box or tray at least 60 cm long, with cardboard walls on the two long sides to keep the wind in
- A small electric fan or hair dryer with a cool setting, and an adult to run it
- Three dry materials of different grain sizes: fine flour or cornstarch (silt-sized), dry play sand or sugar (sand-sized), and aquarium gravel or dry lentils (gravel-sized)
- A teaspoon, a ruler or tape measure, masking tape, a marker
- Safety goggles, a notebook and a pencil

Steps

1. Lay the tape down the middle of the tray and mark it every 5 cm from 0 at the fan end to the far end.
2. Set the fan at the 0 mark so it blows straight down the tray. Decide on one fan setting and one distance and do not change them for the whole experiment.
3. Place one level teaspoon of sand in a small pile at the 5 cm mark. Put on goggles. Have your parent switch on the fan for exactly 10 seconds, then off.
4. Measure how far the farthest grains traveled and where most of the pile ended up. Sketch the shape the sand made, and note whether grains hopped, slid or flew. Record everything in a table: Material, Farthest grain (cm), Where most landed (cm), How it moved.

5. Sweep the tray clean and repeat twice more with sand. Then run three trials each with the flour and with the gravel, the same way.
6. Average the three trials for each material. Draw a bar graph of average farthest distance for the three grain sizes.
7. Extra trial: pile 3 teaspoons of sand at the 10 cm mark and run the fan for 30 seconds. Look for a gentle slope on the fan side and a steep face on the far side. Measure the steep face's angle with a protractor if you can. You have built a dune.
8. Write a conclusion: which size traveled farthest and why, which stayed put, and how this matches saltation, suspension and creep.

Tips

- If the flour rises as a cloud and leaves the tray, that is suspension, exactly what happens in a dust storm. Record it as "carried out of the tray" and note how high it rose.
- Keep the spoonfuls level and the piles the same shape, so that only grain size changes.
- If nothing moves, bring the fan a little closer, write down the new distance, and start all trials over so they match.

Check your work

- I kept the fan setting, fan distance, run time and pile size the same and changed only the grain size.
- I ran three trials for each material, averaged them and drew a bar graph.
- I can explain which grains moved by saltation, which by suspension and which by creep, and what the dune's two slopes mean.

FIELD NOTEBOOK

1. Draw a dune in cross-section with the wind arrow, the gentle windward slope, the crest, the slip face and the angle of repose labeled, and three hopping grains drawn in saltation arcs.
2. Draw the four dune shapes from above (barchan, transverse, longitudinal, star) with wind arrows showing the wind direction that builds each one.
3. Copy your bar graph of distance against grain size into your notebook and write two sentences under it comparing your result with Bagnold's findings.

> **From history.** When war came in 1940, Bagnold's desert driving became a weapon. He founded the Long Range Desert Group, small patrols that crossed the Libyan sands to scout and raid far behind enemy lines using the sun compass and the tire tricks he had worked out as a hobby. Long after, in 2015, NASA's Curiosity rover drove up to a field of dark dunes on Mars that the mission had named the Bagnold Dunes, and watched sand grains and ripples moving just as his book predicted, though in a wind far thinner than any on earth.

WORKED EXAMPLES

Example 1. Aerial photographs of a barchan dune 4 m high taken in 1950 and 1990 show that its crest moved 600 m downwind. (a) What was its average migration rate in meters per year? (b) A road lies 3 km downwind. At that rate, when would the dune reach it? (c) A nearby dune 8 m high is fed by the same stream of sand. About how fast would you expect it to move, and why?

(Use the map or drawing "Sand leaves the back and lands on the front, so the dune moves." shown earlier in this lesson.)

1. (a) Time: 1990 − 1950 = 40 years. Rate = 600 m ÷ 40 years = 15 m per year.
2. (b) 3 km = 3,000 m. Time = 3,000 m ÷ 15 m per year = 200 years, so around 2190, if the wind and sand supply stay the same.
3. (c) Bagnold showed that a dune's speed is roughly inversely proportional to its height for the same sand flow: the same sand has twice the hill to shift. A dune twice as high moves about half as fast: 15 ÷ 2 ≈ 7.5 m per year.
4. This is why small barchans catch up with and run into big ones, and why the smallest dunes in a field are the most dangerous to roads.

Answer: (a) 15 m per year. (b) In about 200 years, around 2190, assuming constant conditions. (c) About 7 or 8 m per year, half as fast, because the same sand must move twice the dune.

Example 2. Bagnold found that the amount of sand the wind carries rises roughly with the cube of the wind speed. Call the sand moved by a 6 m/s wind in one hour 1 unit. (a) How many units does a 12 m/s wind move in an hour? An 18 m/s gale? (b) Which moves more sand: a 6 m/s breeze blowing for 30 days, or an 18 m/s gale blowing for 1 day?

1. (a) Speed ratio 12 ÷ 6 = 2, so sand ratio = 2^3 = 8 units per hour. Speed ratio 18 ÷ 6 = 3, so sand ratio = 3^3 = 27 units per hour.
2. (b) Breeze: 1 unit per hour × 24 hours × 30 days = 720 units. Gale: 27 units per hour × 24 hours × 1 day = 648 units.
3. The one-day gale moves almost as much sand as a whole month of breezes, and the breeze must be above the lifting speed the whole time, which real breezes rarely are.
4. So most of a desert's sand moves on a few stormy days a year, not a little every day. Average rates hide this.

Answer: (a) About 8 units per hour at 12 m/s and 27 units per hour at 18 m/s. (b) The month of breeze moves 720 units and the single day of gale 648 units, nearly the same, so one storm does the work of a month.

Example 3. You pour dry sand into a cone on a plate. The cone is 8 cm high and its base is 26 cm across. (a) What is the angle of repose of your sand? (b) A dune's slip face is 10 m high and stands at the same angle. How far does the slip face stretch horizontally from crest to foot?

1. (a) The radius of the base is 26 ÷ 2 = 13 cm. The slope has rise 8 cm over run 13 cm, so tan θ = 8 ÷ 13 ≈ 0.62.
2. An angle whose tangent is 0.62 is about 32°, which is within the 32° to 34° range for dry sand. You can check by drawing a triangle 8 cm by 13 cm and measuring the angle with a protractor.
3. (b) Same angle, so rise ÷ run = 8 ÷ 13. Run = 10 m × 13 ÷ 8 = 16.25 m, about 16 m.
4. Every slip face on earth stands at about this angle, which is why dunes of every size have the same profile.

Answer: (a) About 32°. (b) About 16 m from crest to foot.

PRACTICE

1. EASY Describe saltation in two sentences and tell why it keeps most blowing sand within a meter of the ground.
2. EASY Which of these can ordinary wind carry in suspension across an ocean: gravel, sand, silt? Which does it leave behind entirely? Explain.
3. EASY Draw or describe a barchan dune. Which way do its horns point, and what two conditions build barchans?
4. MEDIUM A barchan's crest was 240 m from a fence post in 2004 and 60 m from it in 2024. (a) Find its migration rate. (b) In what year will it reach the post if nothing changes? (c) Name two things that could change the answer.
5. MEDIUM Using the cube rule, how many times more sand does a 10 m/s wind move than a 5 m/s wind? A 15 m/s wind than a 5 m/s wind?
6. MEDIUM Data reading. A student sets a sand trap at ground level and counts grains caught per minute at different wind speeds measured 1 m above the ground:

   Wind speed (m/s) | Grains caught per minute
   3 | 0
   4 | 0
   5 | 5
   6 | 40
   7 | 135
   8 | 320

   (a) Between which two speeds does the sand begin to move? (b) When the wind rises

from 6 to 8 m/s, by what factor does the catch increase? (c) Is the relationship between wind speed and sand moved a straight line? Give evidence from the table.

7. MEDIUM Data reading. Dust storms reported at one weather station on the southern Great Plains (simplified record):

   Year | Dust storms
   1932 | 14
   1933 | 38
   1934 | 22
   1935 | 40
   1936 | 68
   1937 | 72
   1938 | 61
   1939 | 30
   1940 | 17

   (a) Which year had the most storms? (b) The Soil Conservation Service began its work in 1935. Does the table by itself prove that soil conservation ended the storms? What else changed around 1939 to 1940? (c) Describe the overall shape of the data in one sentence.
8. HARD Experiment design. You want to test whether a row of “trees” (pencils stuck upright in clay) placed in front of a sand pile reduces how far the wind carries the sand. State the independent and dependent variables, at least three controls, a prediction, and how many trials you would run and why.
9. HARD A fence post in the desert is worn thin about 30 cm above the ground but is barely scratched at 1.5 m. Explain this using what Bagnold learned about saltation. Then explain why desert rocks on pedestals are often narrower at the base than at the top.
10. CHALLENGE Write a paragraph connecting Bagnold’s threshold wind speed and his cube rule to Hugh Bennett’s cures for the Dust Bowl. Explain why a shelterbelt of trees, stubble left on a field and strips of standing crops all work on the same principle, and why one bad week of wind can undo a year of calm.

COMMON MISTAKES

- Thinking blowing sand floats high in the air like dust. Sand hops within a meter of the ground; only fine silt and clay rise in suspension.
- Thinking a dune’s steep side faces the wind. The wind side is the gentle slope; the steep slip face is downwind, where sand drops over the crest.
- Thinking erosion by wind happens evenly, a little every day. Most sand moves on a few days of strong wind, because the amount moved grows with the cube of the speed.

> **Make it a game · Dune Dash.** Make a game board: a strip of paper 40 cm long marked every 2 cm, with a road at the far end. Your dune is a coin at the start. A parent rolls a die each turn for the wind speed (1 to 6). Your dune moves the cube of the roll divided by 20, rounded to the nearest whole square (1 moves 0, 2 moves 0, 3 moves 1, 4 moves 3, 5

moves 6, 6 moves 11). Before each roll, you may spend a turn planting a windbreak that subtracts 2 from the next roll. Can you keep the dune off the road for 12 turns? Then switch roles.

Scripture. “And every one that heareth these sayings of mine, and doeth them not, shall be likened unto a foolish man, which built his house upon the sand: And the rain descended, and the floods came, and the winds blew, and beat upon that house; and it fell: and great was the fall of it.” (Matthew 7:26–27, KJV)

Loose sand cannot hold a slope steeper than its angle of repose, and wind moves it with every gale. Jesus used a fact everyone in a dry land knew to teach that a life needs a foundation that does not shift, which is to hear His words and do them.

Practice answers

1. Saltation is the hopping of sand grains: the wind lifts a grain, it flies a short low arc, lands and knocks more grains into the air. The hops are only a few centimeters high because sand is too heavy for the wind to carry up and keep up, so the sand stays near the ground while finer dust rises in suspension.
2. Silt (and clay) can be carried in suspension across an ocean. Sand travels only by hopping and stays near the ground. Gravel is too heavy for wind to lift at all and is left behind as desert pavement.
3. A crescent-shaped dune with a gentle outer (windward) slope and a steep inner slip face. The horns point downwind. Barchans form where sand is scarce and the wind blows mostly from one direction.
4. (a) It moved $240 - 60 = 180$ m in 20 years, so 9 m per year. (b) $60 \text{ m} \div 9 \text{ m per year} \approx 6.7$ years, so around 2030 or 2031. (c) A change in wind strength or direction, a change in sand supply, vegetation taking root on the dune, a windbreak or fence, or the dune growing (slowing it) or shrinking (speeding it up).
5. $10 \div 5 = 2$, and $2^3 = 8$ times more. $15 \div 5 = 3$, and $3^3 = 27$ times more.
6. (a) Between 4 and 5 m/s, which is the threshold Bagnold measured for dune sand. (b) $320 \div 40 = 8$ times. (c) No. Equal steps in wind speed give unequal, rapidly growing steps in sand: 0, 5, 40, 135, 320. From 5 to 6 m/s the catch grows by 35 grains, from 7 to 8 by 185. A straight line would give equal steps.
7. (a) 1937. (b) No. Storms kept rising for two years after 1935 and fell sharply only at the end of the decade, when the drought also broke and rains returned. Two things changed at once, better farming and more rain, so the table alone cannot separate them. (c) Storms rose through the mid-1930s to a peak in 1937 and then fell quickly to the levels of the early 1930s.
8. Independent variable: whether a windbreak is present (and perhaps how many pencils or how close together). Dependent variable: the farthest distance sand travels, or the mass of sand that passes a line, in a 10-second run. Controls: same fan setting and distance, same run time, same amount and type of sand, same pile shape and position, same tray. Prediction: the windbreak will slow the wind at the ground below the lifting speed, so sand will travel much less far. Run at least three trials for each condition and average them, because small differences in how the pile is placed change single results.
9. Saltating sand grains fly in low arcs, mostly within a few tens of centimeters of the ground, with the heaviest and most frequent impacts near the surface. So abrasion is strongest low down and almost absent above a meter. Rocks are sandblasted most near their base, where

the hopping grains strike, and so are worn into pedestals that are narrow at the bottom and wider above.

10. A strong answer explains that sand and silt lift only when the wind at the ground passes a threshold (about 4 to 5 m/s for sand), and that above the threshold the amount moved rises with the cube of the speed. Trees, stubble and crop strips all roughen the ground and slow the wind in the lowest meter, holding it below the threshold, so that grains never begin to saltate and so never kick up the dust that rides in suspension. Because moving sand depends on the cube of the wind, a week of gales can move more soil than a year of ordinary breezes, so the protection has to be in place before the storm, not after it, which is why Bennett wanted the soil covered all year round.

6.4 Rapid Canyon Carving: Mount St. Helens (1982) and Canyon Lake Gorge, Texas (2002)

OBJECTIVES

- Tell how the Canyon Lake Gorge was cut in days in 2002 and how a mudflow and the floods after it cut canyons at Mount St. Helens from 1982 on, and name the processes (plucking, abrasion, hydraulic action) that did the work.
- Explain why a river's power to erode rises steeply with its flow, so that one great flood can do more than many ordinary years, and why a canyon's depth does not by itself tell its age.
- Compute canyon-cutting rates from measurements and state the museum claim, the observation and the creation reading for a canyon's age.

Warm-up. Pack a cup of damp sand into a tray and tilt it slightly. Pour 100 mL of water onto the top from a spoon, a little at a time, over a full minute. Look at the channel it cut. Smooth the sand flat again and pour another 100 mL all at once from a cup. Compare the two channels in one sentence: same water, what was different?

Video. Coming soon. Canyon Lake Gorge Texas 2002 flood formation, Mount St. Helens 1980 eruption and 1982 mudflow canyons, how floods carve bedrock, stream table canyon demonstration, Grand Canyon layers; search USGS, Texas Water Development Board, NASA Earth Observatory, Smithsonian, PBS, Moody Science classics and nature-documentary channels.

KEY TERMS

canyon (gorge)
A deep, narrow valley with steep rock walls cut by flowing water.

discharge
The amount of water a river carries past a point each second, measured in cubic meters per second (m^3/s).

stream power
The rate at which a stream can do work on its bed. It rises steeply with discharge and slope, so a flood many times larger than normal has far more than many times the power.

plucking
Erosion in which fast water pries whole blocks of rock loose along cracks and carries them away. It is the main way floods cut bedrock canyons quickly.

abrasion
Wearing away of a river bed by sand and stones the water drags and bounces along it.

lahar

A fast-moving mudflow of volcanic ash, rock and water, often made when an eruption melts snow and ice.

CORE IDEAS

The story. In the first week of July 2002 rain fell on the Texas Hill Country as if it would never stop; in places nearly a meter fell in a week. Canyon Lake, a reservoir on the Guadalupe River north of San Antonio that the U.S. Army Corps of Engineers had finished in 1964, filled to the brim and, for the first time in its history, spilled over its emergency spillway, a wide grassy saddle beside the dam. Water poured down the gentle valley below for about six weeks, and at its height the flow reached roughly 1,450 cubic meters per second, more than a large river. When the water finally dropped, the people of Comal County walked out to look and found that the valley was gone. In its place lay a gorge 2.2 km long and about 7 m deep, in places 12 m, with vertical rock walls, waterfalls, pools and fresh springs. The flood had stripped off the soil and gravel and cut straight down into the limestone bedrock, laying bare its layers, its fossil shells and even dinosaur footprints that had been buried under meters of rock. Visitors said it looked ancient. It was a few weeks old.

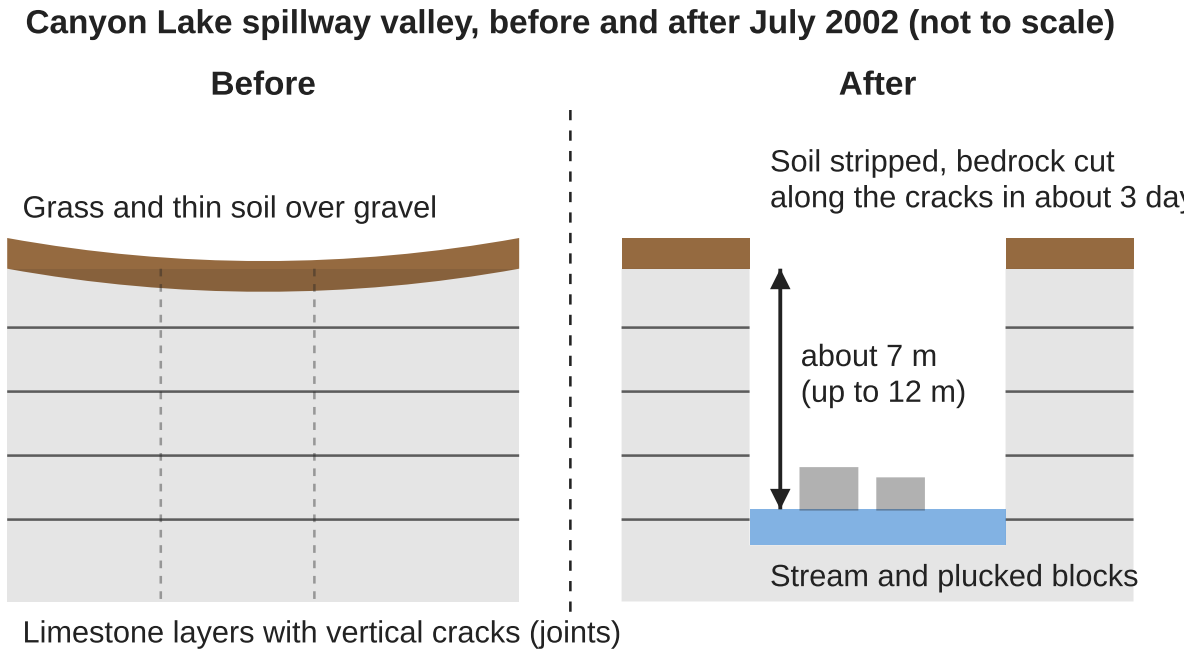
How they figured it out. Two geologists, Michael Lamb and Mark Fonstad, set out to learn exactly how the gorge had been cut. They had something geologists almost never have: surveys of the valley from before the flood, a day-by-day record of the flow, and a fresh canyon to measure. They found that most of the cutting had happened not over six weeks but in about three days, at peak flow. The water had not ground the rock away grain by grain. It had **plucked** it. Limestone is cut by cracks called joints into blocks, and when the flow grew strong enough it pried the blocks up and rolled them downstream, leaving stepped waterfalls that retreated upstream the way Niagara does. Below a certain flow nothing moved; above it the canyon deepened by meters a day. Their study, published in 2010 in *Nature Geoscience*, gave scientists a measured example of a bedrock canyon carved by one flood. A better-known example had come twenty years earlier. On May 18, 1980, Mount St. Helens in Washington erupted. The north side of the mountain slid away in the largest landslide ever recorded, 2.5 km^3 of rock that filled the North Fork Toutle River valley to an average depth of 45 m, and hot flows of ash and pumice buried the land north of the crater under a plain of loose deposits. On March 19, 1982, a smaller eruption melted snow in the crater and sent a **lahar**, a mudflow, across that plain. Within hours it had cut channels through deposits laid down only two years before, and over the next few years floods and streams deepened them into canyons tens of meters deep, which U.S. Geological Survey scientists mapped as they grew.

The big idea. Water cuts rock in three ways. **Hydraulic action** is the pounding and prying of the water itself. **Abrasion** is the sandpapering of the bed by sand and stones dragged along it. **Plucking** lifts out whole blocks along cracks. All three depend on **stream power**, which grows much faster than the flow does: a flood with ten times the normal discharge has far more than ten times the power, because it is also deeper and faster. And rock has thresholds. A block that an ordinary flow cannot budge in a thousand years is rolled away the first hour a big enough flood arrives. So the work of cutting a canyon is not spread evenly over time; most of it may be done in a few rare days. Mount St. Helens shows how fast loose

material goes; Canyon Lake shows that hard limestone can go nearly as fast when the water is big enough. Both canyons have steep walls, exposed layers, waterfalls and a small stream at the bottom that could never have cut them. A canyon's depth tells you how much rock was removed. It does not tell you how long the removal took. For that you need to know how big the water was, which is exactly what the rock cannot tell you by itself.

In the world today. Engineers learned from Canyon Lake. Emergency spillways on many dams are simply grassed slopes over soil and rock, built in the hope that they will rarely be used. In February 2017 the main spillway of Oroville Dam in California broke apart during heavy rains, water went over the emergency spillway for the first time, and the hillside below eroded so fast that nearly 190,000 people downstream were told to leave. Spillways are now tested against the question Lamb and Fonstad asked: how big a flow will start to pluck this rock? Geologists use the same thinking to read the past, working backward from the boulders moved and the channels cut to how large and fast the water must have been, as you will see in the next unit on the Channeled Scablands.

God's handiwork. Job said that the waters wear the stones, and Genesis tells us that after the Flood the waters returned from off the earth continually, draining over the land for months. A draining ocean is more water than any spillway has ever carried. Canyon Lake Gorge and the canyons at Mount St. Helens are small, measured samples of what water does when there is enough of it, and they teach humility about time. Two canyons can look alike, one cut in days and one that a sign says took millions of years, and the honest observer admits that the look of the rock cannot tell them apart. What we can measure, we measure; what we cannot, we hold with an open hand, trusting the record God has given in His word and in His world.



The Canyon Lake spillway valley before and after the July 2002 flood. Water stripped the soil and plucked limestone blocks along their cracks, cutting a gorge 2.2 km long and about 7 m deep in about three days of peak flow.

⏳ Thinking About Time

What the sign says. Textbooks and park signs say the Colorado River carved the Grand Canyon slowly, a little each year, over about 5 to 6 million years, and that the Glen Rose Limestone exposed in Canyon Lake Gorge is Cretaceous, laid down about 110 million years ago. (Cretaceous is a museum word for a set of rock layers; you will see it on signs.)

What we observe. We observe that a lahar and the floods that followed it cut canyons tens of meters deep through loose volcanic deposits within a few years at Mount St. Helens after 1982, and that a flood of about 1,450 m^3/s cut about 7 m of limestone bedrock in roughly three days at Canyon Lake in 2002. We observe that both canyons have steep walls, exposed layers, waterfalls and small streams that could not have cut them. The measured rate in a big flood is millions of times faster than the slow rate assumed for the Grand Canyon, and no one measured the Colorado River millions of years ago.

How Christians read it. Christians who hold to a recent creation read the Grand Canyon and other great canyons as cut rapidly, either as the Flood waters drained off the continents (Genesis 8:3) or when large lakes left behind after the Flood broke through their rims and emptied in days. The rapid canyons of 1982 and 2002 are small-scale examples that such carving really happens. Both readings agree on what the rock is and how water cuts it; they differ on how much water and how much time, and the time is the part that was not observed.

Try it. Pour 1 L of water on a damp sand slope slowly over ten minutes, then pour 1 L all at once on a fresh slope. Measure both channels and write one sentence about what the depth of a channel can and cannot tell you.

Genesis 8:3

PICTURE STUDY



Mount St. Helens Erupting, May 18, 1980, Austin Post, United States Geological Survey, May 18, 1980 · Color photograph taken from an aircraft · U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington

Austin Post was a glacier scientist who had spent decades photographing mountains from the air for the U.S. Geological Survey. On the morning of May 18, 1980, he flew toward Mount St. Helens and photographed the eruption in progress, a column of ash climbing more than 20 km into the sky from a summit that had just lost its top 400 m.

Everything in this lesson's Mount St. Helens story begins in this picture. The missing north side of the mountain had already slid into the valley below as the largest landslide ever recorded, the hot flows that built the pumice plain were pouring north out of the crater, and the ash falling from this cloud would be the material that a mudflow would carve into canyons two years later.

Look closely

- Find the top of the mountain. Does it look like a cone or like something has been taken away?
- Look at the shape of the ash column. Where does it rise straight up, and where does it spread sideways? What does that tell you about the air high above?
- Compare the size of the forested ridges in the foreground with the column. About how many times higher than the ridges does the ash reach?
- Where would the material that fell from this cloud and flowed out of the crater end up? Which direction did the 1982 mudflow take?

Talk about it

1. The 1980 deposits were laid down in hours and were cut into canyons within a few years of 1982. What does this teach about how fast both deposition and erosion can happen?
2. Why was it important that USGS scientists mapped these deposits right away, before streams began cutting them?
3. A visitor to the Mount St. Helens canyons today sees layered walls and a small stream at the bottom. What might they wrongly conclude if they did not know the history?

> **Safety first.** This project uses several liters of water and a bucket. Work outdoors or in a bathtub, keep towels ready, and do not pour sand down the drain. Lift the bucket with two hands or have a parent help.

EXPERIMENT: TRICKLE OR FLOOD: DOES THE SAME WATER CUT A DEEPER CANYON RELEASED FAST?

Canyon Lake Gorge was cut by a few days of peak flow, not by six weeks of average flow. You will give two identical sand slopes the same total amount of water, one as a slow trickle and one as a sudden flood, and measure the channel each one cuts.

Question: Does 2 L of water cut a deeper and wider channel when it is released in 10 seconds than when it trickles out over 10 minutes? Predict which channel will be deeper, which will be longer, and where the sand that was removed will end up.

You will need

- A long shallow tub or tray at least 60 cm long, propped so it tilts gently toward one end
- Damp sand, about 10 cups, plus a thin layer of packed potting soil or coffee grounds to stand for the soil cover
- A 2 L bottle with a small hole punched in the cap for the trickle, and a 2 L jug or bucket for the flood
- A measuring jug, a bucket of water, a ruler, a wooden skewer or thin stick to probe depth
- A notebook, a pencil and a stopwatch

Steps

1. Pack damp sand into the upper two thirds of the tub to a depth of about 6 cm and smooth it into a gentle slope toward the low end. Press a 1 cm layer of soil on top. Leave the low end empty as the “river below.”
2. Mark the top of the slope where the water will land. Measure and record the slope’s height at the top, middle and bottom with the ruler.
3. Trickle trial: fill the bottle with 2 L and set it, hole down, in a cup at the top of the slope so it drips steadily onto the mark. Time how long it takes to empty; aim for about 10 minutes. Watch and jot down what the water does each minute.

4. When the bottle is empty, measure the channel: its deepest point with the skewer and ruler, its width at that point, its length, and where the washed-out sand came to rest. Sketch the channel from above and in cross-section. Record everything in a table.
5. Rebuild the slope and soil layer exactly as before, with the same measurements. Flood trial: pour 2 L from the jug onto the mark in about 10 seconds. Observe, then measure the same four things and sketch.
6. Repeat both trials once more if you have time and average the depths and widths.
7. Write a conclusion: which release cut deeper and wider, which carried sand farther, whether the slow trickle removed the soil layer at all, and how this compares with Canyon Lake's three days of peak flow versus six weeks of spill.

Tips

- Keep the slope angle, the sand dampness, the soil layer and the landing spot the same. Only the time the water takes to arrive changes.
- Watch for little waterfalls that retreat upstream in the flood trial. You are seeing the same process that cut the steps in Canyon Lake Gorge.
- If the trickle just soaks in, that is a real result: record it. Low flows often cannot move anything at all.

Check your work

- I gave both slopes the same 2 L of water and changed only how fast it arrived.
- I measured depth, width, length and where the sand went for both trials and recorded them in a table with sketches.
- I can explain, using thresholds and stream power, why the flood cut more than the trickle even though the water was the same.

FIELD NOTEBOOK

1. Draw Canyon Lake Gorge in cross-section before and after the 2002 flood, labeling the soil cover, the limestone layers, the joints (cracks), the plucked blocks and the depth of about 7 m with a scale bar.
2. Draw a timeline from May 1980 to 1985 for Mount St. Helens: the eruption and landslide, the pumice plain, the March 1982 mudflow and canyons, and the streams deepening them. Add one sentence under each event.
3. Make a Thinking About Time page for canyons in three columns: What the sign says, What we observe, How Christians read it. Fill each column with at least two facts from this lesson.

> **From history.** The first scientist to travel the length of the Grand Canyon by river was John Wesley Powell, a one-armed veteran of the Civil War who lost his right arm at Shiloh in 1862. In 1869 he and nine men set out in four wooden boats from Green River, Wyoming, and three months later six of them emerged at the foot of the canyon, having mapped a river no one had run before. Powell later became the second director of the

> U.S. Geological Survey, the agency whose scientists mapped the new canyons at Mount St. Helens 111 years after his voyage.

WORKED EXAMPLES

Example 1. Canyon Lake Gorge was cut about 7 m deep into limestone in roughly 3 days of peak flow. (a) What was the average cutting rate in meters per day and in centimeters per hour? (b) A textbook figure for how fast the Colorado River cuts down into the Grand Canyon is about 0.3 mm per year. At that rate, how long would 7 m take? (c) How many times faster was the Canyon Lake flood?

(Use the map or drawing "Seven meters of limestone in about three days." shown earlier in this lesson.)

1. (a) 7 m ÷ 3 days ≈ 2.3 m per day. In centimeters per hour: 230 cm ÷ 24 h ≈ 9.7 cm per hour, nearly 10 cm every hour.
2. (b) 7 m = 7,000 mm. 7,000 mm ÷ 0.3 mm per year ≈ 23,000 years.
3. (c) Convert the flood rate to mm per year to compare: 2.3 m per day = 2,300 mm per day × 365 days ≈ 840,000 mm per year. 840,000 ÷ 0.3 ≈ 2,800,000. The flood rate was nearly three million times the textbook rate.
4. Note what this does and does not show. It shows that bedrock can be cut millions of times faster than the slow rate when the water is big enough. It does not by itself tell us how the Grand Canyon was cut; it tells us the slow rate is not the only possibility.

Answer: (a) About 2.3 m per day, or nearly 10 cm per hour. (b) About 23,000 years at 0.3 mm per year. (c) Roughly 3 million times faster.

Example 2. At its peak the Canyon Lake spillway carried about 1,450 m³/s for roughly 3 days. The gorge it cut is about 2,200 m long and 7 m deep; assume an average width of 40 m. (a) How much water passed over the spillway in those 3 days? (b) What volume of rock and soil was removed? (c) About how many cubic meters of water passed for each cubic meter of rock removed?

1. (a) Seconds in 3 days: 3 × 24 × 3,600 = 259,200 s. Water: 1,450 m³/s × 259,200 s ≈ 376,000,000 m³, about 376 million m³.
2. (b) Rock: 2,200 m × 40 m × 7 m = 616,000 m³.
3. (c) 376,000,000 ÷ 616,000 ≈ 610. About 610 m³ of water per cubic meter of rock, roughly the volume of a small house of water for every cubic meter of limestone.
4. The width is an assumption; if the gorge averaged 20 m wide the rock volume would be half and the ratio about 1,200. Always say which numbers are measured and which are assumed.

Answer: (a) About 376 million m³ of water. (b) About 616,000 m³ of rock and soil (using a 40 m average width). (c) Roughly 600 m³ of water for every cubic meter removed.

Example 3. The 1980 landslide at Mount St. Helens moved about 2.5 km³ of rock into the North Fork Toutle valley, filling it to an average depth of 45 m along about 23 km. The summit dropped from 2,950 m to 2,549 m. (a) How much lower is the mountain? (b) What area did the landslide cover, in km²? (c) What was the average width of the filled valley? (d) Within a few years of the 1982 mudflow, canyons about 30 m deep had been cut into these deposits. What fraction of the average fill depth is that?

1. (a) 2,950 − 2,549 = 401 m, about 400 m lower.
2. (b) Volume ÷ depth = area. 2.5 km³ = 2,500,000,000 m³. 2,500,000,000 m³ ÷ 45 m ≈ 55,600,000 m² ≈ 56 km².
3. (c) Area ÷ length = width. 56 km² ÷ 23 km ≈ 2.4 km wide on average.
4. (d) 30 m ÷ 45 m = 0.67, about two thirds of the average fill depth within a few years, through loose material laid down in 1980.

Answer: (a) About 400 m. (b) About 56 km². (c) About 2.4 km. (d) About two thirds.

PRACTICE

1. EASY What happened at Canyon Lake, Texas, in July 2002, and about how long did the gorge take to form?
2. EASY Name the three ways flowing water erodes rock and say which one did most of the work at Canyon Lake Gorge.
3. EASY What is a lahar? What did the lahar of March 19, 1982, do at Mount St. Helens?

4. MEDIUM Why is it important that the Mount St. Helens canyons were cut in loose deposits while Canyon Lake Gorge was cut in limestone bedrock? What does each one teach?
5. MEDIUM A small canyon was cut 12 m deep in 4 days. A textbook gives a slow river-cutting rate of 0.2 mm per year. (a) Find the flood's rate in meters per day. (b) How long would 12 m take at the slow rate? (c) What is the one thing you would need to know to decide which rate applied to a canyon you had never seen cut?
6. MEDIUM Data reading. Three canyons compared:

   Canyon | Depth | Time to cut | Material
   Canyon Lake Gorge, Texas | 7 m | about 3 days (measured) | limestone bedrock
   Mount St. Helens channels | about 30 m | a few years after 1982 (observed) | loose ash and debris
   Grand Canyon, Arizona | about 1,800 m | about 5 to 6 million years (textbook claim) | hard layered rock

   (a) Compute the cutting rate in meters per day for the first two canyons. (b) Convert the Grand Canyon claim to meters per day (use 5.5 million years and 365 days a year). (c) Which entry in the time column is an observation and which is an interpretation? How can you tell from the table?
7. MEDIUM Data reading. A simplified record of spillway flow at Canyon Lake, with the flow needed to begin plucking limestone blocks estimated at about 600 m^3/s:

   Day | Flow (m^3/s)
   1 | 200
   2 | 900
   3 | 1,450
   4 | 1,100
   5 | 500
   10 | 150
   40 | 20

   (a) On which days was the flow above the plucking threshold? (b) Explain why the gorge grew very little between day 5 and day 40 even though water flowed the whole time. (c) If the flood had peaked at 500 m^3/s instead, what would you predict for the gorge?
8. HARD Experiment design. You want to test whether a "bedrock" layer with cracks (a slab of hard-packed damp sand scored with a knife into blocks) is cut faster by a flood than an uncracked slab. State the independent and dependent variables, at least three controls, and how you would make the result fair and repeatable.
9. HARD In three or four sentences, explain why a canyon's depth tells you how much rock was removed but not how long it took. Use the idea of a threshold and the cube-like growth of stream power in your explanation.
10. CHALLENGE Write a Thinking About Time paragraph for the Grand Canyon. State fairly what the sign says, state what has actually been observed about canyon cutting at

Mount St. Helens and Canyon Lake, and give the reading of Christians who hold to a recent creation. End with one sentence on what both readings agree about.

COMMON MISTAKES

- Thinking a deep canyon must be very old. Depth measures rock removed, not time; big floods cut meters of bedrock in days.
- Thinking erosion is spread evenly over the years. Most of a canyon's cutting may happen in a few days when the flow passes the threshold that moves blocks.
- Thinking fast carving is only possible in soft material. Mount St. Helens cut loose deposits, but Canyon Lake cut solid limestone bedrock.

Make it a game · Flood or Trickle. Make twenty cards. Half describe erosion done fast (a mudflow cuts a canyon in a day, a spillway flood plucks limestone, a dam breaks) and half describe slow or gentle processes (a stream rounds a pebble, drizzle soaks a field, a trickle over moss). Shuffle. A parent flips a card and you shout "Flood!" or "Trickle!" and then, in one breath, name the process at work (plucking, abrasion, hydraulic action, deposition) for a bonus point. Then reverse roles. First to fifteen points wins.

Scripture. "And the waters returned from off the earth continually: and after the end of the hundred and fifty days the waters were abated." (Genesis 8:3, KJV)

Moses records months of water draining off the land after the Flood. Canyon Lake Gorge and the Mount St. Helens canyons let us watch, on a small scale and with instruments, what large amounts of moving water do to rock in a short time. Observation and Scripture both tell us that fast water does great work.

Practice answers

1. After nearly a meter of rain in a week, Canyon Lake reservoir spilled over its emergency spillway for the first time. The water cut a gorge 2.2 km long and about 7 m deep into limestone bedrock. Water flowed for about six weeks, but most of the cutting happened in about three days of peak flow.
2. Hydraulic action (the force of the water), abrasion (sand and stones grinding the bed) and plucking (prying whole blocks loose along cracks). Plucking did most of the work at Canyon Lake.
3. A lahar is a fast volcanic mudflow of ash, rock and water, often made when an eruption melts snow. The 1982 lahar poured across the loose deposits from the 1980 eruption and cut channels into them within hours; floods and streams then deepened the channels into canyons tens of meters deep over the next few years.
4. Loose ash and debris are easy to erode, so the Mount St. Helens canyons show how fast water shapes soft material but could be dismissed as a special case. Canyon Lake shows that solid limestone bedrock can also be cut by meters in days when the flow is large enough, which is the harder case. Together they show rapid canyon cutting in both soft and hard material.
5. (a) 12 ÷ 4 = 3 m per day. (b) 12 m = 12,000 mm; 12,000 ÷ 0.2 = 60,000 years. (c) How much water flowed through it, and how fast: the size of the largest flow, which the rock alone cannot tell you.

6. (a) Canyon Lake: 7 ÷ 3 ≈ 2.3 m per day. Mount St. Helens: about 30 m in a few years, say 3 years or about 1,100 days, is about 0.03 m per day, 3 cm a day on average, though most of the cutting came in a few floods. (b) 5.5 million years × 365 ≈ 2.0 billion days; 1,800 m ÷ 2,000,000,000 days ≈ 0.0000009 m per day, less than a thousandth of a millimeter per day. (c) The first two times were measured by people who watched the canyons form (the table says measured and observed); the Grand Canyon time is labeled a textbook claim, because no one observed it and it comes from an assumed rate.
7. (a) Days 2, 3 and 4, about three days, which matches the finding that most cutting happened in three days. (b) Below the threshold the water could not lift blocks, so it mostly washed loose material and trickled through the channel already cut; time alone did little without enough power. (c) With the flow never reaching the threshold, the water would have stripped soil and gravel but cut little or no bedrock gorge, however long it flowed.
8. Independent variable: whether the slab is scored into blocks or left whole. Dependent variable: the depth (and volume) of the channel cut by one 2 L flood. Controls: same sand mix and dampness, same slab thickness and slope, same water volume, same pour speed and height, same landing spot, same tub. Make it fair by rebuilding both slabs the same way, running each condition at least three times, averaging, and measuring depth at the same place with the same probe. Prediction: the cracked slab will lose whole blocks and cut much deeper, as plucking did at Canyon Lake.
9. Depth measures the amount of rock gone, which is the result; time is how long the water worked, which is not written in the rock. Because rock has a threshold, flows below it remove almost nothing no matter how long they last, while stream power grows much faster than discharge, so a flood a few times larger than normal can do thousands of times the work. Therefore the same depth could come from a very long time at low flow or a very short time at high flow, and to choose between them you must know how big the biggest flow was, which the canyon cannot tell you by itself.
10. A strong answer says the sign claims the Colorado River cut the canyon slowly over about 5 to 6 million years, states that this is a claim built on a slow rate no one measured in the past, and notes the observations: a lahar and the floods after it cut canyons tens of meters deep in loose deposits within a few years of 1982 and a flood cut 7 m of limestone in about three days in 2002, and both canyons look old to visitors. It gives the creation reading that the canyon was cut rapidly by large volumes of water as the Flood drained (Genesis 8:3) or when post-Flood lakes breached, which the small modern examples show is a real process. It closes by noting that both readings agree the layers were laid down first and the canyon was cut through them afterward by water; they differ on how much water and how much time.

Unit 6 review

Answer each question. Show your work for calculations, use complete sentences for explanations, and label every part of your diagram. The test is worth 60 points.

1. (5 pts) Multiple choice. Niagara Falls keeps its height and retreats upstream because (a) the river is getting larger every year (b) a hard cap rock lies on top of softer rock that is undercut by spray (c) the soft rock lies on top of hard rock (d) ice pushes the brink back each winter. Name the hard cap rock at Niagara.
2. (5 pts) Surveys show a point on the crest of the Horseshoe Falls moved about 82 m upstream between 1842 and 1905. (a) Find the average retreat rate in meters per year. (b) At that rate, how long would the 11 km gorge have taken to form? (c) Name one reason the real answer could be very different.
3. (5 pts) Why did the Horseshoe Falls retreat more than ten times faster than the American Falls between 1842 and 1905? What makes the two falls a fair natural comparison?
4. (4 pts) Multiple choice. A delta forms because (a) the sea pushes sand up the river (b) the river speeds up at its mouth and digs a hole (c) the river slows in still water and drops its load (d) wind blows sand into the river. Which grains settle nearest the mouth, and which travel farthest?
5. (6 pts) Diagram. Draw a cross-section of a delta showing the river, the sea or lake, and the topset, foreset and bottomset beds. Label each bed with the grain size you expect in it and draw an arrow showing the direction the delta grows.
6. (5 pts) A river delivers 60 million tonnes of sediment a year. Settled mud has a density of about 1.5 tonnes per cubic meter. (a) What volume of sediment is that per year? (b) Spread evenly over a 40 km² delta lobe, how thick a layer would it make in one year? (Hint: 1 km² = 1,000,000 m².)
7. (4 pts) Multiple choice. Most wind-blown sand travels by (a) floating high in the air for hundreds of kilometers (b) hopping in low arcs near the ground (saltation) (c) rolling as whole dunes (d) dissolving in rain. Which kind of grain does travel high in the air for long distances?
8. (5 pts) Bagnold found that sand moved by wind rises with the cube of the wind speed. (a) How many times more sand does a 12 m/s wind move than a 4 m/s wind? (b) A barchan dune moved 450 m between 1960 and 2020. Find its migration rate. (c) Would a dune twice as tall, fed by the same sand, move faster or slower? Why?
9. (5 pts) Describe the two slopes of a dune and the angle of repose. Then explain in two sentences how a shelterbelt of trees or stubble left on a field keeps soil from blowing, using the idea of a threshold wind speed.
10. (4 pts) Multiple choice. Most of Canyon Lake Gorge in Texas was cut (a) over the six weeks the spillway flowed, a little each day (b) in about three days of peak flow when water plucked limestone blocks along their cracks (c) by wind after the flood (d) over thousands of years before the dam was built. What is the name of the erosion process that did most of the work?

11. (6 pts) Canyon Lake Gorge was cut about 7 m deep in roughly 3 days. (a) Find the rate in meters per day. (b) A textbook gives a slow river-cutting rate of 0.3 mm per year. How long would 7 m take at that rate? (c) In one sentence, say what a canyon's depth tells you and what it does not.
12. (6 pts) Written explanation. Write a Thinking About Time answer for a great canyon in three or four sentences: what the sign says, what has been observed about canyon cutting at Mount St. Helens and Canyon Lake, and how Christians who hold to a recent creation read it. State one thing both readings agree about.

UNIT PROJECT: MY EROSION AND DEPOSITION LAB BOOK

Put together a lab book showing how you measured erosion and deposition in four model experiments. Include: your waterfall retreat table and graph from Lesson 6.1 with a labeled cross-section of Niagara's cap rock and undercut; your delta table, graph and sketches from Lesson 6.2 with the topset, foreset and bottomset beds pointed out in a photograph or drawing of your model; your wind-tunnel bar graph of distance against grain size from Lesson 6.3 with a labeled dune cross-section and a note on the angle you measured; and your trickle-versus-flood table and sketches from Lesson 6.4 with a before-and-after drawing of Canyon Lake Gorge.

Finish with a one-page Thinking About Time summary in your own words for the Niagara Gorge or a great canyon: what the sign says, what we observe, and how Christians read it, with Genesis 8:3 or Psalm 46:2–3 copied out and one sentence on what every age built from a rate depends on.

- **Accuracy**: Rates, conversions and processes (undercutting, sorting, saltation, plucking) are correct, and every diagram is labeled with the right terms.
- **Records**: Data tables and graphs from all four experiments are the student's own, complete, dated, and averaged or repeated where the method called for it.
- **Explanation**: The Thinking About Time summary states the sign's claim fairly, names what is observed, gives the creation reading clearly, and names the assumption behind any age built from a rate.
- **Care**: The lab book is neat, the drawings are clear, and photographs or sketches of the models are mounted or described so a reader can follow the work.

Answer key

1. (b). The cap is dolostone (the Lockport), lying over softer shale and sandstone.
2. (a) 82 ÷ 63 ≈ 1.3 m per year. (b) 11,000 ÷ 1.3 ≈ 8,500 years. (c) The rate has not been constant: the river's flow was larger in the past and is smaller today after diversion, the cap thickness and soft rock varied along the gorge, and retreat happens in sudden collapses.
3. The Horseshoe Falls takes about nine tenths of the river's water, so far more water and spray attack the shale beneath it. The two falls cut the same rock layers side by side in the same climate, so rock type and weather are the same and flow is the main difference.
4. (c). Gravel and coarse sand settle nearest the mouth; silt and clay travel farthest.

5. The drawing should show flat topset beds of gravel and coarse sand at river level, sloping foreset beds of sand in front of them stepping down into the water, and a thin flat bottomset layer of silt and clay on the sea or lake floor, with an arrow pointing seaward.
6. (a) 60,000,000 ÷ 1.5 = 40,000,000 m^3. (b) 40 km^2 = 40,000,000 m^2; 40,000,000 m^3 ÷ 40,000,000 m^2 = 1 m per year.
7. (b). Fine silt and clay (dust) travel high in suspension.
8. (a) 12 ÷ 4 = 3; 3^3 = 27 times more. (b) 450 ÷ 60 = 7.5 m per year. (c) Slower, about half as fast, because the same stream of sand must move twice as much dune.
9. A dune has a gentle windward slope of about 10 to 15 degrees up which sand hops, and a steep downwind slip face at the angle of repose, about 32 to 34 degrees, where sand drops over the crest and slides. Trees and stubble roughen the ground and slow the wind in the lowest meter below the speed (about 4 to 5 m/s for sand) at which grains begin to lift. Grains that cannot lift cannot saltate or kick dust into suspension, so the soil stays.
10. (b). Plucking.
11. (a) 7 ÷ 3 ≈ 2.3 m per day. (b) 7,000 mm ÷ 0.3 mm per year ≈ 23,000 years. (c) Depth tells how much rock was removed; it does not tell how long the removal took, because that depends on how big the water was.
12. The sign says the canyon was cut slowly by its river over millions of years (for the Grand Canyon, about 5 to 6 million). What has been observed: a mudflow and the floods that followed cut canyons tens of meters deep in loose deposits within a few years at Mount St. Helens after 1982, and a flood cut about 7 m of limestone bedrock in about three days at Canyon Lake in 2002, and both look old to visitors. Christians who hold to a recent creation read great canyons as cut rapidly by large volumes of water as the Flood drained or when post-Flood lakes breached, which the modern examples show is a real process. Both readings agree that the layers were laid down first and were cut through afterward by moving water; they differ on how much water and how much time.

UNIT 7

Catastrophes

Most of the time the earth changes slowly: a river nibbles its bank, a hillside creeps, a lake gains a millimeter of mud. But some of the biggest marks on the land were made in days. In this unit you will study catastrophes the way a geologist does: by measuring what they left behind. You will walk the dry channels of eastern Washington with J Harlen Bretz, who argued for forty years that a flood deeper than any river had torn across the land in days, and was finally proved right. You will stand at the quarry wall of Dinosaur National Monument, where Earl Douglass found eight tail bones in a row in 1909 and uncovered a graveyard of about 1,500 bones buried fast by moving water.

Then you will go to the root of the argument. At Siccar Point in 1788 James Hutton read the rocks as a record of immense time, and Charles Lyell turned that reading into a rule: explain the past only by slow processes seen today. Georges Cuvier and William Buckland disagreed, and so, a century later, did the rocks of the scablands. You will learn to separate uniformity of law, which every scientist accepts, from uniformity of rate, which is an assumption, and to calculate how the same pile of layers gives wildly different ages depending on the rate you assume.

Finally you will read Genesis 7 and 8 as what they are: a dated log of a year-long catastrophe, with two sources of water, 150 days of prevailing, and a slow draining that ended with a promise. Every lesson in this unit carries a Thinking About Time box, because catastrophes are where the age question comes up most sharply. You will practice stating what the museum sign says, what is actually observed, and how Christians who hold to the Flood read the same evidence, fairly and without mockery, with Psalm 46 in mind: “though the waters thereof roar and be troubled,” God is our refuge.

BEFORE YOU BEGIN

- Knows how rock layers form from sediment and can name a few sedimentary rocks (sandstone, mudstone, limestone) and read a simple cross-section (Units 5 and 6).
- Can describe erosion and deposition by water and give one example of rapid canyon cutting (Unit 6).
- Can convert between millimeters, centimeters, meters and kilometers, find percents and averages, and work a rate problem (distance or thickness divided by time).
- Can read a data table and a line graph and state what a variable is.

MASTERY CHECKLIST

- I can describe the main landforms of the Channeled Scablands, explain how Glacial Lake Missoula formed and drained, and tell why Bretz’s flood was rejected in 1927 and accepted later.
- I can explain what a bone bed is, list the clues (articulation, wear, current alignment, rock type) that show rapid burial by moving water, and read a bone count or

orientation table.

- I can define uniformitarianism and catastrophism, name Hutton, Lyell, Cuvier and Buckland, and distinguish uniformity of law from uniformity of rate.
- I can calculate how long a layer or canyon would take under different assumed rates and say which assumption each answer depends on.
- I can place the events of Genesis 7 and 8 on a timeline, convert the ark’s dimensions to meters, and list what a global Flood would be expected to leave in the rocks.
- I can write a Thinking About Time box for any catastrophe: what the sign says, what we observe, and how Christians read it.

OPTIONAL BOOKS AND RESOURCES

- **National Park Service, Ice Age Floods National Geologic Trail** (https://www.nps.gov/iafl/index.htm): Free. Maps, photographs and short explanations of Glacial Lake Missoula, the scablands and Dry Falls for Lesson 7.1. Read the dates on the pages as the sign’s claim and talk through the Thinking About Time box.
- **National Park Service, Dinosaur National Monument** (https://www.nps.gov/dino/index.htm): Free. Photographs of the Quarry Exhibit Hall wall, a list of the dinosaurs found there, and the story of Earl Douglass for Lesson 7.2. Have your student find and count bones in a photo of the wall.
- **James Hutton, Theory of the Earth (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/search/?query=Hutton+Theory+of+the+Earth): Free. For a parent to browse with Lesson 7.3; the prose is heavy, but reading aloud the famous closing lines of Hutton’s 1788 paper gives students the voice of the man himself.

7.1 The Channeled Scablands and J Harlen Bretz ★

OBJECTIVES

- Describe the main landforms of the Channeled Scablands (coulees, Dry Falls, giant current ripples, erratic boulders) and explain why J Harlen Bretz said only a flood could have made them.
- Explain how Glacial Lake Missoula formed behind an ice dam and how its sudden draining carved eastern Washington, using discharge, volume and time in metric units.
- Tell how Bretz's idea was rejected in 1927 and accepted decades later, and state what that story teaches about evidence, assumptions and patience in science.

Warm-up. Fill a cup with water and set it at one end of a cookie sheet covered with a thin layer of flour or dry dirt. First pour the water out slowly over two minutes. Look at the marks it leaves. Smooth the flour, refill the cup, and this time dump the whole cup in one second. Compare the two patterns. Which one cut channels? Which one left the flour almost untouched? Write one sentence about what the speed of the water did.

Video. Coming soon. Channeled Scablands, Dry Falls and the Missoula floods, J Harlen Bretz and Glacial Lake Missoula (search USGS, National Park Service Ice Age Floods National Geologic Trail, Washington State Parks, Smithsonian, PBS Nova and Oregon Public Broadcasting science clips, and aerial drone footage of Grand Coulee and Dry Falls).

KEY TERMS

scabland
Bare, rocky land stripped of its soil, where channels have been cut into hard basalt. In eastern Washington the scablands cover about 40,000 square kilometers.

coulee
A steep-walled, dry channel cut into basalt by floodwater. Grand Coulee is about 80 km long.

ice dam
A wall of glacier ice that blocks a river valley and holds back a lake.

discharge
The volume of water flowing past a point each second, measured in cubic meters per second (m^3/s).

erratic
A boulder of rock that does not match the bedrock where it sits, carried there by ice or by floodwater rafting icebergs.

giant current ripple
A ripple mark shaped like the ones in a stream bed but as tall as a house, left by deep, fast floodwater.

CORE IDEAS

The story. In the summer of 1922 a geologist from the University of Chicago named J Harlen Bretz (he insisted that the J had no period) began walking the dry plateau of eastern Washington. He had been a high-school biology teacher in Seattle before he became a geologist, and he had a teacher's habit of looking hard at things. What he saw made no sense. The soil had been stripped away from an area about the size of Massachusetts and Connecticut together, leaving bare black basalt cut by a tangle of dry channels, some of them hundreds of meters deep. The channels braided and crossed each other the way the ripples in a sandy stream bed do, but on a scale of kilometers. In Grand Coulee stood Dry Falls, a horseshoe-shaped cliff about 5.6 km wide and 120 m high with no river at all. Bretz named the region the **Channeled Scablands**, and in 1923 he published a paper saying what he thought it meant: a flood of water deeper than any river on earth had rushed across this land in a matter of days.

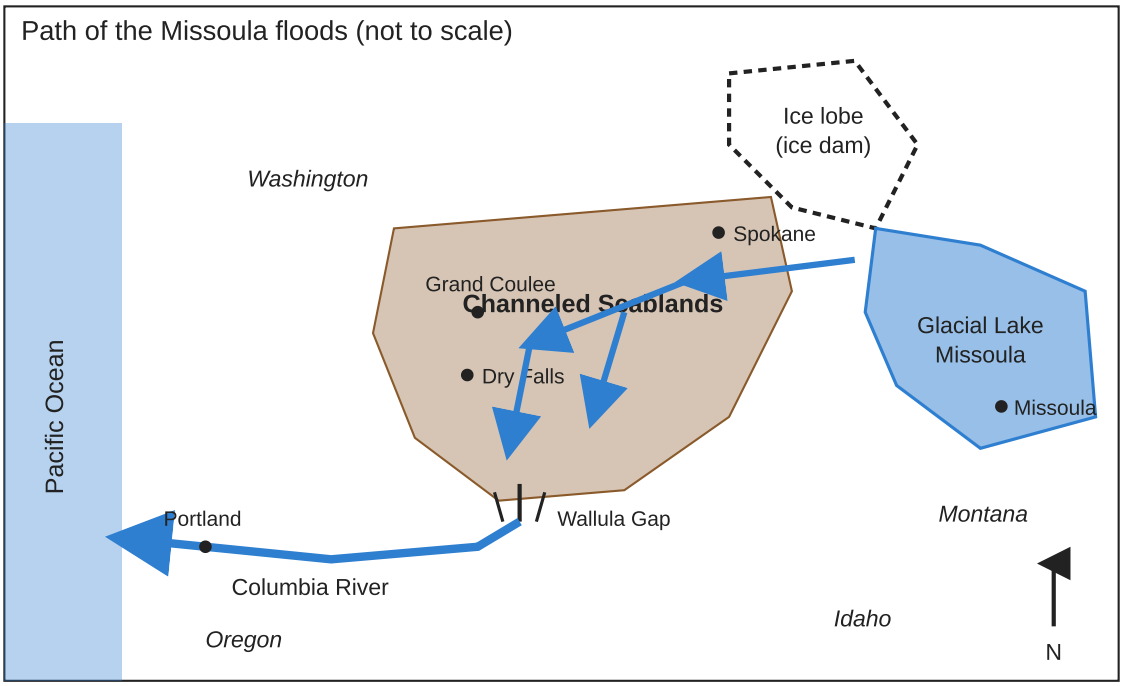
How they figured it out. Bretz listed the evidence like a lawyer. Streams cut narrow V-shaped valleys over long ages; these channels had flat floors and vertical walls, as if gouged all at once. The channels ran uphill in places and spilled over divides, which only water hundreds of meters deep can do. Huge mounds of gravel sat in the channels like the bars in a creek bed, but the gravel was made of boulders. Pieces of granite from Montana and Canada lay on top of Washington and Oregon basalt, hundreds of kilometers from home: **erratics**, which Bretz said had been carried on icebergs floating in the flood. On January 12, 1927, Bretz presented his flood to the Geological Society of Washington in Washington, D.C., and a room full of senior geologists took turns rejecting it. Their main complaint was reasonable: where could so much water have come from? Bretz did not yet know. But another geologist, Joseph Thomas Pardee of the U.S. Geological Survey, had been studying an ancient lake in western Montana since 1910. In 1940 Pardee showed that **Glacial Lake Missoula** had drained suddenly. His best evidence was ripple marks in the lake floor at Camas Prairie, Montana, up to about 15 m high and spaced hundreds of meters apart: **giant current ripples**, the footprints of water moving incredibly fast. Here was Bretz's source.

The big idea. A lobe of the great northern ice sheet had pushed south into the valley of the Clark Fork River in Idaho and blocked it, forming an **ice dam**. Behind it the river backed up into a lake that reached about 600 m deep at the dam and held roughly 2,100 cubic kilometers of water, about as much as Lake Erie and Lake Ontario together. You can still see its old shorelines as horizontal lines on the hills above Missoula, Montana. Ice floats, and when the lake rose high enough, the dam lifted, cracked and burst. Geologists estimate the peak **discharge** at about 17 million cubic meters per second, around ten times the flow of all the rivers of the world combined. The flood crossed Idaho and Washington, stripped the soil, cut the coulees, and backed up behind the narrow Wallula Gap on the Columbia River to form a temporary lake roughly 300 m deep. It then poured down the Columbia past the site of Portland, where the water stood about 120 m deep, and out to the Pacific. All of this took only days.

In the world today. Bretz went back in 1952 with new aerial photographs and found the pattern of channels even clearer from the air. By the 1960s nearly every geologist agreed

with him, and in 1979, at age 96, he received the Penrose Medal, the highest award of the Geological Society of America. He joked to his son that all his enemies were dead, so he had no one left to gloat over. Today the National Park Service runs the Ice Age Floods National Geologic Trail across four states, and Dry Falls has a visitor center on its rim. Scientists also use the Missoula floods to understand giant flood channels photographed on Mars by NASA spacecraft. The scablands have become a textbook example of how a land can be reshaped by a single, brief, enormous event.

God's handiwork. The flood that carved the scablands was far smaller than the Flood of Noah, but it teaches the same lesson about water. Psalm 46 speaks of waters that "roar and be troubled" and of mountains shaken by them, and then says that the God who rules such waters is our refuge. It also teaches a lesson about scientists. The men who laughed at Bretz in 1927 were not foolish; they held a rule, learned from Charles Lyell, that geologists should explain the past only by slow processes seen today. The rock did not fit the rule, so they doubted the rock. Bretz trusted what he could measure. A Christian naturalist should do the same: look, measure, record, and let the evidence speak, even when it says something the experts have ruled out.



The path of the Missoula floods (not to scale). The ice dam near today's Idaho–Montana border failed, and the lake emptied across eastern Washington and down the Columbia River in a few days.

⏳ Thinking About Time

What the sign says. What the sign says: The visitor-center signs and most textbooks say the Missoula floods happened near the end of the last Ice Age, between about 18,000 and 15,000 years ago, and that the ice dam re-formed and burst dozens of times, perhaps 40 or more. The thin repeating layers of the Touchet Beds near Walla Walla are counted as one layer per flood.

What we observe. What we observe: The coulees, Dry Falls, the gravel bars, the giant ripples at Camas Prairie, the shorelines above Missoula and the erratic boulders in the Willamette Valley are all there today for anyone to measure. No one watched a flood. The number of floods and the years between them are worked out from the layers and from dating methods that rest on assumptions about starting amounts and constant rates.

How Christians read it. How Christians read it: Creation geologists accept Bretz's flood completely; it is one of the best-documented catastrophes in geology. They place the Ice Age after the Flood of Genesis, when warm oceans and cooled continents would have piled up snow quickly, so they read the Missoula floods as happening only a few thousand years ago. Some think there were fewer floods than the textbook count, with many of the thin layers laid down by surges within one flood. Everyone agrees on the main point: a canyon system that geologists once said must have taken ages was cut in days.

Try it. Measure the height of the largest ripple you can find in a stream or puddle edge. Divide 15 m by your ripple height to see how many times bigger the Camas Prairie ripples are.

Psalm 46:2–3

PICTURE STUDY



Dry Falls, near Coulee City, Washington, Unknown photographer, U.S. Bureau of Reclamation, September 1935 · Black-and-white photograph · National Archives and Records Administration, Bureau of Reclamation albums of the Columbia Basin Project (public domain); copy on Wikimedia Commons

Dry Falls is a horseshoe-shaped cliff about 5.6 km wide and 120 m high at the head of lower Grand Coulee. Today only a few small lakes lie at its foot. Photographs like this one, taken by

a government survey crew in 1935, show what Bretz saw when he arrived in the 1920s: a waterfall with no water, far larger than Niagara.

When the Missoula floodwater poured over this cliff, geologists estimate it was more than 100 m deep above the brink, so the falls were probably drowned and looked more like a huge rapid than a waterfall. The cliff retreated upstream as the water tore blocks of basalt from its face, the way Niagara retreats today, but in days instead of centuries.

Look closely

- Find the curved edge of the cliff. Compare its shape to the brink of Niagara's Horseshoe Falls, which you studied in Unit 6.
- Look for the plunge-pool lakes at the base. What would have dug those hollows?
- Notice how bare and flat the plateau above the cliff is. Where did the soil go?
- Look for horizontal lines in the cliff face. Each is a separate basalt lava flow, laid down before the flood cut through them.

Talk about it

1. If you saw this cliff with no river nearby, what would you guess had happened here? What evidence would you look for next?
2. Why did Bretz think the water had to be deep as well as fast?
3. What makes a photograph useful evidence in science, and what can it not tell you?

> **Safety first.** This project uses water and loose sand or soil. Work outdoors or over a large tray, wipe up spills so no one slips, and wash hands afterward.

EXPERIMENT: BURST DAM IN A TRAY

Bretz's critics asked how a flood could cut channels into solid rock in days. You will test the simplest part of his claim: does the same amount of water do more work when it is released all at once than when it trickles out slowly?

Question: How does the speed of release change the channel a flood cuts? Prediction: write yours before you begin. What we change: how fast the water is released. What we keep the same: the amount of water, the slope and the sand. What we measure: the length, width and depth of the deepest channel.

You will need

- A large shallow tray, baking pan or plastic storage-box lid
- About 2 liters of damp sand or fine soil
- A plastic cup or small container that holds 250 mL, and a measuring cup
- A stack of books to tilt the tray
- A ruler, a pencil, and your lab notebook
- Optional: a few pebbles and small twigs to act as boulders and trees

Steps

1. Spread the sand about 2 cm deep across the tray and smooth it. Prop one end on books so the tray slopes gently, about the height of one book per 30 cm of tray.
2. Trial 1 (slow release): hold 250 mL of water in the cup at the high end and pour it out as slowly as you can over a full minute. Let the tray drain for a minute. Measure the longest channel: its length, its width at the widest point and its depth at the deepest point. Record all three in a table.
3. Smooth the sand completely. Make sure it is still damp.
4. Trial 2 (burst release): hold the same 250 mL at the same spot and dump it all in one second. Drain, then measure the same three things.
5. Repeat each trial twice more so you have three slow and three burst results. Find the average of each measurement.
6. Optional: place pebbles and twigs in the sand before a burst trial. Record where they end up. Did the water move them or leave them? Compare with the erratics of the scablands.
7. Write a conclusion: Did the burst flood cut a deeper or wider channel than the slow flow? By how many times? Did it leave a flat-floored channel or a narrow groove? Was your prediction right?

Tips

- Damp sand holds a channel shape better than dry sand. If the sand is too wet, the whole surface turns to mud and you cannot measure anything.
- If the burst water simply splashes off the tray, lower the slope and pour from closer to the surface.
- Three trials of each kind are the minimum. Real scientists would do many more and report the spread of results, not just the average.

Check your work

- I can explain why the same volume of water cuts a larger channel when it is released faster.
- I kept the water volume, slope and sand the same in every trial and changed only the release speed.
- I recorded length, width and depth for every trial in a table and found the averages.

FIELD NOTEBOOK

1. Draw a map of the flood’s path from Glacial Lake Missoula to the Pacific, with the ice dam, Spokane, Grand Coulee, Dry Falls, Wallula Gap and Portland labeled. Add a scale bar of 100 km and a north arrow.
2. Sketch a cross-section of Dry Falls as it is today and, beside it, the same cliff with floodwater 100 m deep pouring over it. Label the brink, the plunge pool and the water surface.

3. Make a two-column evidence table titled “Bretz’s Case.” Left column: each landform he found. Right column: why a slow river could not have made it.

From history. The ice dam that held Glacial Lake Missoula was a lobe of the Cordilleran ice sheet that pushed south down the Purcell Trench into the Clark Fork valley near today’s Idaho–Montana border. Joseph Pardee named Glacial Lake Missoula in 1910 after measuring the faint horizontal shorelines on the hills around Missoula, Montana, where they are still visible from downtown on Mount Sentinel and Mount Jumbo. The highest line stands more than 300 m above the city. Pardee kept his thoughts about a sudden drainage mostly to himself for thirty years; it was his 1940 talk in Seattle, describing the giant ripples at Camas Prairie, that gave Bretz the water he needed.

WORKED EXAMPLES

Example 1. Glacial Lake Missoula held about 2,100 cubic kilometers of water. If it drained at the estimated peak discharge of 17 million cubic meters per second the whole time, how long would the lake take to empty? Give the answer in hours.

1. Convert the lake volume to cubic meters. One cubic kilometer is 1,000 m × 1,000 m × 1,000 m = 1,000,000,000 m^3 (one billion). So 2,100 km^3 = 2,100 × 1,000,000,000 = 2,100,000,000,000 m^3, or 2.1 × 10^{12} m^3.
2. Divide the volume by the discharge to get the time in seconds: 2,100,000,000,000 ÷ 17,000,000 ≈ 123,500 seconds.
3. Convert seconds to hours: 123,500 ÷ 3,600 ≈ 34 hours.
4. Check the sense of the answer. The real flow started small, peaked and then fell, so the lake took longer than this, roughly two to three days. The calculation shows the order of magnitude: days, not centuries.

Answer: About 34 hours at peak discharge; in reality a few days, because the flow was not at its peak the whole time.

Example 2. The Amazon, the largest river on earth, has an average discharge of about 209,000 m^3/s. How many Amazons flowing at once would equal the Missoula flood’s peak discharge of 17,000,000 m^3/s?

1. Set up the ratio: flood discharge ÷ Amazon discharge = 17,000,000 ÷ 209,000.
2. Simplify by dividing both numbers by 1,000: 17,000 ÷ 209 ≈ 81.3.
3. Round to a sensible figure. Both inputs are estimates, so say about 80.

Answer: About 80 Amazon Rivers flowing at once.

Example 3. Dry Falls is about 5.6 km wide and 120 m high. Niagara's Horseshoe Falls is about 670 m wide and 57 m high. How many times wider and how many times higher is Dry Falls?

1. Put both widths in the same unit: 5.6 km = 5,600 m.
2. Width ratio: 5,600 ÷ 670 ≈ 8.4.
3. Height ratio: 120 ÷ 57 ≈ 2.1.
4. State the comparison in words: Dry Falls is more than 8 times wider and about twice as high as Horseshoe Falls, and when it ran, the water over its brink was deeper than the whole height of Niagara.

Answer: About 8 times wider and about 2 times higher.

PRACTICE

1. EASY What is a coulee, and what cut the coulees of eastern Washington?
2. EASY In what year did Bretz first publish his flood idea, and in what year did he receive the Penrose Medal? How many years passed between them?
3. EASY Why did the ice dam burst instead of simply melting away slowly?
4. MEDIUM A granite boulder from Montana sits on basalt bedrock in Oregon's Willamette Valley. Explain in two sentences how Bretz said it got there and why a normal river could not have carried it.
5. MEDIUM Convert the volume of Glacial Lake Missoula, 2,100 km^3, into liters. (1 m^3 = 1,000 L.)
6. MEDIUM Data reading. A geologist measures ripple marks at four places. Stream bed A: ripples 1 cm high, 8 cm apart, water 10 cm deep. River bar B: ripples 10 cm high, 1 m apart, water 2 m deep. Tidal channel C: ripples 50 cm high, 6 m apart, water 8 m deep. Camas Prairie D: ripples 15 m high, 150 m apart, water depth unknown. (a) As ripple height increases, what happens to the spacing? (b) Which place had the deepest water when the ripples formed, and how does the pattern in the table support your answer?
7. MEDIUM Data reading. The table shows how a lake drains after a dam fails. Hour 0: discharge 2 million m^3/s. Hour 6: 10 million. Hour 12: 17 million. Hour 24: 12 million. Hour 48: 4 million. Hour 72: 0.5 million. (a) When was the peak? (b) Was the flow above 10 million m^3/s for more or less than 24 hours? (c) Explain why multiplying the peak discharge by the total time would overestimate the water released.
8. HARD Experiment design. You want to test whether a deeper flood moves bigger pebbles. Using a tray of sand, water and pebbles of three sizes, describe the independent variable, the dependent variable, two things you would keep the same, and how you would record the result.
9. HARD Write a short paragraph explaining why the geologists of 1927 rejected Bretz's flood, and what finally changed their minds.
10. CHALLENGE Water backed up behind Wallula Gap to about 300 m deep. If the gap is about 2 km wide at the base and the water flowed through at an average speed of 20 m/s,

estimate the discharge through the gap. (Treat the cross-section as a rectangle.)

COMMON MISTAKES

- Thinking the Missoula floods were caused by rain. The water came from a lake held back by an ice dam; the dam failed and the lake emptied.
- Picturing Dry Falls as a waterfall like Niagara with water dropping through the air. The flood was so deep that the cliff was drowned, and the water tore the rock from below as a giant rapid.
- Assuming that big landforms always mean long times. Bretz's scablands show that the size of a feature tells you how much energy was used, not how long it took.

Make it a game · Bretz on Trial. One player is Bretz, the others are the 1927 geologists. The geologists take turns naming one scabland feature from the lesson (Dry Falls, erratic boulders, giant ripples, channels crossing divides, gravel bars, the Missoula shorelines). Bretz has fifteen seconds to explain how a flood made it and why a slow river could not. A convincing answer scores a point for Bretz; a stumble scores for the geologists. Swap roles after six features. Finish by having everyone name the one piece of evidence that would have convinced them in 1927.

Scripture. "Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah." (Psalm 46:2–3, KJV)

The psalm pictures the kind of roaring water Bretz discovered in the rocks of Washington, water that can move mountains of gravel. It then says the right answer to such power is not fear but trust in the God who made and rules it.

Practice answers

1. A coulee is a steep-walled, flat-floored dry channel cut into basalt. The coulees were cut by floodwater from Glacial Lake Missoula.
2. He published in 1923 and received the medal in 1979: 56 years.
3. Ice floats. When the lake grew deep enough, the water lifted and cracked the ice dam, and once water began to flow under and through it, the dam failed quickly.
4. The boulder was frozen into an iceberg that floated on the floodwater; when the iceberg grounded and melted, the boulder was left behind. A normal river cannot lift a boulder weighing many tons and carry it hundreds of kilometers, but an iceberg floats it easily.
5. 2,100 km^3 = 2.1 × 10^{12} m^3 = 2.1 × 10^{15} L (2,100,000,000,000,000 liters).
6. (a) Spacing increases as height increases, roughly 10 times the height at each place. (b) Camas Prairie D. In every measured case, bigger and more widely spaced ripples go with deeper water, so ripples 15 m high point to water far deeper than 8 m, probably hundreds of meters.
7. (a) At about hour 12. (b) Less than 24 hours: it was at or above 10 million from about hour 6 to somewhere between hours 24 and 48, roughly 20 hours. (c) The discharge was below the

peak most of the time, so peak × total time would count water that never flowed.

8. Independent variable: the depth (or volume) of water released at once, for example 100 mL, 250 mL and 500 mL. Dependent variable: the largest pebble size moved, or how far each pebble size moves. Keep the same: the slope of the tray, the sand depth, the starting position of the pebbles and the pouring spot. Record: a table with water volume in one column and the distance moved by small, medium and large pebbles in the others, repeated three times each.
9. They followed Lyell’s rule that the past should be explained by slow processes seen today, and Bretz could not say where enough water had come from, so a sudden giant flood seemed unscientific. Pardee’s 1940 evidence that Glacial Lake Missoula drained suddenly supplied the source, aerial photographs in the 1950s showed the channel pattern clearly, and more field work confirmed the giant ripples and gravel bars, so by the 1960s most geologists agreed.
10. Cross-section area ≈ 2,000 m × 300 m = 600,000 m^2. Discharge = area × speed = 600,000 × 20 = 12,000,000 m^3/s, about 12 million cubic meters per second, the same order of magnitude as the estimated peak flood.

7.2 Fossil Graveyards: Earl Douglass at Dinosaur National Monument

OBJECTIVES

- Tell how Earl Douglass found the Carnegie Quarry in 1909 and describe what the quarry wall at Dinosaur National Monument shows today.
- Explain what a fossil graveyard (bone bed) is and list the evidence that its animals were buried quickly by moving water or ash rather than slowly over many years.
- Use counts, ratios and orientation data to read a bone bed the way a paleontologist does.

Warm-up. Drop ten toothpicks onto a plate from 30 cm up so they land in random directions. Now tilt the plate and let a little water run across it. Watch what happens to the toothpicks as the water flows. Draw their positions before and after. What did the moving water do to the direction they point?

Video. Coming soon. Dinosaur National Monument Quarry Exhibit Hall wall, Earl Douglass and the Carnegie Quarry, how bone beds form (search National Park Service, Carnegie Museum of Natural History, Smithsonian National Museum of Natural History, Utah Field House of Natural History, SciShow Kids, Homeschool Pop (Alternate), and paleontology field-work footage).

KEY TERMS

fossil graveyard (bone bed)
A single rock layer packed with the bones of many animals, often of several kinds, buried together.

articulated
Bones still joined in life position, as in Douglass’s row of eight tail vertebrae. Articulated bones mean the body was buried before it fell apart.

disarticulated
Bones separated from one another and mixed, which happens when a carcass rots, is scavenged or is tumbled by water before burial.

rapid burial
Covering a body with sediment within days or weeks, before decay and scavengers destroy it. Nearly every good fossil required it.

current alignment
The tendency of long objects such as sticks or bones to line up with the flow that moved them. It is a clue that water, not stillness, laid the bed.

Morrison Formation

A museum word: the name given to the broad band of mudstone and sandstone, stretching across much of the western United States, in which most famous American dinosaur quarries lie.

CORE IDEAS

The story. On August 17, 1909, a paleontologist named Earl Douglass was walking the dry hills near Jensen, Utah, close to the Green River, hunting for dinosaurs for Andrew Carnegie's museum in Pittsburgh. Near the top of a sandstone ridge he spotted eight tail bones of a giant sauropod, later named *Apatosaurus*, lying in a row exactly as they had been in life. Douglass had found the edge of something enormous. He and his crews worked that ridge for the next fifteen years, shipping more than 300 metric tons of fossil-bearing rock to Pittsburgh by wagon and rail. The animals included *Apatosaurus*, *Diplodocus*, *Camarasaurus*, *Stegosaurus*, *Allosaurus*, *Camptosaurus* and *Dryosaurus*. In 1915 President Woodrow Wilson set the site aside as Dinosaur National Monument. Today you can stand in the Quarry Exhibit Hall and look at a wall of tilted sandstone with about 1,500 bones left in the rock, just as they lie.

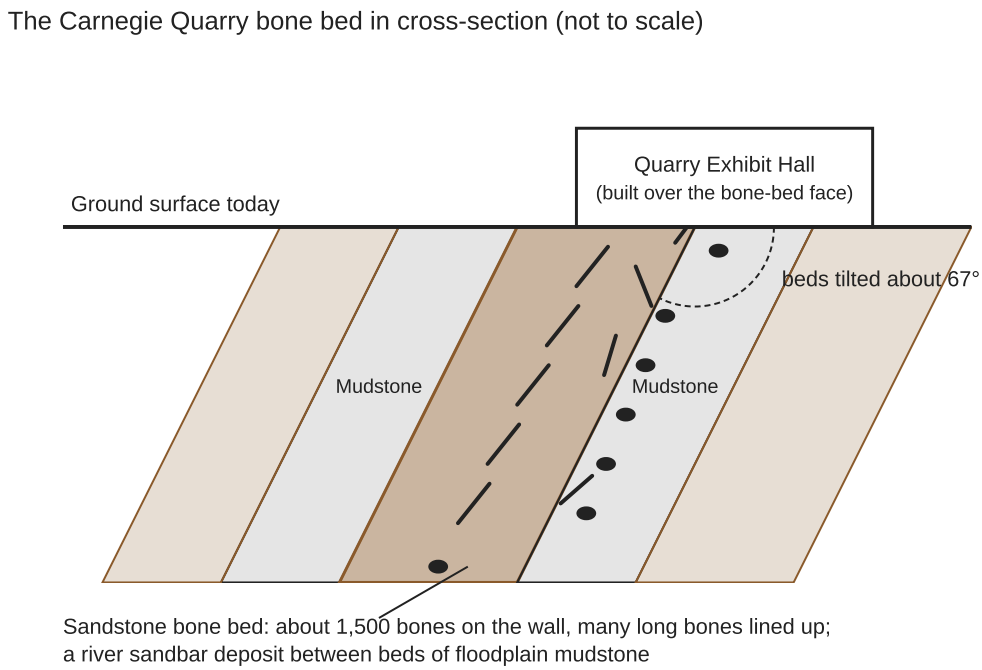
How they figured it out. A single skeleton is a treasure; a whole layer full of them is a puzzle. Douglass's quarry is a **fossil graveyard**, or **bone bed**. Paleontologists read a bone bed by asking questions a detective would ask. Are the bones **articulated**, still joined as in life, or **disarticulated** and scattered? At the quarry, most are scattered, yet a few skeletons are nearly complete, so some bodies were buried whole while others had come apart. Are the bones broken and worn, or sharp-edged? Many are whole and little worn, so they did not tumble far. Do the long bones point in random directions or line up? Many lie roughly parallel, which is **current alignment**, the signature of flowing water. What rock holds them? The bones lie in a sandstone with sloping cross-beds, the kind a river builds on a sandbar. Put together, the clues say that moving water gathered the carcasses of many animals of many kinds and dropped them in a sandbar deposit, which hardened into rock.

The big idea. Fossils are rarer than you might think. When an animal dies on land today, scavengers, insects, bacteria, sun and rain usually destroy the bones within a few years. To become a fossil, a body must be buried quickly, by sediment or ash, before that happens. That is why the great fossil graveyards all tell stories of **rapid burial**. At the Cleveland-Lloyd Dinosaur Quarry, also in Utah, more than 12,000 bones from at least 74 dinosaurs lie jumbled in one layer, and at least 46 of them are the meat-eater *Allosaurus*, far too many predators for a normal living community. At Ashfall Fossil Beds in Nebraska, whole herds of rhinoceroses, horses and camels lie complete, buried under up to 3 m of volcanic ash from an eruption about 1,600 km away in Idaho. In each case the question is not whether the burial was fast. It was. The question is what kind of event, and how big, could do it.

In the world today. The quarry wall at Dinosaur National Monument is tilted about 67 degrees from horizontal, because the layers were bent upward after they formed, when Split Mountain rose. Rangers map every bone on the wall with a numbered grid, exactly as Douglass did with paper and pencil. Many museums in the world own a Carnegie dinosaur: the skeleton of *Apatosaurus louisae*, named for Carnegie's wife, stands in Pittsburgh, and

casts of *Diplodocus carnegii* stand in London, Berlin, Paris and Vienna. The sign at the quarry says the layer is part of the **Morrison Formation**, a museum word you will see at nearly every dinosaur exhibit in America. Learning what the word means, a wide blanket of mudstone and river sandstone stretching from New Mexico to Montana, lets you read any sign accurately, whatever you conclude about its dates.

God's handiwork. The prophet Nahum wrote that "the mountains quake at him, and the hills melt, and the earth is burned at his presence." A bone bed is a record of a day when the earth did quake or flood or burn, and animals that had grazed and hunted were swept together and buried. There is a sadness in a fossil graveyard, but there is also wonder. Every bone is the work of the same Maker who formed the sauropod's great neck and the *Allosaurus*'s curved teeth, and the rock has kept them so well that a boy or girl can trace them today. The naturalist's task is to look carefully, count honestly and say what the bones show. They show creatures made with care, and they show that burial came fast.



The Carnegie Quarry in cross-section. The bone bed is a river-laid sandstone between mudstone layers; all were tilted later when Split Mountain rose. The exhibit hall is built over the exposed face.

⏳ Thinking About Time

What the sign says. What the sign says: The quarry sign says the bones lie in the Morrison Formation from the Late Jurassic, about 149 million years ago, and that a long drought killed the dinosaurs before a river in flood swept their bodies onto a sandbar. The date comes from radioactive decay in volcanic ash layers found in the formation elsewhere and from the sequence of layers above and below.

What we observe. What we observe: About 1,500 bones of at least ten kinds of animals packed in one sandstone bed, many whole and little worn, some skeletons still partly

joined, long bones lined up by a current, and the whole bed later tilted steeply. The bones, the sandstone and the cross-beds are measured; the years and the drought are inferred.

How Christians read it. How Christians read it: Creation geologists agree the animals were gathered and buried fast by moving water. They read the Morrison Formation, which spreads across more than a million square kilometers, as a deposit of the Flood year or its aftermath rather than a river valley lasting millions of years, since no modern river builds a single blanket of sediment that wide. They note that the radioactive dates rest on assumptions about starting amounts and constant rates, and that the drought story, like the Flood reading, is an interpretation of the same bones.

Try it. Count how many of the bones in a photograph of the quarry wall point within about 20 degrees of one direction. Is it more than a quarter? Random directions would give about a quarter.

Nahum 1:5

PICTURE STUDY



Leaping Laelaps, Charles R. Knight, 1897 · Watercolor on paper · American Museum of Natural History, New York

Charles R. Knight was the first great painter of dinosaurs. He worked for the American Museum of Natural History, studying bones in the museum’s halls and living animals at the zoo, then painting what the fossils might have looked like with flesh and skin. This picture shows two *Dryptosaurus* (then called *Laelaps*), meat-eaters from New Jersey, in a fight. It was painted twelve years before Douglass found his quarry.

Knight’s dinosaurs are quick and alive, unlike the sluggish, tail-dragging giants other artists drew. He got that from watching how living animals move. But remember what a painting like this is: the bones are evidence, and everything else, the color, the leap and the fight, is an artist’s careful guess.

Look closely

- Find the two animals. Which parts of them could a paleontologist know from bones alone? Which parts are guesses?
- Look at the ground. Is there any sign of how these animals might later be buried?
- Notice the tails. Why did Knight lift them off the ground when most artists of his day dragged them?
- Look at the hands and feet. Count the claws and compare with a bird’s foot.

Talk about it

1. If you found these two skeletons together in one layer, what questions would you ask before deciding they died fighting?
2. Why do museums show paintings like this beside the real bones? What is helpful about it, and what could be misleading?
3. Knight studied living lizards and birds to paint extinct animals. What does that tell you about how scientists fill gaps in evidence?

> **Safety first.** This project uses water. Work over a tray or outdoors, mop up spills and wash hands afterward. If you use real chicken bones, boil and scrub them first and let an adult handle the hot water.

EXPERIMENT: BONES IN A CURRENT

Paleontologists use the directions of long bones to tell whether a bone bed was laid down by flowing water. You will make two small bone beds, one in still water and one in a current, and measure the difference.

Question: Does flowing water line up long objects? Prediction: write yours. What we change: whether the water is moving or still. What we keep the same: the number and size of the sticks, the tray and the sand. What we measure: the angle of each stick compared with the flow direction, and the percent of sticks within 20 degrees of it.

You will need

- A shallow tray or baking pan with about 1 cm of damp sand
- 20 craft sticks or toothpicks (or 20 cleaned chicken bones of similar size) to serve as long bones
- A pitcher of water and a cup
- A protractor, a ruler, a pencil and your lab notebook
- A stack of books to tilt the tray

Steps

1. Still-water bed: lay the tray flat. Drop the 20 sticks from about 30 cm so they land in random directions. Gently pour a cup of water over them from directly above so it spreads without flowing anywhere. Let it settle.
2. Mark a flow line on the tray from one end to the other. Use the protractor to measure the angle between each stick and that line (0 to 90 degrees). Record all 20 angles in a table.
3. Count how many sticks are within 20 degrees of the line and work out the percent: (number within 20 degrees ÷ 20) × 100.
4. Current bed: smooth the sand and drop the sticks again at random. Tilt the tray on books so the flow line runs downhill. Pour the pitcher steadily from the high end for 30 seconds so water flows across the sticks.
5. Measure and record the 20 angles again, and find the percent within 20 degrees.
6. Repeat both beds twice more and average the percents. Draw a bar graph: still water versus current.
7. Write a conclusion: Did the current line the sticks up? Did any stack like a logjam? If you had found a bed with 75 percent of the bones within 20 degrees, what would you say made it?

Tips

- A random direction can be anything from 0 to 90 degrees from the line, so only about 22 percent of random sticks should fall within 20 degrees. Anything much higher means something lined them up.
- Sticks roll and point downstream most clearly when the water flows fast enough to move them but not so fast that it washes them off the tray.
- Record the angle of every stick, not only the ones that look lined up. Paleontologists call leaving out the awkward ones cherry-picking.

Check your work

- I can explain why a high percent of parallel long bones points to flowing water.
- I measured and recorded every stick in every trial and computed the percent correctly.
- I changed only one thing, moving versus still water, between my two beds.

FIELD NOTEBOOK

1. Draw the quarry wall as a rectangle tilted about 67 degrees and scatter at least twenty bone shapes in it, with some lined up and a short articulated run of tail bones like the one Douglass found. Label the sandstone and the mudstone above and below.
2. Sketch the stages of a bone bed forming as four small panels: animals alive, carcasses in moving water, bones dropped on a sandbar and covered, and the wall exposed today.
3. Make a table of the dinosaurs found at the Carnegie Quarry (Apatosaurus, Diplodocus, Camarasaurus, Stegosaurus, Allosaurus, Camptosaurus, Dryosaurus) with a column for plant-eater or meat-eater and a column for approximate length.

From history. Andrew Carnegie, the steel maker, became a dinosaur hunter after reading a newspaper story in 1898 about a colossal skeleton in Wyoming. He told his museum director to get one for Pittsburgh. The crews found *Diplodocus carnegii* at Sheep Creek, Wyoming, in 1899, and when King Edward VII admired a drawing of it, Carnegie had a full plaster cast made for the British Museum in London, unveiled in 1905. More casts followed for museums in Berlin, Paris, Vienna, Bologna, St. Petersburg, La Plata, Madrid and Mexico City. For many Europeans, the Pittsburgh cast was the first dinosaur they ever saw.

WORKED EXAMPLES

Example 1. The Carnegie Museum's *Apatosaurus louisae* is about 22 m long, *Stegosaurus* about 9 m and *Allosaurus* about 8.5 m. You want to draw all three on one page at a scale of 1:100, with a 1.5 m tall student beside them. How long is each drawing?

1. At 1:100, every 100 cm in real life becomes 1 cm on paper, so divide each real length in centimeters by 100. That is the same as writing the length in meters and changing the unit to centimeters.
2. *Apatosaurus*: 22 m = 2,200 cm → 22 cm on paper.
3. *Stegosaurus*: 9 m → 9 cm. *Allosaurus*: 8.5 m → 8.5 cm.
4. Student: 1.5 m → 1.5 cm, about the height of a fingernail beside a 22 cm sauropod.

Answer: *Apatosaurus* 22 cm, *Stegosaurus* 9 cm, *Allosaurus* 8.5 cm, student 1.5 cm.

Example 2. At the Cleveland-Lloyd Dinosaur Quarry, at least 74 individual dinosaurs have been identified, and at least 46 of them are the meat-eater *Allosaurus*. What percent of the animals are predators? In a living community of large animals, predators are usually about 1 in 10 or fewer. How many times greater than that is the quarry's share?

1. Percent predators: 46 ÷ 74 = 0.62, so about 62 percent.
2. A normal share of 1 in 10 is 10 percent.
3. Ratio: 62 ÷ 10 ≈ 6.
4. Interpretation: the bed is not a snapshot of a herd with its hunters. Something gathered or trapped an unusual number of predators, which is one reason this quarry is still debated.

Answer: About 62 percent predators, roughly six times the share expected in a living community.

Example 3. A class measures the direction of 40 long bones in a photograph of a bone bed. 28 of them point within 20 degrees of a single line. If bones were pointed at random, about what percent would fall within 20 degrees of any chosen line? Compare with the class result.

(Use the map or drawing “Many of the long bones in the quarry wall lie roughly parallel, as in this sketc” shown earlier in this lesson.)

1. A bone’s angle to a line can be anything from 0 to 90 degrees, so there are 90 degrees of possible angles.
2. The window within 20 degrees of the line covers 20 of those 90 degrees: 20 ÷ 90 = 0.22, or about 22 percent.
3. The class result: 28 ÷ 40 = 0.70, or 70 percent.
4. 70 percent is more than three times the random expectation of 22 percent, so the bones were almost certainly lined up by a current.

Answer: Random: about 22 percent. Observed: 70 percent, strong evidence of current alignment.

PRACTICE

1. EASY What did Earl Douglass find on August 17, 1909, and why was it so exciting?
2. EASY Give two reasons an animal that dies on land today usually does not become a fossil.
3. EASY What is the difference between an articulated and a disarticulated skeleton? Which tells you burial was fastest?
4. MEDIUM Douglass shipped about 320 metric tons of fossil rock between 1909 and 1924. About how many metric tons per year is that? If a railroad boxcar of that day carried about 20 metric tons, how many boxcars in all?
5. MEDIUM Name three pieces of evidence at the Carnegie Quarry that point to moving water rather than still water or dry land.
6. MEDIUM Data reading. A paleontologist sorts 200 bones from one square of a bone bed by condition. Whole and unworn: 128. Whole but rounded by tumbling: 12. Broken with sharp edges: 48. Broken and rounded: 12. (a) What percent of the bones are rounded in any way? (b) What percent are broken in any way? (c) Which conclusion do the data support best: the bones tumbled a long way in a river, or they were moved only a short distance?
7. MEDIUM Data reading. Four fossil sites are described. Site 1: 300 bones, 95 percent articulated, in fine volcanic ash. Site 2: 1,500 bones, 10 percent articulated, in cross-bedded sandstone, long bones parallel. Site 3: 20 bones, 0 percent articulated, scattered through 10 m of mudstone. Site 4: 12,000 bones, 5 percent articulated, in a single mud layer, bones in random directions. (a) Which site shows the fastest burial of whole bodies? (b) Which site best matches the Carnegie Quarry? (c) Which site is least like a single catastrophe, and why?

8. HARD Experiment design. You want to find out whether the size of a bone affects how far a current carries it. Describe a tray experiment: independent variable, dependent variable, three things to keep the same, and the table you would record.
9. HARD A museum sign calls the quarry rock “Morrison Formation, Late Jurassic.” Explain in a short paragraph what each of those words refers to, what at the site is directly observed, and what is an interpretation.
10. CHALLENGE Suppose the quarry wall exposes about 1,500 bones over an area of roughly 60 m by 15 m. (a) How many bones per square meter is that? (b) If a complete sauropod skeleton has about 200 bones, about how many complete skeletons’ worth of bone does the wall hold? (c) Why would the real number of individual animals be different from your answer to (b)?

COMMON MISTAKES

- Thinking fossils form whenever an animal dies. Most bodies are destroyed; a fossil needs rapid burial, which is why bone beds are records of unusual events.
- Assuming that animals found together lived together. A current can gather carcasses from a wide area and from different habitats and drop them in one place.
- Reading the tilt of the quarry wall as the way the bones were laid down. The sandbar was nearly flat when the bones were buried; the layer was tilted afterward when the mountain rose.

> **Make it a game · Bone Bed Detective.** Your parent describes a made-up fossil site in three clues, such as “bones of five kinds mixed together,” “most bones lined up northeast,” and “some skeletons still joined.” You have twenty seconds to say whether the site was buried fast or slowly, by water or by ash, and to name the one clue that decided it. Score a point for each correct call with a correct reason. After five sites, swap roles and invent sites for your parent. A site with contradictory clues is worth two points if you can explain the contradiction.

> **Scripture.** “The mountains quake at him, and the hills melt, and the earth is burned at his presence, yea, the world, and all that dwell therein.” (Nahum 1:5, KJV)

A bone bed is a page from a day when the earth did quake or flood or burn. Nahum reminds us that such days are not outside God’s rule; the Maker of the sauropod is the Lord of the catastrophe that buried it.

Practice answers

1. Eight articulated tail vertebrae of an Apatosaurus lying in a row as in life, near Jensen, Utah. A row of connected bones meant a large, well-preserved skeleton was likely still in the rock, and it turned out to be the edge of a huge bone bed.
2. Any two: scavengers eat and scatter the bones; bacteria and insects rot the body; sun, rain and frost break the bones down; it is not buried quickly by sediment.
3. Articulated bones are still joined in life position; disarticulated bones are separated and mixed. An articulated skeleton shows the fastest burial, before the body could fall apart.

4. 1924 − 1909 = 15 years; 320 ÷ 15 ≈ 21 metric tons per year. 320 ÷ 20 = 16 boxcar loads.
5. Any three: many long bones lie parallel (current alignment); the bones sit in a cross-bedded sandstone like a river sandbar; animals of many kinds are mixed together as a current would gather them; most bones are disarticulated but not badly worn, so they were moved but not far.
6. (a) Rounded: 12 + 12 = 24 out of 200 = 12 percent. (b) Broken: 48 + 12 = 60 out of 200 = 30 percent. (c) Moved only a short distance. Long tumbling rounds bones, and only 12 percent are rounded; most bones are whole and sharp-edged.
7. (a) Site 1: nearly all skeletons articulated and buried in ash. (b) Site 2: many bones, few articulated, river sandstone with aligned bones. (c) Site 3: few bones spread through a thick layer with none articulated, which fits slow accumulation over time rather than one event.
8. Independent variable: the length (or mass) of the stick or bone, such as 3 cm, 6 cm and 9 cm. Dependent variable: the distance each is carried downstream. Keep the same: the water volume and pouring speed, the tray slope, the sand surface and the starting position. Table: one row per stick with its size, its start position, its end position and the distance moved, repeated three times per size, with averages.
9. Morrison Formation names the wide band of mudstone and sandstone layers in which the bones lie, something that can be mapped and seen. Late Jurassic is a museum word for the slot the formation is given in the standard geologic time scale. Observed: the rock type, the bones, their positions and the cross-beds. Interpreted: the age in years, which rests on dating methods and assumptions, and the story of how long the layer took to form.
10. (a) Area = 60 × 15 = 900 m^2; 1,500 ÷ 900 ≈ 1.7 bones per square meter. (b) 1,500 ÷ 200 ≈ 7 or 8 skeletons’ worth. (c) Bones come from many different animals and kinds, most individuals are represented by only a few bones, and many bones were carried away or never buried, so the number of animals is larger than the number of complete skeletons the bones could build.

7.3 Catastrophism versus Uniformitarianism: Hutton, Cuvier and Lyell

OBJECTIVES

- Define uniformitarianism and catastrophism, name the scientists who shaped each (Hutton, Lyell, Cuvier, Buckland) and tell what happened at Siccar Point in 1788.
- Distinguish uniformity of law from uniformity of rate, and explain why the same finished pile of layers can be read as slow or fast depending on the rate assumed.
- Calculate how long a layer or canyon would take to form under different assumed rates and state which assumption each answer depends on.

Warm-up. Look at a glass of water with a spoonful of soil stirred in. Time how long it takes for the water to clear. Now imagine the same soil arriving a pinch at a time over a whole year instead. Would the layer on the bottom look different in the end? Write down one way you could tell which had happened, and one way you could not.

Video. Coming soon. James Hutton at Siccar Point, Charles Lyell and the Principles of Geology, uniformitarianism and catastrophism explained for students (search Smithsonian, USGS, the Geological Society of London, Royal Society of Edinburgh, SciShow, PBS Eons for museum-view context, and Moody Science classics for a creation-friendly treatment).

KEY TERMS

uniformitarianism
The idea, pressed by Hutton and Lyell, that the earth's past should be explained only by processes seen today, acting at about today's rates, over immense time.

catastrophism
The idea, held by Cuvier and Buckland, that much of the rock record was made by sudden, violent events far larger than anything seen in ordinary times.

uniformity of law
The principle that the laws of nature (gravity, chemistry, the behavior of water) were the same in the past as now. Nearly all scientists, including creation geologists, accept this.

uniformity of rate
The further claim that processes ran at about the same speed in the past as they do now. This is the part that catastrophists, old and new, reject.

unconformity
A surface in the rock where one set of layers lies on top of another that was tilted or worn away first. Hutton's unconformity at Siccar Point is the most famous.

extrapolation

Stretching a measured rate beyond the time or place it was measured, for example using today's mud settling rate to date a layer no one watched form.

CORE IDEAS

The story. In June 1788 three friends rowed a small boat along the rocky coast of Berwickshire, Scotland, and landed at a point of rock called Siccar Point. One of them was James Hutton, an Edinburgh doctor turned farmer turned geologist. The other two were the mathematician John Playfair and the young chemist Sir James Hall. At their feet, nearly vertical beds of gray rock stood on end, and lying across their tops, almost flat, were beds of red sandstone. Hutton explained what he saw: the gray beds had been laid down flat under the sea, hardened, tilted on end, worn away, and then buried under new sand, which had hardened in turn and been lifted into the air. Each step, he said, took ages. Playfair wrote later that the mind seemed to grow giddy by looking so far into the abyss of time. Hutton had already read his *Theory of the Earth* to the Royal Society of Edinburgh in 1785, and he ended it with a famous line: we find no vestige of a beginning, no prospect of an end.

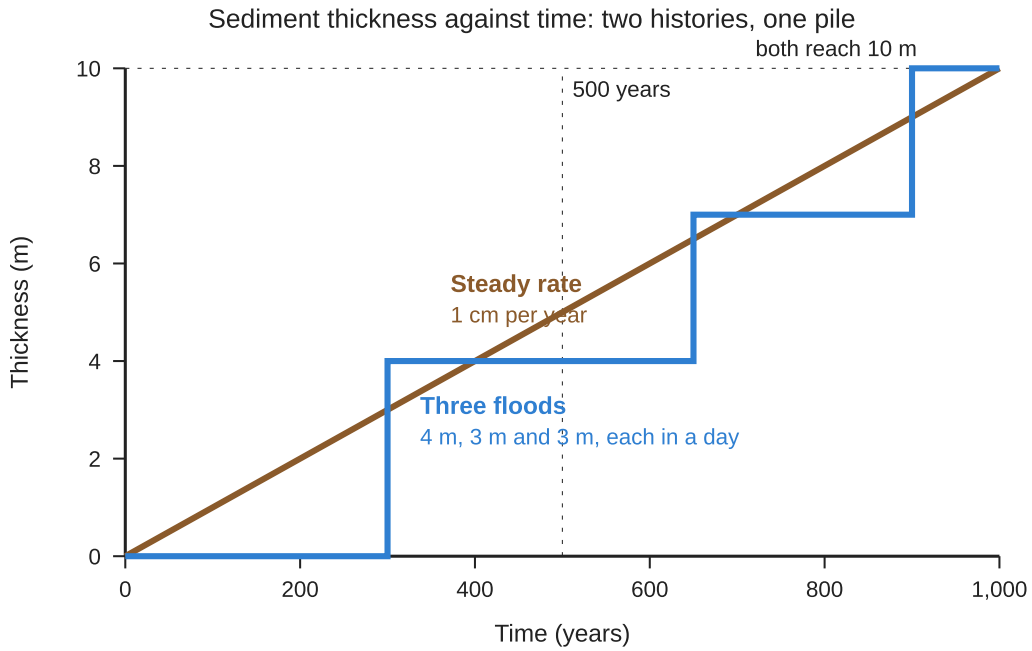
How they figured it out. Hutton reasoned from processes he could watch. Rivers carry mud to the sea; the sea lays it in layers; heat deep below hardens and lifts them; rain and frost wear them down; and the cycle repeats. If those slow processes made all the rock, the earth must be enormously old. Not everyone agreed. In Paris, Georges Cuvier, the greatest anatomist of the age, found that the fossils in the rock layers around the city changed abruptly from one layer to the next, with sea creatures replaced by land animals and back again. In 1812 he argued that the earth's surface had suffered sudden "revolutions," great floods that swept away whole populations of animals. In England, William Buckland of Oxford gathered bones from caves and in 1823 argued that a universal flood had left its marks across Europe. Then came Charles Lyell. In *Principles of Geology* (1830 to 1833) he insisted that geologists should explain the past only by "causes now in operation," and only at the strengths seen today. A young Charles Darwin carried the first volume aboard the *Beagle* in 1831 and became Lyell's most famous follower. In 1832 the philosopher William Whewell gave the two sides their names: **uniformitarians** and **catastrophists**.

The big idea. The quarrel is really about two different claims bundled together. The first is **uniformity of law**: water flowed downhill, rock weathered and sand settled in the past exactly as they do now, because the laws of nature do not change. Everyone accepts this; without it no one could read rocks at all. The second is **uniformity of rate**: the processes ran at about the speed they run today, so a thick layer means a long time. This is the claim the catastrophists denied, and here is the heart of the matter. A pile of layers ten meters thick looks the same whether it grew a millimeter a year for ten thousand years or arrived in five floods lasting a day each. The finished rock does not carry a clock. To turn thickness into years you must **extrapolate** a rate, and the rate you choose decides the answer before you begin. Honest geologists on both sides know this; the difference lies in which assumption they think the evidence supports.

In the world today. For more than a century after Lyell, catastrophe was almost a forbidden word in geology, which is why Bretz's flood was laughed at in 1927. Yet the rocks kept

pushing back. Lyell himself visited Joggins, Nova Scotia, in 1842 and saw fossil tree trunks standing upright through several meters of layers; trees that must have been buried before they could rot. Bretz won his argument. In 1980 the physicist Luis Alvarez and his geologist son Walter found a thin layer rich in the rare metal iridium in rocks at Gubbio, Italy, and argued that a giant asteroid had struck the earth, a layer that museum signs now date to 66 million years ago. Also in 1980 Mount St. Helens laid down thick layered deposits in hours. The geologist Derek Ager summed up the new mood in 1973: the history of any one part of the earth, like the life of a soldier, consists of long periods of boredom and short periods of terror. Mainstream geology now accepts catastrophes freely, while keeping Lyell's long ages between them.

God's handiwork. A Christian naturalist stands with Hutton on uniformity of law. God "appointed the ordinances of heaven and earth" (Jeremiah 33:25), and the steadiness of those laws is why experiments work. But Scripture also records that the world "being overflowed with water, perished" (2 Peter 3:6), and Peter says that people who insist "all things continue as they were from the beginning of the creation" are choosing to forget it. So the course takes the catastrophist side on rate: the great Flood of Genesis, and the upheavals that followed it, did in a year what Lyell would spread over ages. You do not have to take that on authority. The rest of this unit will show you how to read a layer, a bone bed and a canyon, ask what rate is being assumed, and decide for yourself what the evidence can and cannot settle.



Two histories, one pile of rock. The steady line and the three-flood line both end at 10 m after 1,000 years. The finished layers alone cannot tell you which path happened; you need other clues, such as whether the surfaces between layers show roots, burrows and weathering.

⏳ Thinking About Time

What the sign says. What the sign says: Textbooks teach that the present is the key to the past: because mud settles in lakes at about a millimeter a year and rivers cut rock at fractions of a millimeter a year, thick piles of layers and deep canyons must record millions of years. A museum sign on the Grand Canyon, for example, says its layers took hundreds of millions of years to form.

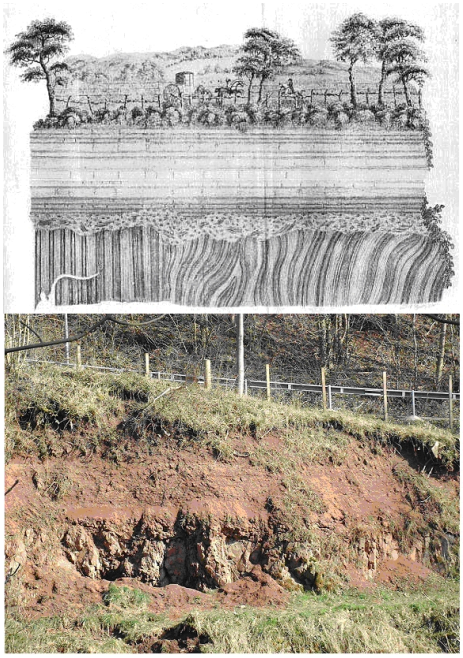
What we observe. What we observe: Rates measured today vary enormously. A lake may gain a millimeter of mud in a year, while Mount St. Helens laid down meters of fine layers in an afternoon in 1980 and the Missoula flood cut canyons in days. At Joggins, fossil trees stand upright through several meters of strata, so those layers piled up faster than a trunk rots. Many layer boundaries show no soil, roots or burrows, which would take time to form. The thickness is measured; the years are extrapolated.

How Christians read it. How Christians read it: Creation geologists accept uniformity of law but not uniformity of rate. They read Genesis 7 and 8 as the record of a year-long global catastrophe that laid down most of the fossil-bearing layers quickly, with the Ice Age and smaller catastrophes following. They note that mainstream geology has itself returned to catastrophes, from Bretz to the Alvarez impact, while keeping long ages between them. The difference is not whether floods can lay down rock fast, which everyone now agrees, but how much of the record they account for.

Try it. Take any rate you can measure at home, such as how fast a dripping tap fills a cup, and extrapolate it: how long to fill a bathtub? Then ask what would have to stay the same for your answer to be right.

2 Peter 3:5–6

PICTURE STUDY



Unconformity at Jedburgh (Allar's Mill on the Jed Water), John Clerk of Eldin, engraved for James Hutton's Theory of the Earth, drawn 1787, published 1795 · Engraving (book plate) · Plate in volume 1 of Hutton's Theory of the Earth (Edinburgh, 1795); the bank itself is at Inchbonny on the Jed Water, near Jedburgh

In 1787, a year before the boat trip to Siccar Point, Hutton found the same kind of rock puzzle in a river bank near Jedburgh, in the Scottish Borders. His friend John Clerk of Eldin, a skilled draftsman, drew it on the spot, and the drawing was engraved as a plate for Hutton's book. The Commons image sets his engraving beneath a modern photograph of the same bank, so you can compare the two. It is one of the first scientific pictures of an unconformity: a surface where one set of rock layers rests on another set that had already been tilted and worn.

Clerk added the road, the carriage and the little figures on top. They are not decoration. They show the scale, and they make Hutton's point: people go about their business on a surface made by a history they never suspected.

Look closely

- Find the vertical beds at the bottom. In what position were they first laid down, and what had to happen to stand them on end?
- Find the horizontal beds above. Trace the line where they meet the vertical ones. That line is the unconformity.
- Notice the thin layer of soil and grass at the top with the road on it. How many separate events can you count in this one cliff?
- Look for broken pieces of the lower rock caught in the base of the upper layers. What would that show?

Talk about it

1. Hutton read this cliff as a record of immense time. Which steps in his story are observed in the rock, and which are assumptions about how long each step took?
2. Could tilting, planing and reburying happen quickly in a great catastrophe? What would you look for at the unconformity surface to decide?
3. Why is a drawing made on the spot valuable to later scientists, even after photographs exist?

EXPERIMENT: LAYERS FAST AND SLOW

Hutton and Lyell assumed that layers form slowly. You will make layers two ways with the same materials and then see whether a visitor can tell, from the finished jar, which way each one formed.

Question: Can the finished layers alone reveal whether they formed in one event or several? Prediction: write yours. What we change: the number of settling events (one shake or three shakes). What we keep the same: the materials, the amounts and the jars. What we measure: the number of layers and the thickness of each in millimeters.

You will need

- Two identical clear jars with lids (1 liter is ideal)
- Equal mixes for each jar: about 100 mL coarse gravel or aquarium stones, 100 mL sand, 100 mL garden soil and 50 mL flour or powdered clay
- Water to fill each jar three-quarters full
- A ruler marked in millimeters, a marker, and your lab notebook
- A kitchen timer

Steps

1. Put the same mix into both jars and add water to the same level. Jar A is the one-event jar. Jar B is the three-event jar.
2. Jar A: shake hard for 30 seconds, set it down and start the timer. Do not touch it again. After 10 minutes, mark the water level and the top of the sediment. Count the layers you can see and measure each one’s thickness.
3. Jar B: shake hard for 30 seconds and set it down for 10 minutes. Shake again for 30 seconds and wait 10 minutes. Shake a third time and wait 10 minutes. Then count and measure the layers.
4. Record for each jar: number of visible layers, thickness of each in mm, and what material is at the bottom, middle and top.
5. Cover the labels, mix up the jars and ask a family member who did not watch to guess which jar was shaken three times. Ask what clue they used. Record their guess and reason.
6. Leave both jars overnight. Next day measure again. Did the thin flour layer settle further? Did the fine layers get sharper?
7. Write a conclusion: What did each shake produce? Could your visitor tell one event from three? What extra evidence would you need in real rock to decide, such as roots,

burrows or weathered surfaces between layers?

Tips

- Each shake usually makes one set of layers, coarse at the bottom and fine at the top, called a graded bed. Three shakes should make three graded beds if you wait long enough between them.
- If the water stays cloudy, the finest particles are still falling. Fine clay can take hours; that is why Jar B needs the same waiting time after each shake.
- Measure from the outside of the jar with the ruler held vertical. Record every layer, even thin ones you can barely see.

Check your work

- I can explain what a graded bed is and why one shake makes one.
- I measured and recorded every layer in both jars in millimeters.
- I can say what the finished jar alone can and cannot tell about how it formed.

FIELD NOTEBOOK

1. Draw Siccar Point as a cross-section: vertical gray beds below, a wavy unconformity line, and gently tilted red sandstone above. Number Hutton’s steps in order beside it.
2. Copy the two-line graph from this lesson and add a third line of your own: two floods instead of three, ending at the same 10 m. Label all three.
3. Make a timeline from 1785 to 1980 with Hutton, Cuvier, Buckland, Lyell, Whewell, Bretz, Ager and the Alvarez team on it, each with one word: uniform or catastrophe.

> **From history.** William Whewell, the Cambridge professor who named the uniformitarians and catastrophists in an 1832 review of Lyell’s book, had a gift for words. The next year, at a meeting of the British Association for the Advancement of Science, the poet Samuel Taylor Coleridge complained that the people in the room should not be called philosophers. Whewell proposed a new word, by analogy with artist: scientist. It took decades to catch on, but it is the word we use today. Whewell himself leaned toward the catastrophists, and he warned that geologists should not assume the present rates of nature were a measure of the past.

WORKED EXAMPLES

Example 1. A layer of mudstone is 10 m thick. (a) If it formed at the rate measured in a quiet lake today, about 1 mm per year, how many years did it take? (b) If instead each flood of a nearby river laid down 2 m of mud in a day, how many floods and how many days of deposition does the layer represent?

1. (a) Convert to the same unit: 10 m = 10,000 mm.
2. Time = thickness ÷ rate = 10,000 mm ÷ 1 mm per year = 10,000 years.
3. (b) Number of floods = 10 m ÷ 2 m per flood = 5 floods.
4. Days of deposition = 5 floods × 1 day = 5 days (the time between floods is unknown from the layer itself).
5. Compare: the same 10 m of rock gives 10,000 years under one assumption and 5 days of actual deposition under the other. The layer did not change; the assumed rate did.

Answer: (a) About 10,000 years. (b) Five floods and about 5 days of deposition. The answer depends entirely on the rate assumed.

Example 2. Use the graph in this lesson. (a) What is the thickness on each line at 500 years? (b) What is the average rate of the three-flood line over the full 1,000 years? (c) During the first flood, 4 m arrived in one day. What was the rate that day in millimeters per day, and how many times faster is it than the steady line's daily rate?

(Use the map or drawing "Read the thickness on each line at 500 years." shown earlier in this lesson.)

1. (a) Steady line at 500 years: 5 m. Three-flood line at 500 years: 4 m (only the first flood, at 300 years, has happened).
2. (b) Average rate = total thickness ÷ total time = 10 m ÷ 1,000 years = 1 cm per year, exactly the same as the steady line.
3. (c) Flood-day rate: 4 m = 4,000 mm in 1 day = 4,000 mm per day.
4. Steady line daily rate: 1 cm per year = 10 mm ÷ 365 days ≈ 0.027 mm per day.
5. Ratio: 4,000 ÷ 0.027 ≈ 150,000. The flood-day rate is about 150,000 times the steady rate, yet the two lines share the same average.

Answer: (a) 5 m and 4 m. (b) 1 cm per year, the same as the steady line. (c) 4,000 mm per day, about 150,000 times the steady daily rate.

Example 3. A gorge is 300 m deep. (a) If the river in it cuts down 0.1 mm per year, as measured over recent decades, how long would it take to cut the gorge? (b) If a flood like Bretz's cut rock at 10 cm per hour, how many days would the same gorge take?

1. (a) 300 m = 300,000 mm. Time = 300,000 mm ÷ 0.1 mm per year = 3,000,000 years.
2. (b) 300 m ÷ 0.1 m per hour = 3,000 hours.
3. Convert hours to days: 3,000 ÷ 24 = 125 days.
4. State what each answer assumes: (a) assumes today's trickle never changed; (b) assumes a flood of Missoula size and no slower cutting afterward. Which is right must be decided from the shape of the gorge, not from the arithmetic.

Answer: (a) About 3 million years. (b) About 125 days. The gorge is the same; the rate assumption makes the difference.

PRACTICE

1. EASY Who went to Siccar Point in June 1788, and what did they see there?
2. EASY Match each person with the view he is known for: Hutton, Cuvier, Lyell, Buckland. Views: catastrophist, uniformitarian.
3. EASY In one sentence each, explain the difference between uniformity of law and uniformity of rate.
4. MEDIUM Sort these statements as supporting a uniform (U) or catastrophic (C) reading of a layer: (a) a soil with roots lies between two layers; (b) a tree trunk stands upright through three layers; (c) the layer has thousands of thin bands, each with burrows on top; (d) the bones in the layer are lined up by a current.
5. MEDIUM A sandstone layer is 6 m thick. Under a rate of 2 mm per year, how long did it take? Under a rate of 50 cm per hour (a flood), how many hours?
6. MEDIUM Data reading. The table gives measured deposition rates. Deep ocean floor: 0.002 mm per year. Quiet lake: 1 mm per year. River delta front: 10 mm per year. Mount St. Helens pyroclastic flow, June 12, 1980: several meters in a few hours. Missoula flood gravel bar: tens of meters in a few days. (a) What is the ratio of the delta rate to the lake rate? (b) Between the slowest and the fastest steady rate in the table, how many times larger is the fastest? (c) Why can the two catastrophic entries not be written as a rate per year in the same way?
7. MEDIUM Data reading. A geologist measures how fast a cliff retreats at a waterfall. Years 1 to 10: 1.0 m per year. Years 11 to 20: 1.1 m per year. Years 21 to 30: 0.9 m per year. During one flood in year 31: 8 m in two days. (a) What was the average yearly rate over the first 30 years? (b) If a student uses the 30-year average to estimate how long the waterfall took to retreat 300 m, what answer would she get? (c) Why could the true time be much shorter?
8. HARD Experiment design. Design a jar experiment to test whether the thickness of a graded bed depends on how much sediment is stirred up. Give the independent

variable, dependent variable, three controlled variables, and the number of trials.

9. HARD Write a paragraph explaining why Bretz's flood was rejected in 1927 even though his evidence was good, using the words uniformity of rate and extrapolation.
10. CHALLENGE A pile of layers is 1,000 m thick. Reading A says it formed at a steady 0.1 mm per year. Reading B says it formed in 20 catastrophic events of 50 m each, with long quiet gaps between. (a) How many years does Reading A require? (b) Under Reading B, how many years of deposition does the rock itself record if each event lasted a week? (c) Explain why Reading B cannot, by itself, tell you how long the gaps lasted, and what you would look for at the boundaries to find out.

COMMON MISTAKES

- Thinking uniformitarianism means no catastrophes ever happened. Lyell allowed earthquakes, volcanoes and floods; he insisted only that they were never bigger or more frequent than today's.
- Thinking catastrophism means ignoring present-day processes. Cuvier and Bretz studied present processes closely; they concluded that some past events were larger than any now seen.
- Assuming that because the laws of nature are constant, the rates of processes must be too. A river obeys the same laws at a trickle and in flood, but it does a million times more work in flood.

Make it a game · Rate or Law?. Your parent reads statements one at a time, such as "Water always flows downhill," "Mud settles at one millimeter a year," "Gravity was the same in the past," "Niagara has always retreated one meter a year," or "Sand always settles before clay." You shout LAW if it is a claim about how nature works, or RATE if it is a claim about how fast, and say whether it could have been different in a great flood. One point per correct call, two if you can give an example from this unit. Play to ten, then switch roles.

Scripture. "For this they willingly are ignorant of, that by the word of God the heavens were of old, and the earth standing out of the water and in the water: Whereby the world that then was, being overflowed with water, perished:" (2 Peter 3:5–6, KJV)

Peter says that people who claim "all things continue as they were from the beginning" are choosing to forget the Flood. The verse does not forbid science; it warns against one assumption, uniformity of rate, that leaves out the greatest catastrophe of all.

Practice answers

1. James Hutton, John Playfair and Sir James Hall. They saw nearly vertical gray rock beds with nearly flat red sandstone beds lying across their tops: an unconformity.
2. Hutton: uniformitarian. Cuvier: catastrophist. Lyell: uniformitarian. Buckland: catastrophist (in his 1823 book).
3. Uniformity of law says the laws of nature worked the same way in the past as now. Uniformity of rate says processes ran at about the same speed in the past as now.

4. (a) U, the soil needed time to form. (b) C, the trunk had to be buried before rotting. (c) U, each band was lived on before the next arrived. (d) C, moving water laid it down quickly.
5. 6 m = 6,000 mm; 6,000 ÷ 2 = 3,000 years. 6 m = 600 cm; 600 ÷ 50 = 12 hours.
6. (a) 10 ÷ 1 = 10 times. (b) 10 ÷ 0.002 = 5,000 times. (c) They happened in hours or days and then stopped; stretching them into a yearly rate would suggest the deposit kept growing all year, which it did not. A per-year rate only makes sense for a process that keeps going.
7. (a) About 1.0 m per year (the three decades average to 1.0). (b) 300 ÷ 1.0 = 300 years. (c) Floods like the one in year 31 do many years of work in days; if such floods were common or larger in the past, the 300 m could have been cut in far less time.
8. Independent: the amount of sediment mix added (for example 100 mL, 200 mL, 300 mL). Dependent: the thickness in mm of the graded bed after settling. Controlled: the same water volume, the same shaking time and strength, the same jar size and the same settling time. Trials: at least three jars per amount, with averages.
9. Geologists trained on Lyell assumed uniformity of rate: the past had to be explained by processes at today’s speeds. A flood far larger than any river was outside that rule, so they preferred to extrapolate slow river erosion over long ages even where the landforms did not fit. Their rejection came from the assumption, not from the rocks, and when a source of water was found the same evidence convinced them.
10. (a) 1,000 m = 1,000,000 mm; ÷ 0.1 = 10,000,000 years. (b) 20 weeks, less than half a year of actual deposition. (c) The rock records the events, not the pauses. Boundaries that show soils, roots, burrows, weathering or erosion channels point to long pauses; sharp, clean, unweathered boundaries point to short ones.

7.4 Genesis 7–8 as a Catastrophe: The Flood Year, Day by Day

OBJECTIVES

- Read Genesis 7 and 8 as a dated record of a catastrophe: name the two sources of water, the length of the rain, the 150 days of prevailing, the resting of the ark and the drying, and place them on a timeline.
- Convert the ark's dimensions from cubits to meters, find its length-to-width ratio and volume, and explain why that ratio matters for a floating vessel.
- State what a year-long global Flood would be expected to leave in the rocks, compare that list with the catastrophes of Lessons 7.1 to 7.3, and tell how a museum sign or documentary that calls the Flood a myth or a local event should be read.

Warm-up. Take a sheet of paper and a pencil. Read Genesis 7:11, 7:12, 7:24, 8:4, 8:5, 8:13 and 8:14 aloud with a parent. Every time you hear a number (a day, a month, a year, a count of days), write it down. How many numbers did you find? Which ones are dates and which ones are lengths of time? Keep the list; you will build a timeline from it.

Video. Coming soon. Noah's Flood in Genesis 7 and 8 as history, George Smith and the Gilgamesh flood tablet at the British Museum, how big was the ark in meters, hull proportions and stability (search the British Museum, Smithsonian and Moody Science classics for the tablet and flood traditions, ship-stability and naval-architecture explainers for the hull test, and nature footage of large floods and draining lakes).

KEY TERMS

cubit
An ancient unit of length from the elbow to the fingertip, about 45 cm (some royal cubits were about 52 cm). The ark was 300 cubits long, 50 wide and 30 high (Genesis 6:15).

fountains of the great deep
The first source of Flood water named in Genesis 7:11: water bursting up from beneath the earth's surface when the deep was "broken up," which creation geologists read as the crust itself tearing open.

windows of heaven
The second source named in Genesis 7:11: rain from above, which fell for forty days and forty nights.

prevail
The word Genesis uses for the waters rising and holding power over the land. The waters "prevailed upon the earth an hundred and fifty days" (Genesis 7:24).

global flood

A flood that covers all the land on earth at once, as Genesis 7:19 describes: “all the high hills, that were under the whole heaven, were covered.” A local flood covers one valley or region.

flood tradition

A story of a great flood handed down by a people; hundreds have been recorded from every inhabited continent. The Babylonian one on the Gilgamesh tablets is the most famous.

CORE IDEAS

The story. On the evening of December 3, 1872, a young man named George Smith stood before the Society of Biblical Archaeology in London and read from a broken clay tablet. Smith had started work as an engraver of banknotes. He taught himself cuneiform, the wedge-shaped writing of ancient Mesopotamia, in his lunch hours at the British Museum, and in 1867 the museum hired him. Sorting through thousands of tablet pieces from the ruined library of Nineveh, he had found a story: a man warned by a god to build a boat, animals taken aboard, a great flood, the boat grounding on a mountain, and a dove, a swallow and a raven sent out to look for dry land. It was the Babylonian flood story, part of the *Epic of Gilgamesh*. The room was electrified. The oldest library in the world remembered a flood. Genesis 7 and 8 had told it, with far more precision, all along.

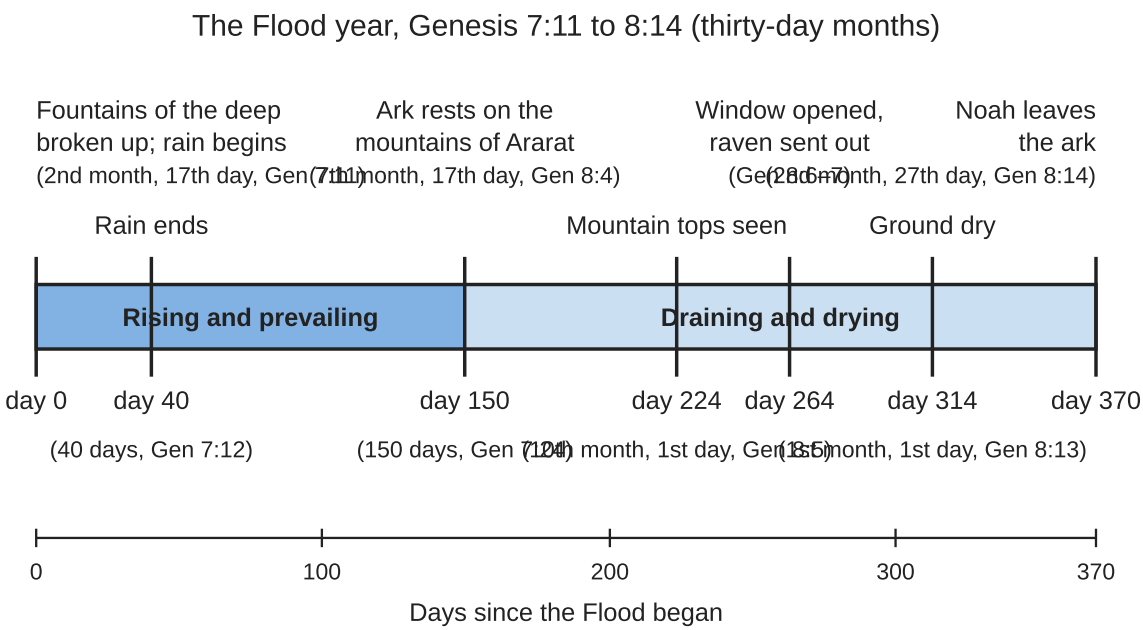
How they figured it out. Read Genesis 7 and 8 the way a geologist reads a field notebook and you find a dated log of a catastrophe. It opens with a date: “In the six hundredth year of Noah’s life, in the second month, the seventeenth day of the month.” It names two sources of water. “The fountains of the great deep” were broken up, and “the windows of heaven were opened.” Rain fell forty days. The waters **prevailed** until “all the high hills, that were under the whole heaven, were covered,” and rose fifteen cubits higher still. They prevailed 150 days. Then God “made a wind to pass over the earth,” the fountains and windows were stopped, and the waters “returned from off the earth continually.” On the seventeenth day of the seventh month the ark grounded on the mountains of Ararat. On the first day of the tenth month the mountain tops showed. On the first day of the next year the ground was dry, and on the twenty-seventh day of the second month Noah went out. Count the days with thirty-day months and the Flood year runs 370 days from first date to last, 371 counting both ends. Notice that the water came first from below, not only from rain; that the draining took longer than the rising; and that “returned continually” describes oceans draining off the land, not a puddle drying.

The big idea. If this record is history, the earth should carry its marks, so a creation geologist asks what a year-long **global flood** ought to leave behind. Breaking up the **fountains of the great deep** means the crust itself tore open, the kind of event you met in Unit 2 with catastrophic plate tectonics; it would drive hot water, ash and enormous waves across the continents. Water holding power over all the land for months means mud, sand and lime laid down in flat layers across whole continents, with sea creatures buried on what is now dry land and even on mountains (Unit 5). Animals caught in moving water means bone beds: creatures of many kinds swept together, sorted and buried fast, like the Carnegie

Quarry (7.2). Waters returning continually off the land means draining currents cutting canyons through soft fresh sediment in days (7.1 and Unit 6). Afterward, warm oceans under ash-dimmed skies would bring an Ice Age. Each of these is what we find. Mainstream geologists explain the same layers, fossils and canyons with many smaller events spread across long ages. The course's reading is that one great catastrophe, recorded by a family who lived through it, accounts for most of it. You now know enough to compare the two readings honestly, feature by feature.

In the world today. Flood traditions have been collected from peoples on every inhabited continent: Mesopotamia, Greece, India, China, the Pacific islands, the Americas. Most share a warning, a boat or a refuge, a few survivors and birds sent out, and most differ in the details, as memories do when passed down for centuries. A Christian reads them as scattered memories of the event Genesis records exactly. In 1997 two scientists at Columbia University, William Ryan and Walter Pitman, proposed that the Black Sea filled suddenly when the Mediterranean broke through the Bosporus, and suggested that this local flood lies behind the story. You will meet that idea in documentaries and on museum walls. Read it as you read any claim: what is observed (drowned old shorelines under the Black Sea), what is inferred (the date and the link to Noah), and what the text says (water above "all the high hills, that were under the whole heaven"). A local flood needs no ark and no year.

God's handiwork. The Flood record ends not with ruin but with a promise: "While the earth remaineth, seedtime and harvest, and cold and heat, and summer and winter, and day and night shall not cease" (Genesis 8:22). That verse is the real charter of science. Hutton and Lyell were right that nature is steady, and here is why: God promised it after the Flood and sealed the promise with the rainbow (Genesis 9:13). The steadiness of seasons, tides, decay rates and river flows that lets you measure anything at all is His faithfulness. So the catastrophist and the uniformitarian each hold a piece of the truth. There was a day when the fountains of the deep broke open, and there is a promise that such a day will not come again by water. A Christian naturalist measures today's steady rates with confidence and remembers the one great exception.



The Flood year from Genesis 7:11 to 8:14, counted with thirty-day months. Day 0 is the seventeenth day of the second month of Noah's six hundredth year; day 370 is the twenty-seventh day of the second month of the next year.

⏳ Thinking About Time

What the sign says. What the sign says: Most textbooks and museum signs treat the Genesis Flood as a story rather than an event, and say the fossil-bearing layers of the continents took hundreds of millions of years to form. Some scientists say the story remembers a real but local flood, such as river floods in Mesopotamia or the sudden filling of the Black Sea that William Ryan and Walter Pitman proposed in 1997.

What we observe. What we observe: Sedimentary layers blanket the continents, often flat and traceable for hundreds of kilometers; marine fossils lie on every continent and on high mountains; bone beds hold animals of many kinds buried fast; many layer boundaries are sharp and unweathered; and flood traditions are found among peoples worldwide. Genesis 7 and 8 themselves give dates, durations and a global description. The layers and fossils are measured; the ages and the "myth" label are interpretations.

How Christians read it. How Christians read it: The course reads Genesis 7 and 8 as history, a global Flood in Noah's six hundredth year, which Bible chronologies place roughly 4,300 to 4,500 years ago (Archbishop James Ussher worked it out as 2348 B.C. in 1650). Creation geologists read most fossil-bearing rock as laid down in the Flood year and its aftermath, with the Ice Age following. They point out that the text (Genesis 7:19–20, 9:11) and Jesus (Luke 17:26–27) treat the Flood as a real event that covered all the high hills, which a local flood cannot do.

Try it. Read Genesis 7 and 8 aloud and list every number: days, months, years, cubits. Mark each one on a timeline and count the days of rising and the days of draining.

> *Genesis 7:19–20*

PICTURE STUDY



The Deluge, John Martin, 1834 · Oil on canvas · Yale Center for British Art, New Haven, Connecticut

John Martin was an English painter who loved enormous scenes of judgment and catastrophe: Belshazzar's feast, the fall of Babylon, the destruction of Pompeii, and the Flood. He painted the Deluge more than once; this version, painted in 1834, won a gold medal at the Paris Salon of 1835, was shown at the Royal Academy in London in 1837, and now hangs in the Yale Center for British Art. Martin read the science of his day and said he had tried to show the sun, moon and a comet all pulling on the waters at once, so that the sea itself heaves up over the land.

People, animals and whole hillsides are swept away in a single rush of water and rock. Martin wanted viewers to feel how small a human being is before such power, and how the only safety lay in the ark, which in this painting is almost too far off to see.

Look closely

- Find the wall of water and rock coming from the upper left. Is this rain filling a valley, or something larger?
- Look for the tiny figures clinging to the rocks in the foreground. What do they tell you about the scale of the scene?
- Find the lightning and the light breaking through the clouds. Where is the light coming from, and what might Martin mean by it?
- Look at the colors. Where is the painting darkest, and where is it brightest? How does that guide your eye?

Talk about it

1. Genesis names two sources of water, from below and from above. Which one has Martin painted most clearly? Which would you add?
2. A painting is an artist's reading of a text. Which details here come from Genesis 7, and which are Martin's imagination?
3. Martin painted terror; Genesis 8:22 ends with a promise. If you painted a companion picture of the Flood's end, what would be in it?

> **Safety first.** This project uses a tub of water and small weights such as coins. Work outdoors or on a floor that can get wet, keep small weights away from young children, mop up spills, and wash hands afterward.

EXPERIMENT: ARK PROPORTIONS IN A TUB: DOES HULL SHAPE CHANGE STABILITY?

Genesis 6:15 gives the ark's proportions as 300 by 50 by 30 cubits, a length six times its width. You will build three foil hulls of the same size but different proportions, load each one the same, and test which stays upright in waves.

Question: Does the length-to-width ratio of a hull change how much tilt it can take before it capsizes, and how many waves it can survive? Prediction: write yours before you build. What we change: the length-to-width ratio (1:1, 3:1 and 6:1). What we keep the same: the amount of foil, the hull height, the load and the waves. What we measure: the tilt angle at which each hull capsizes, and the number of waves each survives before water comes over the side.

You will need

- Heavy-duty aluminum foil, three pieces each 30 cm by 30 cm
- A ruler, a pencil and a protractor
- About 30 identical coins or metal washers for loads
- A large tub, sink or baby bath with water about 10 cm deep
- A stiff piece of cardboard or a plastic lid to make waves
- Your lab notebook

Steps

1. Make three box-shaped hulls from the three identical foil squares, each with sides folded up 3 cm high. Hull A: 12 cm by 12 cm (ratio 1:1). Hull B: 21 cm by 7 cm (ratio 3:1). Hull C: 24 cm by 4 cm (ratio 6:1). Fold the corners tightly so they do not leak. Write each hull's length, width and ratio in a table.
2. Float each hull and add the same load, 10 coins, spread evenly over the floor. Check that each hull floats level. Record how deep each one sits in the water (the draft) in millimeters.
3. Tilt test: with the hull floating still, slowly push one long side down with a pencil until water comes over the edge or the hull rolls over. Have a helper hold the protractor at

the end of the hull and read the tilt angle at that moment. Do this three times per hull and record every angle.

4. Wave test: hold the cardboard at one end of the tub and push it back and forth steadily, once per second, with the same swing each time. Count the waves until water comes over the side. Stop at 30 if the hull is still dry. Point the hull across the waves (sideways to them) for the first round, then end-on for a second round. Record both counts for each hull.
5. Find the average tilt angle and the average wave count for each hull. Draw two bar graphs: tilt angle against ratio, and waves survived against ratio.
6. Write a conclusion: Which ratio took the most tilt? Which survived the most waves? Was any hull good at one test and poor at the other? What do your results suggest about a hull six times longer than it is wide, and what would you want to test next, such as different hull heights or a heavier load?

Tips

- Keep the foil squares identical so every hull has the same amount of material; that is one of your controlled variables.
- A hull that leaks at a corner will sink in every test and spoil the data. Test for leaks before loading.
- Make the waves the same each time by counting aloud and keeping the swing of the cardboard the same. A second helper who only makes waves helps keep this fair.

Check your work

- I built three hulls with the same foil, height and load, and changed only the length-to-width ratio.
- I recorded every tilt angle and wave count in a table and found the averages.
- I can explain what my results suggest about the ark's 6:1 proportion, and what they cannot settle.

FIELD NOTEBOOK

1. Draw the Flood-year timeline from this lesson in your notebook, with the dates from Genesis 7:11, 7:12, 8:4, 8:5, 8:13 and 8:14 written on it in day numbers, and color the rising and draining parts differently.
2. Draw the ark to scale at 1:1,000 (13.5 cm long, 2.25 cm wide, 1.35 cm high) as a plan view and a side view, and draw a 1:1,000 school bus (about 1.2 cm long) beside it.
3. Make a two-column table titled "What a global Flood should leave." Left column: five things Genesis 7 and 8 describe. Right column: the matching feature in the rocks and where in this course you studied it.

> **From history.** George Smith's tablet, now called Tablet XI of the *Epic of Gilgamesh*, came from the library of King Ashurbanipal at Nineveh, dug up by Austen Henry Layard and Hormuzd Rassam in the 1840s and 1850s and shipped to the British Museum. Smith made three journeys to Nineveh to find more pieces; on the first, in 1873, he found a

> missing fragment of the flood story within days of arriving. He died of fever in Aleppo on the third journey, in 1876, at thirty-six. The British Museum still displays the Flood Tablet, and it remains one of the most famous objects in the museum.

WORKED EXAMPLES

Example 1. Genesis 6:15 gives the ark as 300 cubits long, 50 cubits wide and 30 cubits high. Using a cubit of 0.45 m, find the ark's dimensions in meters, its length-to-width ratio, and its volume. How many Olympic swimming pools (about 2,500 m^3 each) is that?

1. Length: 300 × 0.45 = 135 m. Width: 50 × 0.45 = 22.5 m. Height: 30 × 0.45 = 13.5 m.
2. Length-to-width ratio: 300 ÷ 50 = 6, so 6:1. The ratio does not depend on which cubit you use, because both numbers are multiplied by the same cubit.
3. Volume of a box = length × width × height = 135 × 22.5 × 13.5 ≈ 41,000 m^3.
4. Pools: 41,000 ÷ 2,500 ≈ 16. The ark held about the volume of 16 Olympic pools, and its 6:1 proportion is close to the proportions of many modern cargo ships.

Answer: About 135 m by 22.5 m by 13.5 m; ratio 6:1; volume about 41,000 m^3, roughly 16 Olympic pools.

Example 2. Count the Flood year. Using thirty-day months, find the number of days (a) from the start of the Flood (2nd month, 17th day) to the ark resting on Ararat (7th month, 17th day); (b) from the ark resting to the mountain tops appearing (10th month, 1st day); (c) from the start of the Flood to Noah leaving the ark (2nd month, 27th day of the next year).

(Use the map or drawing "Use the timeline to check each count." shown earlier in this lesson.)

1. (a) From the 17th day of month 2 to the 17th day of month 7 is exactly five months: 5 × 30 = 150 days. This matches Genesis 7:24 and 8:3, which say the waters prevailed 150 days.
2. (b) From the 17th of month 7 to the 1st of month 10: 13 days to the end of month 7, then months 8 and 9 (60 days), then 1 day into month 10: 13 + 60 + 1 = 74 days. So the tops appeared on day 150 + 74 = day 224.
3. (c) From the 17th of month 2 to the same date a year later is 12 × 30 = 360 days; add 10 more days to reach the 27th: 370 days. Counting the first and last days both, 371 days, the figure often quoted.
4. Check: rising and prevailing took 150 days; draining and drying took 370 − 150 = 220 days, nearly half again as long.

Answer: (a) 150 days. (b) 74 days, so day 224. (c) 370 days, or 371 counting both ends; about a year and ten days.

Example 3. Could rain alone have done it? Genesis says rain fell forty days and nights. Suppose it fell everywhere at the rate of a severe storm, 50 mm per hour, the whole time. How deep a layer of water would that add? Compare with the height of Mount Ararat, about 5,100 m, and say what the comparison shows about the two sources of water in Genesis 7:11.

1. Hours of rain: 40 days × 24 hours = 960 hours.
2. Depth: 50 mm per hour × 960 hours = 48,000 mm = 48 m.
3. Compare: 48 m is less than one percent of 5,100 m. Even a storm that never paused could not raise the sea to the mountain tops.
4. Conclusion: Genesis names the fountains of the great deep first and the rain second. Water from below, and the land itself sinking and rising (Psalm 104:8), must have done most of the work. That is why creation geologists treat the Flood as a tectonic event, not only a rainstorm.

Answer: About 48 m, far less than the height of the mountains; the fountains of the great deep, not rain, must have been the main source.

PRACTICE

1. EASY Genesis 7:11 names two sources of Flood water. What are they, and which is named first?
2. EASY How many days did the rain fall, and how many days did the waters prevail? Give the verse for each.
3. EASY The ark was 300 cubits by 50 cubits by 30 cubits. Using a cubit of 45 cm, give its size in meters and its length-to-width ratio.
4. MEDIUM Some scholars use a royal cubit of about 52 cm. Recalculate the ark’s length with that cubit. How many meters longer is it than with a 45 cm cubit? Does the length-to-width ratio change? Explain.
5. MEDIUM Using thirty-day months, how many days passed from the mountain tops appearing (10th month, 1st day) to the ground being dry (1st month, 1st day of the next year)? What day of the Flood year is that?
6. MEDIUM Data reading. The table lists events of the Flood year by day number: day 0, fountains broken up and rain begins; day 40, rain ends; day 150, ark rests; day 224, mountain tops seen; day 264, raven sent; day 314, ground dry; day 370, Noah leaves the ark. (a) Which gap between listed events is the longest, and how long is it? (b) What fraction of the 370 days was spent rising and prevailing (day 0 to day 150)? Give it as a percent. (c) A student claims the draining took about as long as the rising. Do the data support that claim?
7. MEDIUM Data reading. A student tested four foil hulls of equal volume and load. Ratio 1:1: capsized at 42° tilt, survived 3 side-on waves. Ratio 3:1: 38°, 9 waves. Ratio 6:1: 35°, 24 waves. Ratio 10:1: 24°, 25 waves. (a) As the ratio increases, what happens to the

capsize angle? (b) As the ratio increases, what happens to the number of waves survived? (c) Which ratio gives the best balance of the two measures, and why?

8. HARD Experiment design. You want to find out whether a hull's height (the depth of its sides) affects how many waves it survives. Describe the independent variable, the dependent variable, three things to keep the same, and how you would make the waves fair from trial to trial.
9. HARD A documentary says the Genesis Flood was really the filling of the Black Sea. In a short paragraph, use the words of Genesis 7:19–20 and the length of the Flood year to explain why the text describes something larger than a local flood, and state fairly what the Black Sea idea does and does not claim.
10. CHALLENGE Suppose the sedimentary rock on a continent averages 1,500 m thick, and suppose it was laid down during the 150 days the waters prevailed. (a) What is the average rate in meters per day? (b) In millimeters per hour? (c) Compare that rate with the Mount St. Helens deposits of 1980 (meters in a few hours) and with a quiet lake (1 mm per year), and say which observed process it resembles.

COMMON MISTAKES

- Thinking the Flood was only forty days of rain. The rain lasted forty days, but the waters rose and prevailed for 150 days and the whole event lasted a year and ten days, and the first source named is water from beneath the earth.
- Reading "fifteen cubits upward" as the total depth of the Flood. The verse says the waters rose fifteen cubits above the mountains they covered, not fifteen cubits in all.
- Assuming that a steady world today proves there was never a catastrophe. Genesis 8:22 promises steadiness after the Flood; the promise itself points back to the day the steadiness was broken.

> **Make it a game · Flood-Year Relay.** Write the seven events of the Flood year (fountains broken up, rain ends, ark rests, mountain tops seen, raven sent, ground dry, Noah leaves) on seven cards and the day numbers (0, 40, 150, 224, 264, 314, 370) on seven more. Shuffle both piles face down across the room. On "go," race to lay them out in order on the floor as a timeline, matching each event with its day. Time yourself; then play again and try to beat your time. For a harder round, a parent removes one day card and you must work out the missing number from the months in Genesis 7 and 8 before you can finish.

> **Scripture.** "In the six hundredth year of Noah's life, in the second month, the seventeenth day of the month, the same day were all the fountains of the great deep broken up, and the windows of heaven were opened." (Genesis 7:11, KJV)

The Flood record begins with a date, like a ship's log or a field notebook. Genesis does not say "once upon a time"; it tells us the year, the month and the day, and it names the water from below before the water from above.

Practice answers

1. The fountains of the great deep, which were broken up, and the windows of heaven, which were opened. The fountains of the great deep are named first.
2. Rain: forty days and forty nights (Genesis 7:12). Prevailing: an hundred and fifty days (Genesis 7:24).
3. 135 m long, 22.5 m wide, 13.5 m high; ratio 300:50 = 6:1.
4. 300 × 0.52 = 156 m, which is 156 − 135 = 21 m longer. The ratio stays 6:1, because length and width are both multiplied by the same cubit, so the cubit cancels out.
5. From the 1st of month 10 to the 1st of month 1 is three months: 3 × 30 = 90 days. Day 224 + 90 = day 314.
6. (a) Day 40 to day 150: 110 days. (b) 150 ÷ 370 ≈ 0.41, about 41 percent. (c) No. Draining and drying ran from day 150 to day 370, 220 days, about one and a half times the rising phase.
7. (a) The capsize angle falls as the hull gets longer and narrower; narrow hulls roll over more easily. (b) Waves survived rise sharply up to 6:1 and then level off. (c) 6:1. It keeps most of the tilt resistance (35° versus 42°) while gaining almost all of the wave survival; going to 10:1 adds only one wave but loses 11° of tilt.
8. Independent variable: side height, for example 2 cm, 3 cm and 4 cm, with the same length-to-width ratio. Dependent variable: the number of waves before water comes over the side. Keep the same: the hull ratio, the load, the water depth and the hull’s direction to the waves. Fair waves: one person pushes a cardboard paddle the same distance at the same count (once per second) every trial, and each hull is tested three times with the results averaged.
9. Genesis 7:19–20 says all the high hills under the whole heaven were covered and the waters rose fifteen cubits above them, and the waters prevailed 150 days with the whole year spent on the ark, which no flood of one basin could do; a local flood would drain in days and leave hills uncovered. The Black Sea idea claims that the Mediterranean broke through the Bosporus and drowned old shorelines, which is observed, and suggests that memory of it lies behind flood stories, which is an inference. It does not claim that water covered mountains or lasted a year.
10. (a) 1,500 ÷ 150 = 10 m per day. (b) 10 m = 10,000 mm; 10,000 ÷ 24 ≈ 420 mm per hour. (c) It is far faster than a lake (about 3.6 million times) but slower than the Mount St. Helens flows, which laid meters in hours; it resembles continuous catastrophic deposition from moving water and ash, not quiet settling.

Unit 7 review

Answer each question. Show your work for calculations, use complete sentences for explanations, and label every part of your diagram. The test is worth 60 points.

1. (4 pts) Multiple choice. Where did the water that carved the Channeled Scablands come from? (a) forty days of rain (b) a lake held back by an ice dam in Montana (c) the melting of a glacier over Spokane (d) the Columbia River in a normal spring flood. Name the lake.
2. (6 pts) Diagram. Draw a simple map of the Missoula flood path. Show and label the ice dam, Glacial Lake Missoula, the Channeled Scablands, Dry Falls, Wallula Gap, the Columbia River and the Pacific Ocean, with arrows showing the direction the water flowed and a north arrow.
3. (5 pts) Glacial Lake Missoula held about 2,100 km³ of water. If it drained in 3 days (72 hours), what was the average discharge in cubic meters per second? (1 km³ = 1,000,000,000 m³; 1 hour = 3,600 s.) Compare with the Amazon’s average of about 209,000 m³/s.
4. (4 pts) Multiple choice. Which observation at a bone bed is the strongest sign that flowing water laid it down? (a) the bones are very large (b) many long bones lie parallel to one another (c) the bones are all from one kind of animal (d) the rock is gray. Explain your choice in one sentence.
5. (5 pts) At the Cleveland-Lloyd Dinosaur Quarry, at least 46 of at least 74 dinosaurs are Allosaurus, a meat-eater. (a) What percent is that? (b) Why is that percent surprising for a living community, and what does it suggest about how the bed formed?
6. (5 pts) Explain in two or three sentences why most animals that die today never become fossils, and what that tells you about any layer packed with hundreds of well-preserved bones.
7. (4 pts) Multiple choice. Which statement is uniformity of law rather than uniformity of rate? (a) Mud settles in lakes at one millimeter a year. (b) Rivers have always cut rock as slowly as they do today. (c) Water flowed downhill in the past as it does now. (d) Niagara has always retreated one meter a year. Which scientists are called uniformitarians?
8. (6 pts) A layer of sandstone is 8 m thick. (a) How long would it take to form at a steady 2 mm per year? (b) How many hours would it take at a flood rate of 40 cm per hour? (c) In one sentence, say why both answers can come from the same rock.
9. (5 pts) Data reading. A student measures a waterfall’s retreat: years 1 to 10, 1.0 m per year; years 11 to 20, 1.0 m per year; one flood in year 21, 6 m in a single day. (a) How far did the falls retreat in all 21 years? (b) What percent of the total did the one flood day do? (c) What would be wrong with using the 1.0 m per year rate to date the whole gorge?
10. (5 pts) Genesis 7:11 names two sources of Flood water. Name both, and give the length of the rain and the number of days the waters prevailed, with verse references.

11. (5 pts) The ark was 300 cubits long, 50 wide and 30 high. With a cubit of 0.45 m, find its length, width and height in meters and its length-to-width ratio. Using thirty-day months, how many days passed from the start of the Flood (2nd month, 17th day) to the ark resting on Ararat (7th month, 17th day)?
12. (6 pts) Written explanation. Choose one catastrophe from this unit (the Missoula flood, the Carnegie Quarry bone bed, or the layers at Siccar Point). Write a Thinking About Time box for it in three or four sentences: what the sign says, what is observed, and how Christians who hold to the Flood read it. Be fair to both readings.

UNIT PROJECT: MY CATASTROPHE CASE FILES

Make a set of four case files, one for each lesson, bound together or kept in a folder. Each file has four parts: a labeled drawing (the Missoula flood map with a 100 km scale bar; the Carnegie Quarry wall in cross-section; the Siccar Point or Jedburgh unconformity with Hutton's steps numbered; the ark to scale beside a school bus and the Flood-year timeline); an evidence table listing each observation and what it shows; your own experiment record from that lesson (the burst-dam channel measurements, the bones-in-a-current angles and percents, the two settling jars, and the three-hull tilt and wave data) with its table, graph and conclusion; and a Thinking About Time box in your own words.

Finish with a one-page summary that answers the unit's question: when can a scientist conclude that a landform or a layer was made fast? Give at least three clues from the unit, name one assumption that geologists on each side make, and copy out Genesis 8:22 with a sentence on why a Christian can trust nature's steady rates today while believing the Flood was real.

- **Accuracy**: Landforms, bone-bed clues, the two kinds of uniformity, the ark's dimensions and the Flood-year days are correct, and every drawing is labeled with the right terms and a scale where asked.
- **Records**: All four experiment records are the student's own, complete, dated, in metric units, with averages and a graph where the lesson asked for one.
- **Explanation**: Each Thinking About Time box states the sign's claim fairly, separates what is observed from what is inferred, and gives the creation reading clearly without mocking either side; the summary names real clues and assumptions.
- **Care**: The files are neat, in order, and easy to follow, with drawings that a reader could use to find the features on a real map or wall.

Answer key

1. (b). Glacial Lake Missoula.
2. The map should show the ice lobe blocking a valley at the Idaho–Montana border with the lake to its east (Montana), arrows running west across eastern Washington (scablands, with Dry Falls in Grand Coulee), narrowing through Wallula Gap, then following the Columbia west to the Pacific; north arrow pointing up.
3. 2,100 km^3 = 2.1 × 10^{12} m^3. 72 hours = 259,200 s. 2.1 × 10^{12} ÷ 259,200 ≈ 8,100,000 m^3/s, about 8 million. That is roughly 8,100,000 ÷ 209,000 ≈ 39, about 40 Amazons.

4. (b). Moving water turns long objects to line up with the flow, while still water or dry land leaves them in random directions.
5. (a) 46 ÷ 74 ≈ 62 percent. (b) In a living community predators are usually a tenth or less of the large animals, so the bed is not a snapshot of a herd with its hunters; something gathered or trapped an unusual number of predators, a sign of an unusual event rather than everyday death.
6. Scavengers, insects, bacteria and weather destroy a body within a few years unless it is buried quickly by sediment or ash. A layer full of well-preserved bones therefore records rapid burial of many animals at once, an unusual event such as a flood or ashfall rather than slow, ordinary death.
7. (c). Hutton and Lyell (uniformitarians); Cuvier and Buckland were catastrophists.
8. (a) 8 m = 8,000 mm; 8,000 ÷ 2 = 4,000 years. (b) 8 m = 800 cm; 800 ÷ 40 = 20 hours. (c) The finished layer carries no clock; the time comes from the rate you assume, not from the thickness alone.
9. (a) 10 + 10 + 6 = 26 m. (b) 6 ÷ 26 ≈ 23 percent. (c) One day did nearly a quarter of the work; if floods like that happened often, or larger ones happened in the past, the gorge formed far faster than the steady rate suggests, so the steady rate overestimates the time.
10. The fountains of the great deep (broken up) and the windows of heaven (opened). Rain: forty days and forty nights (Genesis 7:12). The waters prevailed an hundred and fifty days (Genesis 7:24).
11. 135 m by 22.5 m by 13.5 m; ratio 6:1. Five months × 30 days = 150 days, matching Genesis 7:24 and 8:4.
12. Answers vary. Full credit: states the mainstream claim accurately with its date or time claim (for example, the museum says the floods came about 15,000 years ago at the end of the Ice Age; the quarry sign says about 149 million years; textbooks say the Siccar Point beds record immense time); names what is actually measured (channels, ripples, bars; bones, alignment, sandstone; tilted beds under flat beds); gives the creation reading (Ice Age floods a few thousand years ago after the Flood; the bone bed as a Flood-year deposit; the unconformity formed quickly in the Flood), and notes that the rock is the same and the difference lies in the assumed rates and dates, without mocking either side.

UNIT 8

Hazards and Engineering

Through this course you have watched the earth move: the core revealed by seismic waves, plates that grind and dive, mountains that rise and fold, volcanoes that build islands in days and floods that carve canyons in hours. This last unit asks the practical question that every earth scientist is finally asked: since we cannot stop the ground from shaking, the mountains from sliding or the volcanoes from erupting, how do we live wisely beside them? The answer is engineering, watchfulness and preparation, and it is one of the clearest ways the study of God's world turns into love of neighbor.

You will stand under the 660-ton steel ball that steadies Taipei 101, learn why buildings in Mexico City resonated and fell in 1985, and build a shake table to test bracing for yourself. You will follow the scientists at Mount Pinatubo in 1991 who counted earthquakes and measured gas until they were sure enough to move tens of thousands of people out of the way. You will measure the angle of repose of sand, read the signs of a slope about to fail, and hear how Turtle Mountain fell on the town of Frank in 1903. And you will finish with the children of Kamaishi, Japan, who had practiced so well that when the tsunami came in 2011 they ran, and the town ran after them.

The unit is quantitative throughout: natural periods and resonance, energy ratios between earthquakes, rates of bulging and gas release, angles from tangents, creep in centimeters per year, kit water in liters and evacuation times from map scales. It ends with your own family plan, a kit, a hazard map of where you live and a timed drill. "A prudent man foreseeth the evil, and hideth himself" (Proverbs 22:3).

BEFORE YOU BEGIN

- Can explain what seismic waves are, how a seismograph records them and what magnitude measures (Unit 4)
- Can describe how magma rises and the main kinds of volcanoes and their products (Unit 3)
- Can calculate a rate (distance or amount divided by time), a ratio, and a real distance from a map scale
- Can set up a fair test with an independent variable, a dependent variable and controls

MASTERY CHECKLIST

- I can explain why sideways shaking and inertia damage buildings, what resonance is, and how bracing, ductile frames, base isolation and dampers help a building stand.
- I can name the four main signs that magma is rising, the instruments that measure them, and the USGS alert levels, and I can tell the story of the Pinatubo forecast of 1991.
- I can explain how gravity, slope angle, water, rock structure and human cutting cause slopes to fail, tell the kinds of mass wasting apart, and measure an angle of repose.

- I can match each hazard (earthquake, tsunami, flood, tornado, volcano, landslide) to its correct first action.
- I can build and explain a family plan and kit, read a hazard map with a scale, and calculate water needs and evacuation times.
- I can read a data table about hazards and say which conclusion it supports and which it does not.

OPTIONAL BOOKS AND RESOURCES

- **Ready.gov: Build a Kit (FEMA)** (https://www.ready.gov/kit): Free. The official checklist for a family emergency kit, with pages on making a plan and on each kind of hazard. Use it in Lesson 8.4 to check your own kit list.
- **USGS Volcano Hazards Program** (https://www.usgs.gov/programs/VHP): Free. Current alert levels for every monitored U.S. volcano, observatory pages, and plain-language explanations of monitoring instruments and hazards. Check the alert map during Lesson 8.2.
- **The Great ShakeOut** (https://www.shakeout.org/): Free. Register your family for the yearly Drop, Cover and Hold On drill in October and download drill instructions and earthquake safety guides for homes and homeschools.

8.1 Earthquake-Proof Buildings: The Steel Ball in Taipei 101 ★

OBJECTIVES

- Explain why earthquakes damage buildings mainly by sideways shaking and inertia, and why a building whose natural period matches the ground's shaking period can resonate and fail.
- Describe four engineering ideas that help a building survive an earthquake: ductile materials, bracing and shear walls, base isolation and dampers.
- Estimate a building's natural period from its number of stories, and use magnitude differences to compare the energy of two earthquakes.

Warm-up. Hold a ruler upright by its bottom end on a table and jerk the table sideways a few centimeters. Which end of the ruler moves first, and which end lags and then whips? Now tie a washer or key to a string about 30 cm long and swing it gently; count ten swings and time them. Shorten the string to 15 cm and count again. Which pendulum swings faster? Write one sentence. A tall building is a stiff pendulum stood on its end.

Video. Coming soon. How earthquake-resistant buildings work: base isolation, cross-bracing, shear walls, tuned mass dampers, the Taipei 101 damper, shake-table tests and resonance; look for USGS, Smithsonian, Science Max, SciShow, Practical Engineering, Homeschool Pop (Alternate) and university engineering lab channels.

KEY TERMS

inertia
The tendency of a mass to keep doing what it is doing. When the ground jerks sideways, the base of a building moves but the heavy upper floors try to stay put, so the building bends and whips.

natural period
The time a building takes to sway once back and forth on its own; roughly one tenth of a second per story.

resonance
The strong, growing sway that happens when the ground shakes at the same period as a building's natural period, like pushing a swing in time with it.

ductile
Able to bend and stretch without breaking. Steel is ductile; unreinforced brick and plain concrete are brittle and crack.

base isolation
Setting a building on flexible bearings, often layers of rubber and steel with a lead core, so the ground can slide beneath it while the building moves much less.

tuned mass damper

A very heavy weight hung near the top of a tall building and tuned to swing against the building's motion, soaking up energy and reducing sway.

CORE IDEAS

The story. On August 8, 2015, Typhoon Soudelor came ashore in Taiwan and hammered the city of Taipei with wind. High inside the tallest building on the island, a gold-painted steel ball began to move. The ball is 5.5 m across and weighs 660 metric tons. It hangs from thick steel cables between the 87th and 92nd floors of Taipei 101, a tower 508 m tall with 101 floors, finished in 2004. That day the ball swung a full meter from side to side, the largest swing ever recorded for it, and the tower stayed calm. It is a tuned mass damper, and it was built not only for typhoons but for earthquakes, because Taiwan sits where the Philippine Sea plate pushes against the Eurasian plate and the ground shakes often. Taipei 101 is a lesson in one of the great questions of earth science: since we cannot stop the ground from moving, how do we build so that people live?

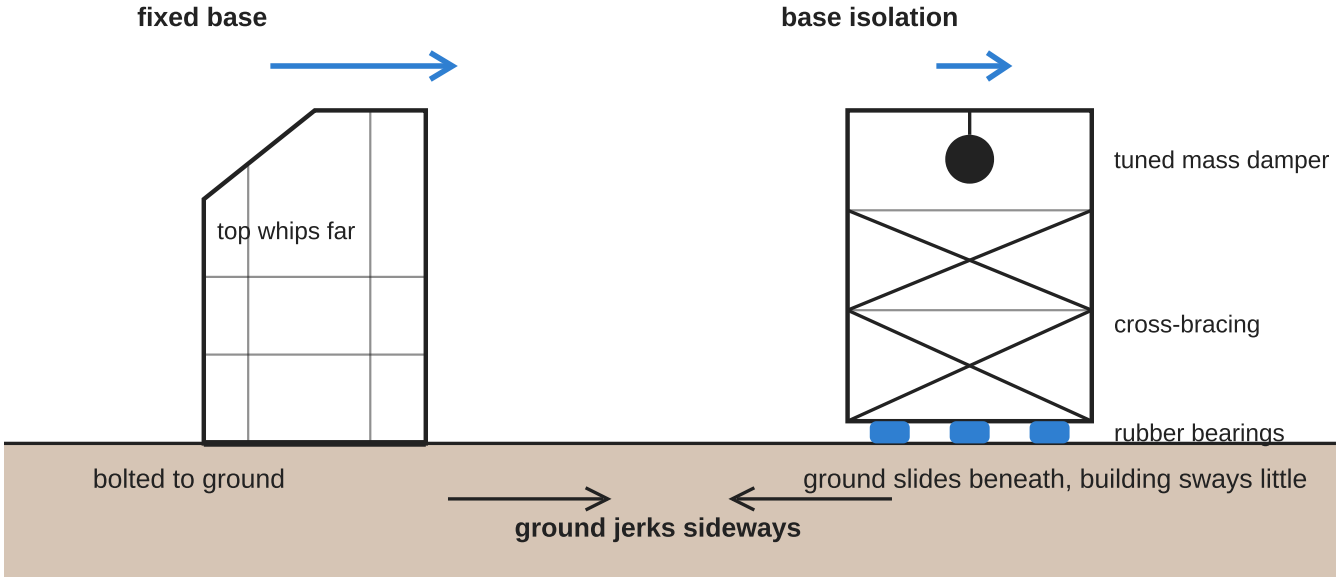
How they figured it out. Earthquakes rarely hurt people by shaking the ground up and down. They hurt people by shaking it sideways, and the reason is **inertia**. When the ground lurches to the left, the foundation goes with it, but the heavy upper floors want to stay where they were. The building bends, then whips back the other way, over and over. Every building has a **natural period**, the time it takes to sway once on its own, and engineers use a rule of thumb: about one tenth of a second per story. A three-story school sways about once every 0.3 s; a twenty-story tower, once every 2 s. The ground also shakes with its own rhythm, which depends on the earthquake and on the soil. On September 19, 1985, a magnitude 8.0 earthquake struck off the coast of Mexico about 350 km from Mexico City. The city is built on the soft clay of an old lakebed, and that clay rang like a bowl of jelly, shaking back and forth about once every 2 s for more than a minute. Buildings of six to fifteen stories, whose natural periods were close to 2 s, swayed farther with every push. Hundreds of them collapsed while shorter and much taller buildings next door stood. That is **resonance**, and it taught engineers that the soil under a building matters as much as the building.

The big idea. A building that survives an earthquake obeys a few rules. First, be **ductile**: steel and well-reinforced concrete can bend a long way and spring back, while plain brick walls crack and fall. Second, be tied together, so that roof, floors, walls and foundation move as one piece and the load has a path to the ground. Third, resist sideways force with diagonal cross-bracing or stiff shear walls, and never leave a weak "soft story" of open parking under a strong building. Fourth, let the ground move without you. In the 1970s a New Zealand engineer named Bill Robinson invented the lead-rubber bearing, a stack of rubber and steel plates with a plug of lead in the middle. Set a building on a row of them and the foundation can slide 20 or 30 cm while the building above barely sways; the lead core bends and heats, eating the energy. The first building to stand on them was the William Clayton Building in Wellington, finished in 1981. Today **base isolation** protects hospitals, city halls and museums, including Los Angeles City Hall and the Utah State Capitol, fitted with isolators long after they were built. Fifth, add dampers. Some are oil-filled pistons like a car's shock absorbers. Some, like the ball in Taipei 101, are a **tuned mass damper**, a

weight whose own swing is tuned to the building's period so that it always moves against the building and drags the motion down.

In the world today. The proof is in the comparisons. On January 12, 2010, a magnitude 7.0 earthquake struck Haiti near Port-au-Prince, where few buildings had been designed for shaking, and tens of thousands of people died under concrete. Six weeks later, on February 27, a magnitude 8.8 earthquake struck Chile, releasing about five hundred times more energy, and about five hundred people died, many of them from the tsunami that followed. Chile had written strict building codes after the giant earthquake of 1960. On March 11, 2011, the magnitude 9.1 earthquake off Japan swayed the skyscrapers of Tokyo for minutes, and not one of them fell. Engineers test these ideas on shake tables that replay recorded earthquakes under full-size houses, and they study every big earthquake to learn which buildings stood and why. An old saying among them is that earthquakes do not kill people; buildings do. That is why building codes, which can look like boring rules, are one of the ways a society loves its neighbor.

God's handiwork. Jesus told of two builders, one who built on rock and one who built on sand, and said that when the floods came and the winds blew, the house on the rock "fell not: for it was founded upon a rock" (Matthew 7:25). God made a world with order in it: inertia, periods, the strength of steel and the softness of clay all follow laws that can be measured and trusted. An engineer who learns those laws and builds a school that will stand is doing work God blesses, and a family that chooses a sound house is being wise, not fearful.



Left: a fixed-base building. The ground moves, the base moves with it, and inertia makes the top whip. Right: base isolation lets the ground slide under the building; cross-bracing stiffens the frame and a tuned mass damper near the top swings against the motion.

PICTURE STUDY



Namazu-e: The God of Kashima Subdues the Great Catfish (print after the Ansei Edo earthquake), Unknown printmaker of Edo (Tokyo), 1855 · Woodblock print, ink and color on paper · Namazu-e collection, International Research Center for Japanese Studies, Kyoto; many other designs survive in the University of Tokyo General Library

On the night of November 11, 1855, a strong earthquake struck Edo, the city we now call Tokyo, and fires burned through the wooden streets. Within weeks, printmakers were selling hundreds of cheap pictures called *namazu-e*, catfish pictures. Old Japanese folklore said that a giant catfish, the namazu, lay under the islands, and that the god of the Kashima shrine kept it pinned beneath a great stone. When the god was away, the catfish thrashed and the earth shook.

In this print the god has returned and is forcing the catfish down with his sword. In other designs, townspeople who lost homes beat the catfish in anger, while carpenters, plasterers and roofers, who now had plenty of work rebuilding the city, thank it. The prints are funny, sad and honest about human nature. They also show what people do when they cannot explain a disaster: they tell a story. Our lesson tells a different one, measured in periods and plate boundaries, but the fear and the rebuilding were just as real in 1855 as today.

Look closely

- Find the catfish. How big is it compared with the god and anything else in the picture? What does its size say about how the earthquake felt?
- Look at the god of Kashima. What is he holding, and what is he trying to do? In the folklore, what happened when he was away?
- Look at the catfish’s face and body. Does the artist make it frightening, foolish or both?
- Notice that the print is in color and was made quickly to sell. What does that tell you about how people wanted to deal with their fear?

Talk about it

1. The namazu story explained the earthquake with a creature and a god. What explanation does this lesson give for why Edo, and Taipei, shake so often?
2. Carpenters in Edo rejoiced because they would rebuild. In what ways did engineers after real earthquakes, such as Mexico City in 1985 and Kobe in 1995, “rebuild” better than before?
3. Why do you think people in every age want a reason for a disaster? How does the Bible’s teaching that God made and rules the earth (Psalm 46) differ from the catfish story?

EXPERIMENT: THE SHAKE TABLE: DOES CROSS-BRACING HELP A TOWER STAND?

Engineers test buildings on shake tables. You will build a small one from two box lids and some marbles, make two matching towers from drinking straws or craft sticks, brace one of them with diagonals and leave the other unbraced, and shake both the same way until something gives.

Question: Does adding diagonal cross-bracing let a tower survive more shaking? Prediction: write it down with your reason. What we change: whether the tower has diagonals. What we keep the same: the height, the number of floors, the tape, the weight on top and how we shake. What we measure: the number of shakes before the tower leans more than 3 cm or a joint breaks.

You will need

- Two shoebox lids or shallow trays of the same size, 8 to 12 marbles, and two wide rubber bands
- About 40 plastic drinking straws or craft sticks, masking tape or small blobs of modeling clay
- A small weight for each tower top, such as a roll of tape or a small bag of coins, both the same
- A ruler, a metronome app or a steady count, and your notebook with a table: Tower, Trial, Shakes until failure

Steps

1. Make the shake table: put the marbles in one lid, set the second lid upside down on top of them, and loop the rubber bands around both lids so the top lid can slide back and forth but not fall off.
2. Build Tower A: a square frame four straws tall (about 60 cm) with three floors, joined with tape or clay. Build Tower B exactly the same, then add a diagonal straw across every side panel so each face has an X or a single slash.
3. Tape the same small weight to the top of each tower. Measure both heights and record them. If they differ by more than 2 cm, fix one.

4. Stand Tower A in the middle of the top lid. Hold the bottom lid still and slide the top lid 3 cm left and 3 cm right once per second, counting each full back-and-forth as one shake. Stop when the tower leans more than 3 cm or a joint lets go. Record the count.
5. Reset and repeat twice more for Tower A, then do three trials for Tower B. Repair joints between trials so each trial starts fair.
6. Find the average shakes for each tower. Then try changing the rhythm: shake twice per second, then once every two seconds. Does either tower have a rhythm at which it sways most? That is its natural period.
7. Optional: set a tower on a plate resting on a layer of marbles or a soft sponge to model base isolation, and compare its sway with the tower taped straight to the lid.
8. Write a conclusion: did bracing help, by how much, and what rhythm made the towers sway most?

Tips

- Shake by the count, not by feel. A steady rhythm is what makes the test fair.
- If both towers survive forever, add more weight to the tops; heavy upper floors make inertia bigger, just as in a real building.
- Draw the braced panel. Notice that a diagonal turns a square that can lean into two triangles that cannot.

Check your work

- I changed only the bracing and kept height, weight and shaking the same.
- I ran three trials for each tower and averaged.
- I can explain, using the words inertia and resonance, why the towers swayed and why one did better.

FIELD NOTEBOOK

1. Draw a fixed-base building and a base-isolated building side by side during an earthquake, with arrows for ground motion and for how much the top of each moves.
2. Make a table titled “Period by Stories” for 1, 3, 10, 20 and 50 stories using the one-tenth-of-a-second rule, and mark which rows would resonate with 2 s shaking.
3. Sketch the Taipei 101 damper from the lesson description: the ball, the cables and the floors it hangs between. Label its mass and diameter.

> **From history.** Long before steel, Japanese carpenters built five-story wooden pagodas, such as the one at Horyu-ji temple that has stood since about A.D. 700, with a thick central pillar called the shinbashira running up the middle and floors that are not rigidly fixed to each other. The floors can shift a little and the pillar steadies them, so very few pagodas have ever fallen in an earthquake. When engineers designed the 634 m Tokyo Skytree, finished in 2012, they built a central concrete column that works like a modern shinbashira.

WORKED EXAMPLES

Example 1. Using the rule of thumb that a building's natural period is about 0.1 s per story, find the natural period of a 5-story, a 20-story and a 50-story building. The old lakebed under Mexico City shook with a period of about 2 s in 1985. Which building was in the most danger?

1. 5 stories: 5 × 0.1 s = 0.5 s.
2. 20 stories: 20 × 0.1 s = 2.0 s.
3. 50 stories: 50 × 0.1 s = 5.0 s.
4. Compare each with the ground's 2 s period. The 20-story building matches it almost exactly, so every push of the ground arrives in time with its own sway.

Answer: Periods of 0.5 s, 2.0 s and 5.0 s. The 20-story building resonates with 2 s shaking and is in the most danger; the short and very tall buildings are out of step with the ground and sway less.

Example 2. Haiti's 2010 earthquake was magnitude 7.0; Chile's, six weeks later, was magnitude 8.8. Each whole step of magnitude releases about 32 times more energy (Lesson 4.2), which is the same as saying energy grows by 10 to the power of 1.5 times the magnitude difference. About how many times more energy did the Chile earthquake release?

1. Find the difference in magnitude: 8.8 − 7.0 = 1.8.
2. Multiply by 1.5: 1.8 × 1.5 = 2.7.
3. Energy ratio = 10 to the power 2.7. Since 10 to the power 2 is 100 and 10 to the power 0.7 is about 5, the ratio is about 100 × 5 = 500.
4. Check with the 32-times rule: 32 × 32 = 1,024 for two whole steps, so 1.8 steps should be somewhat less than that, and 500 fits.

Answer: About 500 times more energy. Yet far fewer people died in Chile, because its buildings had been built to code for shaking. Energy released is not the same as damage done.

Example 3. You want to build a scale model of Taipei 101 for a shake-table display at a scale of 1 to 500. The tower is 508 m tall and the damper ball is 5.5 m across. How tall is the model, and how big is the model ball?

1. At 1 to 500, every real meter becomes 1/500 m, which is 0.2 cm.
2. Tower: 508 m ÷ 500 = 1.016 m, or about 102 cm.
3. Ball: 5.5 m ÷ 500 = 0.011 m, or 1.1 cm.
4. Compare: a meter-tall model with a damper the size of a marble. The ball looks tiny next to the tower, and in the real building it is also only a small fraction of the tower's mass; it works because it is tuned, not because it is huge.

Answer: The model is about 102 cm tall and the ball is about 1.1 cm across, the size of a marble.

PRACTICE

1. EASY Why does an earthquake damage buildings mainly by sideways motion? Use the word inertia.
2. EASY What is resonance? Give the swing example.
3. EASY Name four engineering features that help a building survive an earthquake, and say in a few words what each does.
4. MEDIUM Estimate the natural period of a 30-story building and of a 2-story house. If the ground shakes with a period of 0.3 s, which is in more danger of resonating?
5. MEDIUM Data reading. Three model towers were shaken on a table at three rhythms and the sway at the top was measured. At a shaking period of 0.5 s: 5-story model 6.0 cm, 10-story 1.2 cm, 20-story 0.4 cm. At 1.0 s: 5-story 1.5 cm, 10-story 7.2 cm, 20-story 1.0 cm. At 2.0 s: 5-story 0.5 cm, 10-story 1.4 cm, 20-story 8.1 cm. Which statement do the data support? (a) Taller towers always sway more. (b) Each tower sways most at one particular shaking period, and that period is longer for taller towers. (c) Shaking period has no effect on sway. (d) The 5-story tower is the safest at every rhythm.
6. MEDIUM Data reading. Two earthquakes in 2010: Haiti, magnitude 7.0, depth 13 km, few buildings designed for earthquakes, tens of thousands of deaths. Chile, magnitude 8.8, depth 23 km, strict building code since the 1960s, about 500 deaths. Which conclusion is best supported by this table alone? (a) Deeper earthquakes are less deadly. (b) Larger earthquakes are less deadly. (c) Building design had a larger effect on deaths than magnitude did. (d) Chile had fewer people near the earthquake.
7. MEDIUM Explain how a lead-rubber bearing protects a building. Why is lead in the middle?
8. HARD Experiment design. You want to find out whether a heavier roof makes a model house fail sooner on your shake table. Describe the plan: independent variable, dependent variable, at least three things kept the same, how many trials, and what you will measure.

9. HARD A magnitude 6.0 earthquake and a magnitude 7.0 earthquake strike two cities. How many times more energy does the larger one release? Give two reasons why the damage might not be 32 times greater.
10. CHALLENGE In 1985 the epicenter was about 350 km from Mexico City, yet the city suffered far more than places closer to the fault. In four or five sentences explain why, using the words lakebed, period, resonance and stories.

COMMON MISTAKES

- Thinking a stronger, heavier building is always safer. Heavy upper floors have more inertia and pull harder on the frame; flexible, ductile, well-tied buildings often do better than massive brittle ones.
- Believing that earthquake damage depends only on magnitude. Soil, depth, distance, length of shaking and especially building design decide how many buildings fall.
- Thinking “earthquake-proof” means a building will not move at all. The goal is to let it move safely, by bending without breaking or by sliding on isolators, not to make it rigid.

Make it a game · Period Match. One player is the ground and calls out a shaking period: “half a second,” “one second,” “two seconds,” “five seconds.” The other players are buildings; each has secretly chosen a number of stories from 1 to 50 and written it on a card. When the period is called, any building whose natural period (stories times one tenth of a second) is within 0.2 s of the called period must shout “Resonance!” and sway, and loses one point unless they can name one feature (bracing, isolation, damper, ductile frame) that would save them. Buildings that stay quiet when they should have swayed lose two points. Trade cards each round. Lowest score after six rounds wins.

Scripture. “Therefore whosoever heareth these sayings of mine, and doeth them, I will liken him unto a wise man, which built his house upon a rock: And the rain descended, and the floods came, and the winds blew, and beat upon that house; and it fell not: for it was founded upon a rock.” (Matthew 7:24–25, KJV)

Jesus is teaching about hearing and obeying His words, and He uses a picture everyone understood: the storm comes to both houses, and only the foundation decides which one stands. A good engineer builds the same way, for the storm that will surely come.

Practice answers

1. When the ground jerks sideways, the foundation moves with it, but the heavy upper floors have inertia and try to stay where they are. The building bends and whips back and forth, and that bending is what cracks and breaks it. Up-and-down motion mostly just pushes on the foundation, which buildings are already built to carry.
2. Resonance is the growing sway that happens when something is pushed at the same rhythm as its own natural period. Pushing a child’s swing each time it comes back makes it go higher and higher, while pushing out of time does little. Ground shaking at a building’s natural period does the same to the building.

3. Ductile materials such as steel bend without breaking; cross-bracing and shear walls resist sideways force; base isolation lets the ground slide under the building on flexible bearings; dampers such as a tuned mass damper or oil-piston dampers soak up the energy of swaying. (Also acceptable: tying the structure together, light roofs, avoiding soft stories.)
4. 30 stories: about 3 s. 2 stories: about 0.2 s. The 2-story house is closer to the 0.3 s shaking and more likely to resonate; the tall building sways far out of step with such fast shaking.
5. (b). The 5-story tower peaks at 0.5 s, the 10-story at 1.0 s and the 20-story at 2.0 s, each about ten times its number of stories in tenths of a second. This matches the rule of thumb and shows resonance, not a simple “taller is worse” rule.
6. (c). The larger earthquake caused far fewer deaths, and the clearest difference in the table is the building code. (a) is a guess from only two cases; (b) is the opposite of what physics expects; (d) is not shown in the table at all.
7. The bearing is a stack of rubber and steel plates that is stiff up and down (so it holds the building’s weight) but flexible sideways. During an earthquake the ground and foundation slide tens of centimeters while the building above moves much less, so inertia forces on the floors are small. The lead plug in the middle bends and heats as it moves, turning the energy of motion into heat, and it stiffens the bearing so the building does not sway in ordinary wind.
8. Independent variable: the mass taped to the top of the tower (for example 20 g, 50 g, 100 g). Dependent variable: the number of shakes before the tower leans more than 3 cm or a joint breaks. Keep the same: the tower design and height, the materials and tape, the size and rhythm of each shake, the shake table. Run at least three trials at each mass, repairing the tower between trials, and average the counts. Expect heavier tops to fail sooner because inertia force grows with mass.
9. About 32 times more energy (10 to the power 1.5). Damage depends on more than energy: the depth and distance of the earthquake, the kind of soil (soft lakebed clay amplifies and lengthens shaking), how long the shaking lasts, and above all how the buildings were built, whether to a code with ductile frames, bracing or base isolation.
10. Mexico City is built on the soft clay of an old lakebed. When the seismic waves arrived they shook that clay back and forth with a long period of about 2 s and kept it ringing for more than a minute, much longer and stronger than on hard rock nearby. Buildings of six to fifteen stories had natural periods close to 2 s, so each push of the ground came in time with their sway. That resonance made them lean farther with every cycle until columns failed, while short buildings and very tall ones, whose periods did not match, mostly stood. Distance alone does not decide damage; the soil and the match between ground period and building period matter greatly.

8.2 Volcano Monitoring: Reading Pinatubo's Signs, 1991

OBJECTIVES

- Name the main signs that magma is rising under a volcano (earthquake swarms, ground swelling, gas release, heat) and the instrument that measures each one.
- Tell how scientists at Mount Pinatubo in 1991 read those signs, raised alert levels and evacuated tens of thousands of people before the eruption.
- Calculate rates and ratios from monitoring data, such as the growth of a bulge in meters per day and the rise in gas output.

Warm-up. Put a few spoonfuls of dry flour or sand in a bowl and press it smooth. Slide a deflated balloon under the flour with its neck sticking out over the rim. Blow one small puff into the balloon and look sideways at the surface. Did it rise? Did it crack? Blow another puff and look again. Count how many puffs it takes before the first crack appears. The balloon is magma; the flour is a mountain. Which sign came first, the bulge or the crack?

Video. Coming soon. How scientists monitor volcanoes: seismometers, tiltmeters, GPS, gas sensors, the 1991 Mount Pinatubo eruption forecast, the Mount St. Helens bulge of 1980, USGS volcano observatories; look for USGS, Smithsonian, NASA, SciShow, Science Max and Homeschool Pop (Alternate).

KEY TERMS

volcano observatory
A station where scientists watch a volcano day and night with instruments; the United States Geological Survey runs five, in Alaska, the Cascades, California, Hawaii and Yellowstone.

earthquake swarm
Many small earthquakes close together in time and place, often caused by magma forcing its way through rock.

harmonic tremor
A steady, humming ground vibration that lasts minutes or hours, caused by magma or gas moving through cracks; a strong sign an eruption may be near.

tiltmeter
An instrument like a very sensitive carpenter's level that measures tiny changes in the slope of the ground as a volcano swells or shrinks.

sulfur dioxide
A sharp-smelling gas (SO_2) that escapes from magma as it rises; scientists measure how many tons per day a volcano releases.

lahar

A fast flow of volcanic ash and rock mixed with water, like wet concrete, that races down river valleys during and long after an eruption.

CORE IDEAS

The story. Mount Pinatubo, on the island of Luzon in the Philippines, had been quiet for about five hundred years. On April 2, 1991, steam blasted out of a line of cracks high on the mountain and villagers reported it to the Philippine Institute of Volcanology and Seismology, known as PHIVOLCS. Its scientists set up seismometers and counted small earthquakes under the mountain. In late April a team from the United States Geological Survey flew in to help, bringing more instruments. Through May the earthquakes kept coming, hundreds a day. On May 13 the mountain was breathing out about 500 metric tons of sulfur dioxide gas each day; by May 28 it was about 5,000 tons a day, ten times as much. Then the gas suddenly dropped, which was worse news: the vent had sealed and pressure was building. On June 7 a dome of fresh lava pushed up, and on June 9 the scientists raised the alert to the highest level and told everyone within 20 km to leave. On June 10 Clark Air Base, to the east, was evacuated. On June 12 the first great explosions sent ash 19 km up. The zone was widened to 40 km, tens of thousands of Filipino families moved out, and on June 15 Pinatubo blew apart. The ash column rose about 35 km, and darkness fell at midday. About 5 cubic kilometers of ash and pumice came out, and the summit collapsed into a crater 2.5 km across. It was the second-largest eruption of the twentieth century. A typhoon passed over the same day, soaking the ash so that roofs collapsed under its weight, and several hundred people died. The USGS later estimated that the warnings saved at least 5,000 lives.

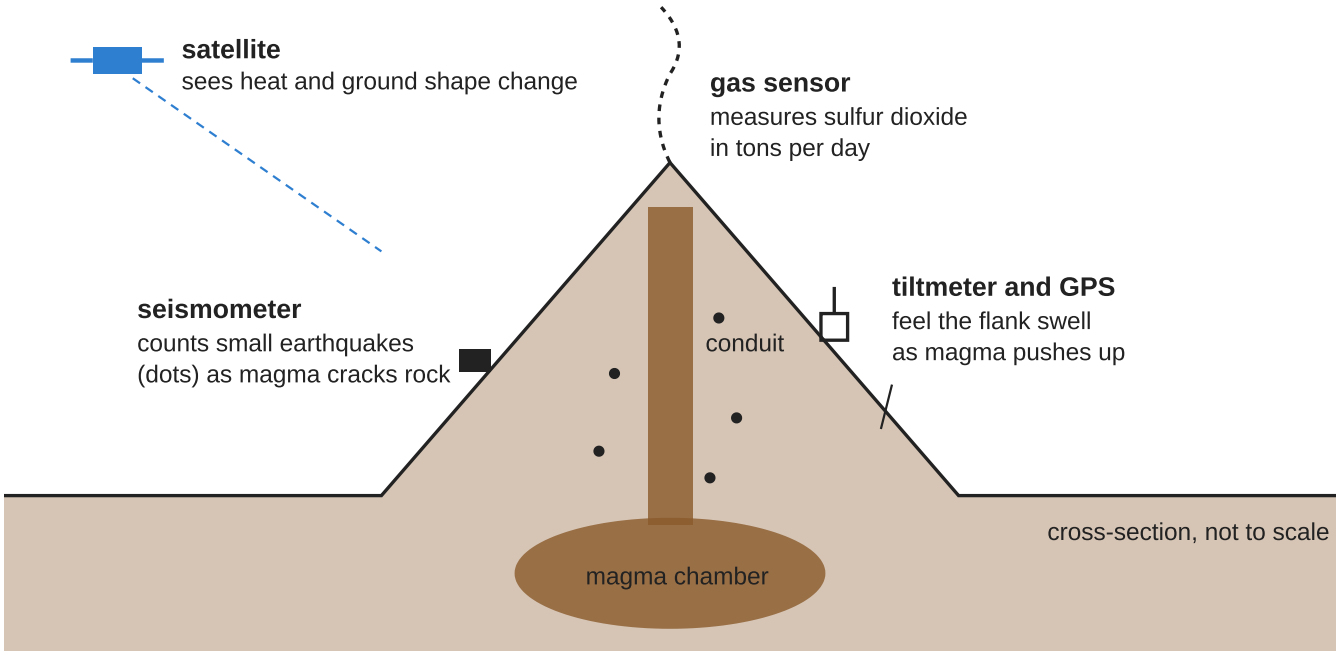
How they figured it out. A volcano cannot be stopped, but a volcano usually gives warning, because magma must push its way up through solid rock, and rock complains. The first instrument is the seismometer (Lesson 4.3). As magma cracks the rock, it makes an **earthquake swarm**, dozens or hundreds of small quakes a day, and the swarm often rises toward the surface as the magma does. When magma or gas flows steadily through the cracks, the ground hums with **harmonic tremor**. The second sign is swelling. Magma takes up space, so the mountain inflates like a slow balloon. A **tiltmeter** feels the slope change by a millionth of a degree; GPS stations measure the ground moving outward by millimeters. At Mount St. Helens in the spring of 1980, USGS crews measured a bulge on the north face growing about 1.5 m a day, until it stood more than 100 m out from the old slope. The third sign is gas. As magma rises, pressure drops and dissolved gases bubble out, especially **sulfur dioxide**, which a spectrometer measures by the sunlight it absorbs. The fourth sign is heat, seen in warming springs and by infrared cameras. No single sign is enough. The scientists at Pinatubo watched all of them climb together, and that is why they were sure.

The big idea. Volcanologists forecast; they do not predict to the hour. They can say an eruption is likely within days or weeks, and they translate that into alert levels that ordinary people and pilots can act on. The USGS uses four: Normal, Advisory, Watch and Warning, with matching aviation colors of green, yellow, orange and red. Raising the level is a heavy decision. Call it too early and people leave their homes and animals for nothing and will not listen next time; call it too late and they die. The scientists also draw a hazard map before

the eruption, showing where ash fall, pyroclastic flows and **lahars** will most likely go, so that evacuation zones make sense. At Pinatubo the lahars went on for years: every rainy season washed loose ash down the rivers as flows like wet concrete that buried whole towns.

In the world today. The USGS Volcano Hazards Program watches more than 160 volcanoes in the United States from its five observatories. In 2018 the Hawaiian Volcano Observatory tracked magma moving down the east side of Kīlauea by earthquakes and tilt, and warned the Leilani Estates neighborhood days before lava broke out of the ground there and destroyed about 700 homes; no one was killed by the lava. Volcano watching also protects airplanes. On December 15, 1989, a Boeing 747 flew into the ash cloud of Redoubt Volcano in Alaska, all four engines stopped, and the plane fell more than 3 km before the crew restarted them and landed safely in Anchorage. Today the Alaska Volcano Observatory and the aviation color code keep jets away from ash.

God's handiwork. The prophet Nahum wrote that "the mountains quake at him, and the hills melt" (Nahum 1:5). A volcano is one of the plainest reminders that the earth is not ours to command. Yet the same God who set fire under the mountains gave people eyes to notice steam on April 2, instruments to count the trembling and the patience to watch for weeks. The scientists at Pinatubo were like the watchman on the wall in Ezekiel 33, whose whole duty was to see the danger coming and blow the trumpet in time.



Four signs that magma is rising, and the instrument that catches each one: earthquakes (seismometer), swelling (tiltmeter and GPS), gas (spectrometer) and heat and shape change seen from a satellite.

PICTURE STUDY



Mount Pinatubo Erupting, Seen from Clark Air Base, Richard P. Hoblitt, United States Geological Survey, June 12, 1991 · Photograph · United States Geological Survey archive (public domain)

This photograph was taken by a USGS volcanologist on June 12, 1991, from Clark Air Base, where the scientists had set up their instruments and where, two days earlier, thousands of American families had been evacuated. It shows the first of the great explosive eruptions, three days before the climax. The ash column rose about 19 km that morning.

Look at the size of the cloud against the buildings. The people who took this picture were doing their job: watching, recording and measuring, so that the far bigger eruption of June 15 would find the valleys empty of people.

Look closely

- Find the base of the column where it meets the mountain. Is the column narrow there and wider higher up? Why might it spread as it rises?
- Look at the texture of the cloud. Does it look like smoke from a fire or like something else? (It is mostly tiny pieces of rock and glass, not smoke.)
- Find something in the foreground that tells you the scale: a roof, a vehicle, a tree. About how many of those would it take to reach the top of the cloud?
- Notice the blue sky. On June 15, with the big eruption and a typhoon, it was dark at noon. What would this scene have looked like then?

Talk about it

1. The scientists stood at this base taking photographs because they had already read the signs. What four signs did they watch, and which one told them the mountain was sealed and pressure was rising?

2. If you lived 15 km from this mountain and the alert went to Warning, what should you take with you and how soon should you go?
3. What do the photograph and the Scripture for this lesson (Nahum 1:5) each say about the power under the mountains?

> **Safety first.** The project uses a balloon and flour or sand indoors. Keep the balloon away from your face when inflating and releasing, do not let small children handle balloon pieces, and wipe up flour so no one slips.

EXPERIMENT: THE BALLOON VOLCANO: DOES THE GROUND TILT BEFORE IT CRACKS?

At Mount St. Helens the bulge was measured for weeks before the eruption. You will build a model mountain over a balloon, inflate it in equal steps, and measure the bulge and the tilt after every step, like a volcanologist with a tiltmeter.

Question: Does a measurable tilt appear before the surface cracks? Prediction: write it down. What we change: the number of puffs in the balloon. What we keep the same: the balloon, the depth of sand, the size of each puff. What we measure: the height of the bulge in millimeters and the tilt of the slope in degrees after each puff, and the puff at which the first crack appears.

You will need

- A balloon, a bendy drinking straw and tape (or a small hand pump)
- A baking dish or tray and enough damp sand, flour or fine soil to make a layer 3 to 4 cm deep
- A ruler, a protractor, a small level (or a phone level app) and a flat craft stick to lay on the slope
- Your notebook with a table: Puff number, Bulge height (mm), Tilt (degrees), Cracks (yes/no, where)

Steps

1. Tape the straw tightly into the neck of the deflated balloon. Lay the balloon flat in the dish with the straw end hanging over the rim, and cover it evenly with 3 to 4 cm of damp sand. Smooth the top and measure its height at the center with the ruler. Record this as puff 0.
2. Lay the craft stick on the sand about 5 cm from the center and set the level on it. Record the tilt as 0 degrees (or whatever the level shows).
3. Blow one steady breath into the straw and pinch it shut. Measure the bulge height at the center and the tilt of the craft stick. Look closely for cracks and record them.
4. Repeat puff by puff, measuring after each one, until the surface cracks open or the balloon shows. Mark the puff at which the first hairline crack appeared.
5. Make a graph: puff number along the bottom, bulge height on the left. Add a second line for tilt. Does the tilt change before the first crack?

6. Model a sealed vent: with a new balloon and fresh sand, stop blowing when the first crack appears and wait. Then add two quick puffs. Does the “eruption” come suddenly? Compare with Pinatubo, where the gas dropped before the explosion.
7. Write a conclusion: how many puffs of warning did your tiltmeter give before the crack? What would you tell a village on the slope?

Tips

- Damp sand holds a shape better than dry; too wet and it will slump instead of cracking.
- If you have no level, measure tilt by laying the protractor against the craft stick and reading the angle from horizontal.
- Repeat the whole experiment with a thicker layer of sand. Does a thicker mountain give more or less warning?

Check your work

- I measured bulge and tilt after every puff and recorded them in a table.
- I graphed both and marked the first crack on the graph.
- I can name the real instruments that match my ruler, my level and my eyes.

FIELD NOTEBOOK

1. Draw a cross-section of a volcano with the four monitoring instruments in place and an arrow from each to the sign it measures.
2. Make a timeline of Pinatubo from April 2 to June 15, 1991, with the gas numbers, the dome, the alert, the evacuations and the eruption.
3. Draw and label the four USGS alert levels and their aviation colors, with one sentence of what a family or a pilot should do at each.

> **From history.** On the morning of May 18, 1980, USGS volcanologist David Johnston was on duty at an observation post about 10 km north of Mount St. Helens. When the bulge collapsed and the mountain exploded sideways at 8:32 a.m., he radioed, “Vancouver! Vancouver! This is it!” and was never found. He had argued for keeping the area closed to visitors, and that closure saved many lives. The USGS named its Cascades Volcano Observatory in Vancouver, Washington, after him.

WORKED EXAMPLES

Example 1. On May 13, 1991, Pinatubo released about 500 metric tons of sulfur dioxide per day. On May 28 it released about 5,000 tons per day. By what factor did the output grow, and what was the average increase per day over those 15 days?

1. Factor of growth: 5,000 ÷ 500 = 10.
2. Total increase: 5,000 − 500 = 4,500 tons per day.
3. Days between May 13 and May 28: 15.
4. Average increase: 4,500 ÷ 15 = 300 tons per day, each day.

Answer: Gas output grew ten times, an average rise of about 300 tons per day every day. A few days later the output fell sharply, which told the scientists the vent had sealed and pressure was building.

Example 2. At Mount St. Helens in April 1980 the bulge on the north face grew about 1.5 m per day. How far would it move out in 4 weeks at that rate? If a survey crew measured 60 m of growth, how many days had passed?

1. 4 weeks = 28 days.
2. Distance = rate × time = 1.5 m/day × 28 days = 42 m.
3. For 60 m: time = distance ÷ rate = 60 m ÷ 1.5 m/day = 40 days.

Answer: About 42 m in four weeks; 60 m of growth means about 40 days. In real life the rate changed from week to week, which is why crews measured every day.

Example 3. On June 9 the evacuation zone around Pinatubo was a circle of radius 20 km. On June 14 it was widened to 30 km. Find the area of each zone and how many times larger the second one is. (Area of a circle = 3.14 × radius × radius.)

1. 20 km zone: 3.14 × 20 × 20 = 3.14 × 400 = 1,256 km².
2. 30 km zone: 3.14 × 30 × 30 = 3.14 × 900 = 2,826 km².
3. Ratio: 2,826 ÷ 1,256 = 2.25.
4. Check: (30 ÷ 20) squared = 1.5 × 1.5 = 2.25. Area grows with the square of the radius.

Answer: About 1,256 km² and 2,826 km². Widening the radius by half made the area 2.25 times bigger, so many more villages had to be moved.

PRACTICE

1. EASY Name four signs that magma is rising under a volcano and the instrument or method used to catch each one.
2. EASY What is a lahar, and why was it a danger at Pinatubo for years after June 1991?
3. EASY List the four USGS volcano alert levels in order and their aviation colors.
4. MEDIUM A volcano’s sulfur dioxide output rises from 200 tons per day to 1,800 tons per day in 8 days. By what factor did it grow, and what is the average rise per day?
5. MEDIUM A tiltmeter shows a volcano’s flank swelling outward at 4 mm per day. How much in 30 days, in centimeters? If a GPS station then reports the swelling has stopped while earthquakes continue, what might that mean?
6. MEDIUM Data reading. A monitoring log for a volcano: Day 1, 12 earthquakes, 300 tons SO_2 per day, tilt 0 microradians. Day 5, 45 earthquakes, 700 tons, tilt 6. Day 10, 160 earthquakes, 2,100 tons, tilt 15. Day 14, 410 earthquakes, 150 tons, tilt 24. Which statement is best supported? (a) All three signs rose steadily through day 14. (b) Earthquakes and tilt rose through day 14 while gas rose and then dropped sharply, which may mean the vent sealed. (c) The volcano is returning to normal by day 14. (d) Gas output is unrelated to earthquakes.
7. MEDIUM Data reading. Evacuation zones at a volcano: radius 10 km, 4,000 people; radius 20 km, 25,000 people; radius 30 km, 110,000 people; radius 40 km, 300,000 people. Scientists expect pyroclastic flows to reach 15 km and heavy ash fall to 35 km. Which radius is the smallest that keeps everyone out of the pyroclastic flow zone, and about how many more people must be moved to also cover heavy ash fall?
8. HARD Experiment design. You want to test whether a thicker layer of sand over the balloon gives more warning (more puffs between the first measurable tilt and the first crack). Describe the plan: independent variable, dependent variable, three things kept the same, how many trials, and how you will measure.
9. HARD In three or four sentences, explain why raising a volcano alert too early can be almost as harmful as raising it too late.
10. CHALLENGE Pinatubo’s ash column reached about 35 km on June 15, 1991. Airliners cruise at about 11 km. How many times higher than an airliner was the column? Explain, using the 1989 Redoubt flight, why volcano observatories send alerts to pilots even for ash that is far below the column’s top.

COMMON MISTAKES

- Thinking scientists can predict the exact day and hour of an eruption. They forecast a likely window of days to weeks from several signs rising together, then raise alert levels step by step.
- Thinking a volcano “gives up” when its gas output falls. A sudden drop in gas while earthquakes and swelling continue can mean the vent has sealed and pressure is rising.
- Believing the danger ends when the eruption ends. Lahars at Pinatubo went on for years, and loose ash on slopes is a hazard every rainy season.

Make it a game · Alert Level. One player is the volcano and secretly decides whether it will erupt this round. Each turn the volcano gives one clue card: “12 quakes today,” “tilt rising,” “SO_2 doubled,” “SO_2 dropped suddenly,” “steam only,” “quakes stopped.” The other players are the observatory. After each clue they must set the alert level: Normal, Advisory, Watch or Warning. When the volcano finally announces “eruption” or “quiet,” score it: a Warning before an eruption earns 3 points; a Warning when it stayed quiet costs 2 points (the villagers lost their crops); Normal when it erupted costs 5. Play five rounds and switch volcanoes.

Scripture. “The mountains quake at him, and the hills melt, and the earth is burned at his presence, yea, the world, and all that dwell therein.” (Nahum 1:5, KJV)

A volcano shows a power no one can command. The prophet says the mountains themselves answer to God. The right response is not panic but humility, and the kind of careful watchfulness that reads the signs He has placed in the trembling ground.

Practice answers

1. Earthquake swarms and harmonic tremor (seismometer); ground swelling (tiltmeter, GPS, satellite radar); gas release, especially sulfur dioxide (spectrometer); heat (thermometers in springs, infrared cameras, satellites).
2. A lahar is a flow of volcanic ash and rock mixed with water, like wet concrete, that rushes down river valleys. Pinatubo left cubic kilometers of loose ash on its slopes, and each rainy season washed it into the rivers as lahars that buried towns and farms.
3. Normal (green), Advisory (yellow), Watch (orange), Warning (red).
4. Factor: 1,800 ÷ 200 = 9. Rise: 1,800 − 200 = 1,600 tons per day over 8 days, so 200 tons per day each day.
5. 4 mm × 30 = 120 mm = 12 cm. Swelling that stops while quakes continue could mean magma has stopped rising for now, or that the rock has begun to crack and release pressure, or that magma is moving sideways; scientists would check the gas and seismic data before deciding.
6. (b). Earthquakes climb from 12 to 410 and tilt from 0 to 24, but gas peaks at 2,100 on day 10 and falls to 150 by day 14. A sudden gas drop with rising quakes and tilt is the pattern seen at Pinatubo just before the explosions.
7. The 20 km zone is the smallest that covers 15 km of pyroclastic flow, which means moving about 25,000 people. Covering 35 km of ash fall requires the 40 km zone, 300,000 people, about 275,000 more. This is why alert levels and hazard maps are weighed so carefully.
8. Independent variable: thickness of the sand layer (for example 2 cm, 4 cm, 6 cm). Dependent variable: number of puffs between the first tilt reading of 1 degree or more and the first visible crack. Keep the same: the balloon and straw, the dampness and type of sand, the size of each puff (one steady breath), the position of the level stick, the dish. Run three trials at each thickness with fresh smoothed sand each time and average the puff counts.
9. If scientists call for evacuation and nothing happens, people lose crops, animals, wages and trust, and the next warning may be ignored. If they wait too long, the eruption catches people in the danger zone and many die. So scientists watch for several signs rising together, not just one, and use alert levels that step up gradually. Good communication, explaining what the signs mean, helps people trust the warning when it finally comes.

10. 35 ÷ 11 ≈ 3.2, so the column was more than three times higher than airliners fly. Ash spreads sideways at every height as winds carry it, so a plane at 11 km can enter ash hundreds of kilometers from the volcano. In 1989 a 747 flew into Redoubt’s ash, the glassy ash melted in the hot engines and all four stopped; the plane fell more than 3 km before the engines restarted. Aviation color codes warn pilots to route around any ash cloud.

8.3 Landslides: The Mountain That Moved at Frank, 1903

OBJECTIVES

- Explain how gravity, slope angle, water, rock structure and human cutting decide whether a hillside holds or fails.
- Tell apart the main kinds of mass wasting (rockfall, rockslide, slump, debris flow and creep) by their speed and water content, and name their warning signs.
- Measure an angle of repose and calculate rates such as creep in centimeters per year and the volume of a slide.

Warm-up. Pour a cup of dry rice or sand slowly onto a plate from a height of a few centimeters until it makes a cone. Look at the side of the cone from table level and guess its angle. Now add a few drops of water to one side with a spoon and watch. Then pour a whole tablespoon of water on it. Write two sentences: what a little water did, and what a lot of water did.

Video. Coming soon. What causes landslides and how slopes fail, angle of repose demonstration, Frank Slide 1903, Oso landslide 2014, debris flows and lahars, USGS landslide hazards; look for USGS, Smithsonian, Science Max, SciShow Kids, Practical Engineering and Homeschool Pop (Alternate).

KEY TERMS

mass wasting
Any downhill movement of rock, soil or mud under gravity, from a sudden rockfall to creep too slow to see.

angle of repose
The steepest angle at which loose material such as sand or gravel will rest without sliding; for dry sand about 30 to 35 degrees.

rockslide
A mass of rock that breaks loose and slides fast along a surface such as a bedding plane or crack.

slump
A block of soil or soft rock that slides down a curved surface and tilts backward as it goes, leaving a crescent-shaped scar at the top.

debris flow
A fast, water-soaked flow of mud, rock and plants that rushes down a valley like wet concrete; on a volcano it is called a lahar.

creep

The slow downhill movement of soil, often only a few centimeters a year, shown by tilted fence posts, bent tree trunks and leaning walls.

CORE IDEAS

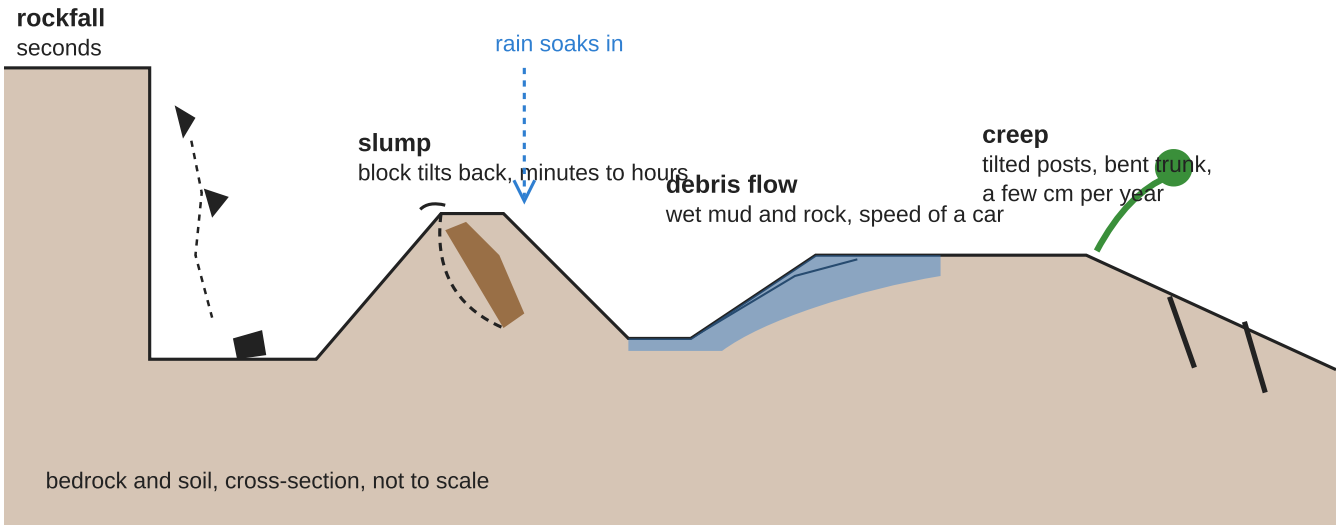
The story. Frank was a young coal-mining town in the Crowsnest Pass of Alberta, Canada, lying in the valley below Turtle Mountain. At ten minutes past four on the morning of April 29, 1903, the top of the mountain's east face let go. Some 30 million cubic meters of limestone, weighing at least 80 million metric tons (recent studies say more), slid and crashed down into the valley, crossed the river and the railway, climbed partway up the far side and stopped. The whole thing took about 100 seconds. The rock buried about 3 square kilometers of the valley floor under boulders the size of houses, along with the mine entrance, the railway line and the eastern edge of the town, and more than 70 people died. Seventeen miners underground dug their way out through a coal seam after about thirteen hours. A railway brakeman named Sid Choquette scrambled across the still-shifting rock in the dark to flag down the approaching passenger train in time. The road through the pass today runs right across the slide, and sensors on Turtle Mountain still watch the cracks at its summit.

How they figured it out. A slope is a tug of war. Gravity pulls every rock and grain of soil straight down, and on a slope part of that pull is aimed downhill. Holding it back are friction between the pieces and the stickiness of clay and roots. The steeper the slope, the bigger the downhill part of gravity, and every loose material has an **angle of repose**, the steepest slope it can hold: about 30 to 35 degrees for dry sand, steeper for rough gravel. Water is the great changer. A little water makes sand stickier, which is why a sandcastle stands. A lot of water fills the spaces between grains, pushes them apart, adds weight and greases the surfaces, and the slope fails. Water also wedges rock apart by freezing in cracks at night and thawing by day. Then there is structure. Turtle Mountain was a fold of thick limestone layers tilted steeply and standing on weaker shale and sandstone, with deep cracks running along the summit. A mine tunneled into the base of the mountain, a warm wet spring melted snow into the cracks, and bitterly cold nights froze it. Geologists afterward concluded that the shape of the mountain made the slide certain some day, and the water and the mining helped choose the day.

The big idea. All downhill movement of earth is **mass wasting**, and the kinds are sorted by speed and water. A rockfall is pieces dropping freely from a cliff, the fastest. A **rockslide** like Frank is a mass moving along a surface, often a bedding plane or crack that slants out of the hill. A **slump** is a block of soil that slides on a curved surface and tilts back, leaving a crescent scar at the top and a bulge at the bottom. A **debris flow** is the wettest and often the deadliest: soil and rock soaked by heavy rain turn to a fluid like wet concrete and race down a valley at the speed of a car, carrying boulders and trees. On a volcano it is a lahar (Lesson 8.2). The slowest is **creep**, soil moving a few centimeters a year, which you can read in tilted fence posts, bent tree trunks and cracked walls. The warning signs of a slope getting ready to fail are new cracks in the ground or in a road, doors and windows that start to stick, springs appearing where none were, tilted poles and trees, and a low rumble during heavy rain.

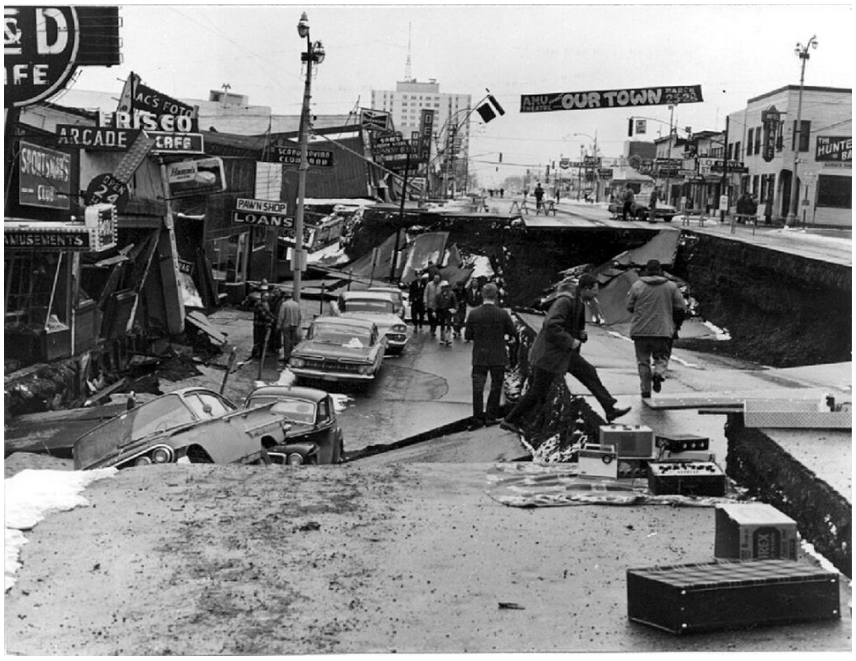
In the world today. On the morning of March 22, 2014, after weeks of unusually heavy rain, a hillside above the North Fork of the Stillaguamish River near Oso, Washington, collapsed. Wet sand, clay and glacial debris flowed about a kilometer across the valley in minutes, dammed the river, buried a highway and a neighborhood, and killed 43 people. The slope had slid before, in smaller ways, and the river had been cutting its toe for years. The USGS and the state now map such slopes with laser scanning from aircraft, which shows old slide scars beneath the trees. Engineers steady slopes with drains that lower the water inside the hill, with rock bolts and retaining walls, with terraces and nets that catch rockfall, and by replanting deep-rooted trees. But the best defense is the simplest: find out where slopes have failed before, and do not build in the path. In the Crowsnest Pass, Turtle Mountain has been watched by tiltmeters, crack meters and GPS since 2003.

God’s handiwork. The psalmist knew mountains could fall: “though the mountains be carried into the midst of the sea” (Psalm 46:2). He wrote that God is our refuge even if they do. A Christian can look steadily at a slope, measure its angle, read the cracks, respect the water and build somewhere safer, not because the earth is an enemy but because wisdom and love of neighbor demand it. The seventeen miners who dug upward through the coal for thirteen hours toward the light are a good picture of hope that works.



Four kinds of mass wasting, fastest to slowest. Water soaking into the hill adds weight, pushes grains apart and lubricates surfaces, so most slides follow heavy rain or snowmelt.

PICTURE STUDY



Fourth Avenue, Anchorage, after the Great Alaska Earthquake, Unknown photographer, United States Geological Survey, March 1964 · Photograph · United States Geological Survey photographic library (public domain)

On the afternoon of March 27, 1964, Good Friday, the largest earthquake ever recorded in North America, magnitude 9.2, shook southern Alaska for about four minutes. In downtown Anchorage, Fourth Avenue tore in two. The north side of the street slid toward the harbor on a layer of weak clay beneath the city and dropped about 3 m, carrying shops, signs and parked cars down with it, while the south side stayed in place.

This was not a building failing; it was the ground itself failing. Shaking turned the wet clay under the city to something like soup, and whole blocks slid toward the low ground. The same thing destroyed the Turnagain Heights neighborhood nearby. It is a reminder that a landslide can happen on a nearly flat city street, if there is weak, wet ground beneath and something to shake it.

Look closely

- Find the line where the street broke. Which side went down? About how far, judging by the shop windows and the people?
- Look at the cars and the signs on the sunken side. Are they smashed, or mostly just lowered? What does that tell you about how the block moved?
- Find the people. What are they doing? How soon after the earthquake do you think this was taken?
- Look for any slope in the picture. The street looks flat, yet the ground slid. Toward where, and why?

Talk about it

1. Which of this lesson's causes of slope failure were at work here: steep angle, water, weak layer, shaking, human cutting? Name every one you can defend.
2. This block moved as a unit and dropped. Which kind of mass wasting in the lesson is it most like, and how is it different from the Frank Slide?
3. Anchorage rebuilt on the same ground, with new rules about what could be built where. What would you want to know before buying a shop on Fourth Avenue?

> **Safety first.** The project uses sand, gravel and water. Work outdoors or over a tray, keep gravel away from small children, and wash hands afterward; do not dig test pits on real steep slopes or near road cuts.

EXPERIMENT: ANGLE OF REPOSE: HOW MUCH WATER DOES IT TAKE TO MAKE A HILL FAIL?

Geologists measure the angle of repose of loose materials and watch what water does to it. You will build small hills of dry sand and gravel, measure their steepest standing angle, then add water in measured spoonfuls until each hill fails, and record how much it took.

Question: Does water make a sand slope stronger at first and then weaker? Prediction: write it down. What we change: the amount of water added, one spoonful at a time. What we keep the same: the material, the amount of it, the way we pour, the tray. What we measure: the angle of the slope after each spoonful, and the spoonful at which it slumps or flows.

You will need

- About 4 cups of dry play sand and 2 cups of fine gravel or aquarium gravel
- A tray or baking sheet, a funnel or a paper cone, a tablespoon and a cup of water
- A protractor, a ruler and a straight stick or pencil to lay along the slope
- Your notebook with a table: Material, Spoonfuls of water, Height (cm), Base radius (cm), Angle (degrees), What happened

Steps

1. Pour dry sand slowly through the funnel from about 5 cm above the tray until it makes a cone about 8 cm tall. Measure the height and the base diameter (half of it is the radius). Lay the stick along the slope and read its angle with the protractor. Record this as 0 spoonfuls.
2. Compute the angle a second way: divide height by radius, then find the angle whose tangent is that number (a calculator's $\tan^{-1}$ key, or the table in the worked example). Compare with the protractor.
3. Add one tablespoon of water evenly over the cone. Try to steepen the slope by pushing up sand with a spoon. Measure the steepest angle it will hold and record it.
4. Keep adding one spoonful at a time, steepening and measuring after each, until the sand slumps, slides or flows. Record the spoonful at which it failed and what the failure looked like: a slump block, a slide, or a flow.

5. Repeat with gravel. Does gravel stand steeper dry? Does it fail at the same number of spoonfuls?
6. Undercutting test: build a fresh dry sand cone, then slowly dig a trench into its base with the spoon, like a river or a road cut at the toe of a slope. How much must you remove before the upper slope lets go?
7. Graph angle against spoonfuls for sand. Write a conclusion: what did a little water do, what did a lot do, and which real-world hills does this explain?

Tips

- Pour from the same low height every time; dropping sand from high up packs it and changes the angle.
- If your sand is already damp, dry it on a tray in the sun first, or your 0-spoonful angle will be too steep.
- Compare your dry sand angle with the textbook range of 30 to 35 degrees. If yours is outside it, think about why: grain shape, dust, moisture.

Check your work

- I measured the angle two ways and they roughly agreed.
- I added water one spoonful at a time and recorded the angle after each.
- I can explain why a damp sandcastle stands but a soaked one flows, and what that means for a hillside in heavy rain.

FIELD NOTEBOOK

1. Draw the four kinds of mass wasting from the figure, labeled, and write the speed of each (seconds, minutes, hours, years).
2. Draw a cross-section of Turtle Mountain as the lesson describes it: steep tilted limestone over weaker rock, cracks at the summit, the mine at the base and the slide path into the valley.
3. Walk around your neighborhood and sketch any sign of creep or slope movement: a tilted post, a cracked retaining wall, a bent tree. If you find none, draw what you would look for.

> **From history.** On June 23, 1925, in the Gros Ventre valley of Wyoming near Jackson Hole, a whole mountainside of sandstone resting on wet shale let go after a rainy spring and slid into the valley, damming the Gros Ventre River and forming Lower Slide Lake. Two years later, in May 1927, the natural dam partly gave way and the flood swept through the little town of Kelly, killing six people. A landslide can make a lake, and a landslide lake can make a flood, so geologists today watch any river dammed by a slide very closely.

WORKED EXAMPLES

Example 1. A cone of dry sand is 8 cm tall and its base is 26 cm across. Find its angle of repose. (Useful tangents: tan 25° = 0.47, tan 30° = 0.58, tan 32° = 0.62, tan 35° = 0.70, tan 40° = 0.84.)

1. Radius = 26 ÷ 2 = 13 cm.
2. Tangent of the slope angle = height ÷ radius = 8 ÷ 13 = 0.615.
3. Find the angle whose tangent is about 0.62: from the table, tan 32° = 0.62.
4. So the slope is about 32 degrees, inside the usual 30 to 35 degrees for dry sand.

Answer: About 32 degrees.

Example 2. The Frank Slide moved about 30 million cubic meters of rock in about 100 seconds. What was the average rate in cubic meters per second? A large dump truck carries about 10 m^3. How many truckloads is 30 million cubic meters?

1. Rate = volume ÷ time = 30,000,000 m^3 ÷ 100 s = 300,000 m^3 per second.
2. Truckloads = 30,000,000 ÷ 10 = 3,000,000.
3. Sense check: three million truckloads moved in under two minutes is why no one could do anything but run.

Answer: About 300,000 cubic meters per second, the equivalent of three million dump-truck loads.

Example 3. A fence post on a hillside was set straight in 2010. In 2022 its base has moved 24 cm downhill from its original line. What is the creep rate in cm per year? At that rate, how long would it take for the soil to move 1 m?

1. Years: 2022 − 2010 = 12.
2. Rate = 24 cm ÷ 12 years = 2 cm per year.
3. Time for 100 cm = 100 ÷ 2 = 50 years.

Answer: 2 cm per year; about 50 years to move a meter. Creep is slow, but a house foundation does not like even that.

PRACTICE

1. EASY List the five kinds of mass wasting in the lesson from fastest to slowest.
2. EASY Why does a damp sandcastle stand while a soaked one flows?
3. EASY Name four warning signs that a slope may be about to fail.

4. MEDIUM A gravel pile is 12 cm tall with a base 30 cm across. Find its angle of repose using the tangent table from the worked example. Is it steeper or shallower than sand?
5. MEDIUM A hillside road cut shows a slump block that moved 1.5 m in one rainy week. On the same hill, creep moves the soil 3 cm per year. How many years of creep equal that one week of slumping?
6. MEDIUM Data reading. A county recorded rainfall and landslides over six months: January 80 mm, 1 slide; February 150 mm, 3; March 310 mm, 11; April 120 mm, 2; May 40 mm, 0; June 20 mm, 0. Which statement is best supported? (a) Landslides happen only in March. (b) Months with more rainfall had more landslides, and the increase was sharp above about 150 mm. (c) Rainfall has no effect on landslides. (d) Landslides cause rainfall.
7. MEDIUM Data reading. Four slopes were surveyed: Slope A, 15 degrees, dry, grass, no history of sliding. Slope B, 35 degrees, wet, bare soil, slid in 2006. Slope C, 35 degrees, dry, forested, no history. Slope D, 25 degrees, wet, bare, river cutting its base, slid in 1998. Rank the slopes from most to least likely to fail in the next heavy rain, and give the two factors that most affected your ranking.
8. HARD Experiment design. You want to test whether plant roots make a soil slope more stable. Describe a plan using two trays of soil, one with grass grown in it for three weeks. Name the independent variable, the dependent variable, four things kept the same, and what you will measure.
9. HARD In three or four sentences, explain why geologists said the Frank Slide was bound to happen someday, and what made it happen on April 29, 1903.
10. CHALLENGE A debris flow travels 6 km down a valley in 15 minutes. Find its speed in km/h. A family hears a rumble when the flow is 2 km upstream. If they can walk uphill out of the valley bottom at 4 km/h and high ground is 200 m away, do they have time? Show your work.

COMMON MISTAKES

- Thinking landslides happen only on steep mountains. Wet, weak ground on a gentle slope, or even a nearly flat city street over soft clay, can slide, as Anchorage showed in 1964.
- Thinking water always weakens a slope. A little water makes sand stickier; it is a lot of water, filling the spaces between grains, that makes a slope fail.
- Thinking a slope that has already slid is now safe. Old slide scars are the best sign that a slope will slide again; that is why geologists map them.

Make it a game · Slide or Stand. Make a deck of slope cards, each listing an angle, a wetness (dry, damp, soaked), a cover (bare, grass, forest), a base (untouched, river-cut, road-cut) and a history (never slid, slid before). Deal one to each player. Players take turns reading their card and declaring “Stand” or “Slide,” then explaining the two strongest factors. The others vote whether the reasoning was sound; a sound call earns 2 points, a sound call that also names the likely kind of movement (slump, debris flow, rockslide, creep) earns 3. Play through the deck.

> **Scripture.** “Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah.” (Psalm 46:2–3, KJV)

The psalm pictures the worst that the ground can do: the earth giving way, mountains sliding into the sea. It does not promise that it will never happen. It says where our refuge is when it does. That is the courage from which careful, watchful science can grow.

Practice answers

1. Rockfall, rockslide, debris flow (all seconds to minutes, debris flow sometimes longer), slump (minutes to hours, sometimes slower), creep (centimeters per year).
2. A little water makes thin films between grains that pull them together (surface tension), so damp sand is stickier than dry. A lot of water fills the spaces completely, pushes the grains apart, adds weight and lubricates them, so the sand flows.
3. New cracks in the ground or pavement; doors and windows that begin to stick; springs or wet ground appearing where none was; tilted poles, trees or fences; a bulge at the base of a slope; a rumble or the sound of trees snapping during heavy rain.
4. Radius 15 cm; 12 ÷ 15 = 0.80, close to tan 40° = 0.84, so about 39 to 40 degrees. Steeper than sand, because rough, angular gravel locks together better than smooth sand grains.
5. 1.5 m = 150 cm; 150 ÷ 3 = 50 years.
6. (b). Slides rise with rainfall and jump from 3 at 150 mm to 11 at 310 mm, suggesting that once the ground is saturated, extra rain triggers many more failures. (a) ignores the other months; (c) contradicts the data; (d) reverses cause and effect.
7. Most likely: B (steep, wet, bare, slid before), then D (wet, bare, undercut by a river, slid before), then C (steep but dry and held by tree roots), least A (gentle, dry, grassed). The strongest factors are water and a history of past sliding; slope angle and vegetation come next.
8. Independent variable: whether the soil has living grass roots or not. Dependent variable: how much water (spoonfuls or milliliters) the tilted tray can take before the soil slides, or the steepest tilt it holds. Keep the same: the soil type and depth, the tray size, the tilt angle, the rate and amount of water added, the time since watering. Grow grass in one tray for three weeks and leave the other bare but watered the same; then tilt both to the same angle and add water in equal measured amounts until each fails, recording the amount. Repeat with fresh trays if possible.
9. Turtle Mountain was built of thick limestone layers folded and tilted steeply, resting on weaker shale and sandstone, with deep cracks running along its summit, so the east face was already leaning out over the valley. That structure made a slide likely in the long run. In the spring of 1903 snowmelt and rain ran into the cracks by day and froze by night, wedging the rock apart, while a coal mine tunneled into the base of the mountain weakened its support. On a cold night after a warm day, the strained rock let go.
10. Speed = 6 km ÷ 0.25 h = 24 km/h. Time for the flow to arrive: 2 km ÷ 24 km/h = 1/12 h = 5 minutes. Time to walk 200 m = 0.2 km ÷ 4 km/h = 0.05 h = 3 minutes. They have about 2 minutes to spare, if they leave at once and do not stop to gather things. This is why people in debris-flow valleys are told to move uphill the moment they hear a rumble in heavy rain.

UNIT 8 · LESSON 8.4 · 2 SESSIONS OF 45 MINUTES

8.4 Family Preparedness: The Children of Kamaishi, 2011

OBJECTIVES

- Identify the natural hazards most likely where you live and match each one to its correct immediate action (Drop, Cover and Hold On; go to high ground; evacuate early; shelter low).
- Build a family emergency plan with meeting places, an out-of-area contact and a kit sized to the family, and explain why drills matter.
- Calculate kit quantities, evacuation times and map distances from a scale, and read a simple hazard map.

Warm-up. Without looking, write down from memory: where your family keeps a flashlight, where the water shutoff valve is, the phone number of one relative who lives in another town, and a place your family could meet if you could not go home. Then check each one. How many did you know?

Video. Coming soon. Family emergency preparedness and building a kit, Drop Cover Hold On and the Great ShakeOut drill, tsunami evacuation and the Kamaishi schools in 2011, NOAA Weather Radio and USGS ShakeAlert earthquake early warning; look for FEMA and Ready.gov, NOAA SciJinks, USGS, American Red Cross, Science Max and Homeschool Pop (Alternate).

KEY TERMS

hazard map
A map that shows where a danger is likely: the floodplain of a river, the runup zone of a tsunami, slopes that have slid, ash and lahar paths near a volcano.

Drop, Cover and Hold On
The earthquake action: drop to hands and knees, cover your head and neck under a sturdy table or beside an inside wall, and hold on until the shaking stops.

emergency kit
Supplies packed and ready for several days without stores, power or clean water: water, food, light, radio, first aid, medicines, documents and cash.

family plan
Written agreements about where to meet, whom to call and what each person does when a hazard strikes, practiced ahead of time.

out-of-area contact
A relative or friend in another region whom every family member can call or text to report where they are, because local phone lines are often jammed after a disaster.

early warning

An alert sent seconds to hours before danger arrives, such as the USGS ShakeAlert system for earthquakes or a tsunami warning from NOAA.

CORE IDEAS

The story. Kamaishi is a town on the northeast coast of Japan, on a bay that has been hit by tsunamis again and again. For several years before 2011, a disaster engineer named Toshitaka Katada had worked with the town's schools, teaching the children three rules. Do not trust the hazard map too much; the sea may come higher than it shows. Do your very best in whatever situation you find yourself. And be the first to run, because when others see you running, they will follow. At 2:46 in the afternoon of March 11, 2011, the ground shook for minutes. At Kamaishi East Junior High School the students did not wait for orders. They ran out of the building and up the road, shouting to the elementary school next door to come, and the older students took the younger ones by the hand. At the first meeting point they saw the cliff behind it crumbling and ran higher. At the second point they decided it still was not high enough and climbed again. Minutes later the tsunami swept over the town's new breakwater and through both school buildings up to the third floor. More than a thousand people in Kamaishi died or went missing that day. Of about 3,000 schoolchildren in the town, nearly every one who was at school lived. Japan called it the miracle of Kamaishi, but Professor Katada said it was not a miracle. It was practice.

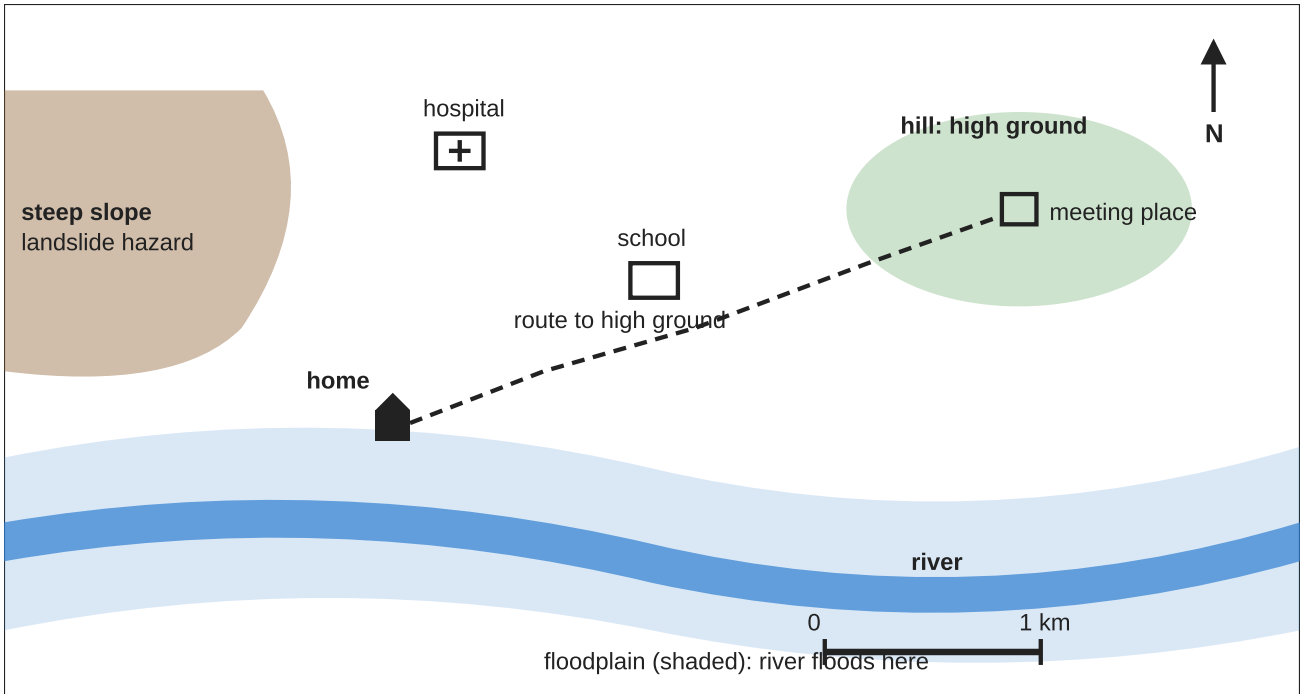
How they figured it out. Preparedness begins with knowing your own ground. Every place has its hazards, and they are not the same: tornadoes in Kansas, hurricanes in Florida, earthquakes and tsunamis in Oregon, floods and landslides in a mountain valley, lahars near Mount Rainier. The United States Geological Survey, state geological surveys and the Federal Emergency Management Agency publish **hazard maps**, and a family can look up its own house. Then each hazard has its own right action, and the actions are different. In an earthquake, **Drop, Cover and Hold On** where you are, because most injuries come from falling objects and from people trying to run outside past windows and bricks. For a tsunami, when the shaking stops, walk fast to high ground and stay there for hours. For a flood or wildfire, leave early, before roads close. For a tornado, go to the lowest inside room, away from windows. For a volcano, follow the alert levels and leave the valleys that lahars will use. Knowing which action fits which hazard is what saved the children of Kamaishi.

The big idea. A **family plan** has three parts. First, places: a meeting spot just outside the house, a second one outside the neighborhood, and the routes to each. Second, people: an **out-of-area contact** whose number is written on a card in every backpack and wallet. Third, jobs: who grabs the kit, who checks on the elderly neighbor, who carries the dog. The **emergency kit** is sized to the family: about 4 liters of water per person per day for at least three days, food that needs no cooking, a flashlight and spare batteries, a battery or hand-crank radio that receives NOAA Weather Radio, a first-aid kit and a week of any medicines, copies of important papers in a bag, some cash in small bills, a whistle, a can opener, warm clothes and blankets, supplies for pets and babies, and a charger. Keep it where everyone knows, and check it twice a year, when the clocks change. In the house, learn where the water shutoff is, and know that the gas is shut off only if you smell it, and turned back on

only by the gas company. And then practice. A plan that has never been run is a plan nobody remembers in the dark.

In the world today. On November 13, 2008, more than five million people in southern California dropped under their desks at the same moment for the first Great ShakeOut drill. Today tens of millions take part every October around the world. On the West Coast, the USGS ShakeAlert system now uses hundreds of seismometers to detect an earthquake in its first seconds and send a phone alert that can arrive before the strong shaking does, giving a few seconds to drop, stop a train or close a valve; public alerts began in California in 2019 and in Oregon and Washington in 2021. The Wireless Emergency Alerts system sends tsunami, flash flood and tornado warnings to every phone in the area. Warning systems are wonderful, but every one of them ends with a person who has to know what to do next. That person can be eleven years old.

God's handiwork. Proverbs 22:3 says, "A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished." Prudence is not fear. Noah, "being warned of God of things not seen as yet, moved with fear, prepared an ark to the saving of his house" (Hebrews 11:7), and his fear was reverence that got to work. A Christian family prepares for the same reasons: because the people under our roof are given to us to protect, and because a prepared family is free to help neighbors instead of needing help. Preparedness is one more way to love your neighbor as yourself.



A family hazard map. Shaded zones show where the river floods and where the slope has slid; the route from home to the meeting place on the hill avoids both. The scale bar lets you measure how far the family must walk.

PICTURE STUDY



Noah's Ark, Edward Hicks, 1846 · Oil on canvas · Philadelphia Museum of Art

Edward Hicks was a Quaker preacher and sign painter from Pennsylvania who painted the scenes he loved again and again, especially the Peaceable Kingdom of Isaiah. In this picture he shows the animals coming to Noah "two and two" (Genesis 7:9), climbing a ramp into the ark while the sky behind grows dark. Hicks based the design on a popular print of his day but filled it with his own patient lines of animals.

Noah is the Bible's great story of preparedness. He was warned, he believed, and he spent years building before a drop of rain fell. Hicks shows the last calm moments before the storm, which is exactly when a wise family's work should already be done.

Look closely

- Find the ramp. Which animals are nearest the door, and which are still far back in the line?
- Look at the sky. Where is the storm coming from? Has the rain started?
- Find the ark itself. How does Hicks show that it is enormous and well built?
- Can you find Noah or his family? If not, where do you think Hicks imagines them?

Talk about it

1. Noah prepared long before the danger came. What are three things your family can prepare now, in calm weather, for a hazard that may come later?
2. Hebrews 11:7 says Noah "moved with fear" and prepared. How is that kind of fear different from panic?
3. The animals went in two by two in good order. Why does order, rather than hurry, matter in an evacuation?

EXPERIMENT: OUR FAMILY PLAN: MAP, KIT AND A TIMED DRILL

You will do what the schools of Kamaishi did: find out your hazards, make the plan, pack the kit and practice until the practice is fast. You will also measure something, the time it takes your family to do the right thing, and see whether it gets shorter.

Question: Does practice make an evacuation faster? Prediction: write it down. What we change: the number of drills. What we keep the same: the starting places, the route, the meeting point, who carries what. What we measure: the time from the alarm until everyone is at the meeting point with the kit.

You will need

- A printed or hand-drawn map of your neighborhood, colored pencils and a ruler
- Index cards, a pen and a plastic bag for each person’s contact card
- A large tub or backpack, the kit items you already have at home, and a list of what is missing
- A stopwatch and your notebook with a table: Drill number, Date, Hazard practiced, Time to meeting point, What went wrong

Steps

1. With a parent, look up your hazards: your state geological survey or USGS hazard pages, the FEMA flood map, and what has actually happened in your county in the last hundred years. Write the top three hazards for your home.
2. On the map, mark your home, your two meeting places (one just outside, one outside the neighborhood), the nearest high ground or shelter, and any flood zone or steep slope. Draw the route to each meeting place and measure it with the scale.
3. Make a contact card for each person: full name, home address, parents’ phone numbers, the out-of-area contact’s name and number, and the two meeting places. Seal each in a bag and put one in every backpack and wallet.
4. Gather the kit. Count the family and compute the water: 4 liters per person per day for three days. Check off each item on the list in the lesson and write down what is missing to buy or borrow. Put the kit where everyone can name the place.
5. Decide jobs: who grabs the kit, who gets the pet, who checks on a neighbor, who calls the contact. Write the jobs on the fridge.
6. Drill 1: at a time a parent chooses, the parent calls the hazard (“Earthquake!” or “Flood warning, we leave now!”). Everyone does the right action for that hazard, then goes to the meeting place with the kit. Time it. Record what went wrong.
7. Repeat the drill a week later and a week after that, same hazard, same start. Record all three times. Then try a different hazard, and try one drill with the lights off and the usual door blocked.
8. Graph the times for drills 1, 2 and 3. Write a conclusion: did practice make you faster, and what is the one thing your family will change?

Tips

- Walk, do not run, in the house; the drill is to be fast by being ready, not by rushing.
- Put water in several smaller bottles rather than one huge jug so a child can carry a share.
- Rotate the food and water every six months when the clocks change, and use the old supplies for a family picnic.

Check your work

- I know my three top hazards and the correct first action for each.
- Our kit holds enough water for everyone for three days and everyone knows where it is.
- We ran at least three drills, timed them, and our time got shorter.

FIELD NOTEBOOK

1. Draw your neighborhood hazard map from the project, with a scale bar, a north arrow, the shaded hazard zones and the route to each meeting place.
2. Make a labeled drawing of your family’s emergency kit, with the quantity of each item for your family size.
3. Draw a four-panel strip: the right first action for an earthquake, a tsunami, a tornado and a flood, each with one sentence.

> **From history.** The first Great Southern California ShakeOut was held on November 13, 2008, with more than five million people practicing Drop, Cover and Hold On at the same moment, while scientists at the USGS published a detailed scenario of what a magnitude 7.8 earthquake on the San Andreas Fault would do to the region. The drill has grown every year since and is now held in October across the United States and in many other countries.

WORKED EXAMPLES

Example 1. A family of five packs water for three days at 4 liters per person per day. How many liters is that? If they use 2-liter bottles, how many bottles? Water has a mass of 1 kg per liter; how heavy is it?

1. Water per day: 5 people × 4 L = 20 L.
2. For three days: 20 L × 3 = 60 L.
3. Bottles: 60 ÷ 2 = 30 bottles.
4. Mass: 60 L × 1 kg/L = 60 kg, which is why the water is stored in a few places, not carried in one bag.

Answer: 60 liters, 30 two-liter bottles, about 60 kg.

Example 2. A tsunami warning says the first wave will reach a town 30 minutes after the earthquake. A family's house is 1.5 km from the hill marked as safe ground. They can walk at 5 km/h. If they leave the moment the shaking stops, how long will the walk take and how many minutes to spare do they have? What if an elderly neighbor walking with them can manage only 2.5 km/h?

1. Walking time = distance ÷ speed = 1.5 km ÷ 5 km/h = 0.3 h = 18 minutes.
2. Spare time = 30 − 18 = 12 minutes.
3. At 2.5 km/h: 1.5 ÷ 2.5 = 0.6 h = 36 minutes, which is 6 minutes too late.
4. So the plan must change: a bicycle or wagon for the neighbor, or a nearer strong tall building marked for vertical evacuation. Starting before the shaking stops is unsafe, so the only time saved is by leaving the instant it does.

Answer: 18 minutes, with 12 to spare, if everyone walks at 5 km/h. With the slower neighbor the walk takes 36 minutes and the wave arrives first, so the family needs a different plan for the neighbor: wheels, or a closer place of safety. Plans are made for the slowest person.

Example 3. On a hazard map with a scale of 1 to 25,000, the distance from a home to the meeting place on the hill measures 6 cm, and the shaded floodplain along the river is 2 cm wide. Find the real distances.

1. At 1 to 25,000, 1 cm on the map is 25,000 cm in the world, which is 250 m.
2. Home to hill: 6 cm × 250 m = 1,500 m = 1.5 km.
3. Floodplain width: 2 cm × 250 m = 500 m.
4. Check: a 1.5 km walk at 5 km/h takes 18 minutes.

Answer: The hill is 1.5 km away and the floodplain is 500 m wide. A route to the hill should cross the floodplain as little as possible.

PRACTICE

1. EASY What are the three parts of Drop, Cover and Hold On, and why is running outside during shaking a mistake?
2. EASY Why should a family have an out-of-area contact rather than only calling each other?
3. EASY List eight items that belong in a family emergency kit.
4. MEDIUM A family of 4 wants a five-day water supply at 4 liters per person per day. How many liters, and how many 4-liter jugs?
5. MEDIUM A hazard map has a scale of 1 to 50,000. The school is 3 cm from the nearest high ground. How far is that in meters? At 5 km/h, how many minutes would the walk take?

6. MEDIUM Data reading. A family timed its evacuation drills: Drill 1, 9 min 40 s, forgot the kit; Drill 2, 6 min 10 s, dog took 2 min to find; Drill 3, 4 min 30 s, no problems; Drill 4 (lights off, front door blocked), 6 min 50 s, took a wrong turn. Which statement is best supported? (a) Practice had no effect. (b) Times fell with practice under the same conditions, and a new condition raised the time again, showing the family needs to practice that case too. (c) The family is slower in drill 4 because they stopped caring. (d) The dog is the main problem.
7. MEDIUM Data reading. ShakeAlert warning time depends on distance from the earthquake, because the alert travels at the speed of light while strong shaking travels at about 3.5 km/s. A table: at 20 km, the alert arrives about 0 s before strong shaking; at 50 km, about 8 s; at 100 km, about 22 s; at 150 km, about 37 s. Why is the warning near the epicenter so short, and what useful things can be done with 20 seconds?
8. HARD Experiment design. You want to find out whether keeping the kit by the front door instead of in the garage makes your family's drill faster. Describe the plan: independent variable, dependent variable, four things kept the same, how many trials, and one problem you must watch for.
9. HARD In four or five sentences, explain Professor Katada's three rules for the Kamaishi children and how each one showed itself on March 11, 2011.
10. CHALLENGE A valley town lies below a volcano, and lahars are forecast to reach the town 45 minutes after an eruption begins. The town is 3 km long along the river and the safe ridge is 1 km from the river on each side. Sirens take 5 minutes to sound after the eruption starts. Walking at 4 km/h, how long does a family at the river's edge need to reach the ridge, and how much time is left after that? Then explain what the town should do about residents who cannot walk that fast.

COMMON MISTAKES

- Standing in a doorway during an earthquake. In modern houses a doorway is no stronger than the rest of the frame, and the door can swing and hurt you; get under a sturdy table or beside an inside wall and hold on.
- Waiting for an official order before leaving a tsunami zone. Strong shaking at the coast is the warning; by the time a siren sounds the wave may be minutes away. Go to high ground as soon as the shaking stops.
- Thinking one drill is enough, or that children should be kept out of planning so they will not worry. Practiced children, like those at Kamaishi, are calmer and safer than unpracticed ones.

> **Make it a game · Hazard Call.** A parent stands at one end of the room and, without warning, calls out a hazard: "Earthquake!", "Tsunami, shaking just stopped!", "Tornado warning!", "Flood coming up the street!" or "Volcano alert, Warning level!" Players must do the right first action within five seconds: drop, cover and hold on; walk fast to the "high ground" corner; crouch low in the "inside room" corner; head for the "car" to leave early; or the same for the volcano. Wrong action or a dash past the "window" costs a

point. After ten calls, the players take turns being the caller and add one twist, such as “lights out” or “front door blocked,” to see who still gets it right.

Scripture. “A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished.” (Proverbs 22:3, KJV)

The proverb praises the person who sees trouble coming and takes shelter in time. Preparedness is not a lack of faith. It is prudence, one of the ways God’s people care for the households He has given them.

Practice answers

1. Drop to hands and knees so you are not knocked down; cover your head and neck under a sturdy table or beside an inside wall; hold on until the shaking stops. Running outside sends you past falling glass, bricks and signs, which cause most injuries, and you cannot run steadily on shaking ground.
2. After a disaster, local phone lines are jammed or down. A call or text to someone in another region often goes through, so each family member reports to that one person and everyone learns where the others are.
3. Any eight: water (4 L per person per day), food needing no cooking, flashlight and batteries, battery or hand-crank radio, first-aid kit, medicines, copies of documents, cash, whistle, can opener, warm clothes and blankets, pet and baby supplies, phone charger.
4. $4 \times 4 \times 5 = 80$ L; $80 \div 4 = 20$ jugs.
5. 1 cm = 50,000 cm = 500 m, so 3 cm = 1,500 m = 1.5 km. Time = $1.5 \div 5 = 0.3$ h = 18 minutes.
6. (b). Drills 1 to 3 under the same conditions fell from 9:40 to 4:30. Drill 4 changed the conditions and the time rose to 6:50 with a new kind of mistake, which is exactly what a drill is meant to reveal.
7. Near the epicenter the strong shaking arrives almost as soon as the seismometers detect the earthquake and the system sends the alert, so there is little or no lead time; farther away the shaking takes longer to arrive and the warning grows. In 20 seconds a person can Drop, Cover and Hold On, a surgeon can lift a scalpel, trains can brake, elevators can stop at a floor and open, and gas valves can close.
8. Independent variable: kit location (front door versus garage). Dependent variable: time from alarm until everyone is at the meeting place with the kit. Keep the same: who starts where, the hazard called, the meeting place and route, the person who carries the kit, the time of day. Run at least two or three drills at each location and average. Watch for the practice effect: the family gets faster with every drill no matter where the kit is, so alternate the locations rather than doing all of one first.
9. The first rule was not to trust the hazard map too much; the children left the first meeting point, which the map had called safe, and climbed higher, and the wave later passed over it. The second was to do your best in whatever situation you are in; the junior high students did not wait for teachers but acted at once and helped the younger children. The third was to be the first to run, because others follow; townspeople who saw the children running ran too. Together the rules turned years of drills into the right decisions in a few minutes, and nearly every child who was at school survived.
10. Walking time = 1 km ÷ 4 km/h = 0.25 h = 15 minutes. Time available after the siren = $45 - 5$ = 40 minutes, so 25 minutes are left. Residents who cannot walk that fast need a plan made

in advance: neighbors assigned to drive or push them, buses staged at known points, and homes nearest the river given the earliest help. The town should drill the plan with those residents, not just the fast walkers, because a plan is only as good as the slowest person it includes.

Unit 8 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The test is worth 60 points.

1. (4 pts) Multiple choice. Earthquakes damage buildings mainly because (a) the ground moves up and down and crushes foundations; (b) the ground moves sideways and the heavy upper floors, because of inertia, lag behind and whip; (c) the air pressure changes; (d) the soil becomes hotter.
2. (5 pts) Using the rule that a building’s natural period is about 0.1 s per story, find the period of a 15-story building. If the ground under a city shakes with a period of about 1.5 s, explain in one or two sentences what is likely to happen to that building and why.
3. (5 pts) Name and briefly explain two different engineering features that help a building survive an earthquake.
4. (6 pts) List the four main signs that magma is rising under a volcano and the instrument or method that measures each one.
5. (5 pts) A volcano’s sulfur dioxide output rises from 400 metric tons per day to 4,000 tons per day over 12 days. By what factor did it grow, and what was the average rise per day? Then say what it might mean if the output suddenly fell to 200 tons per day while earthquakes kept increasing.
6. (4 pts) Multiple choice. The four USGS volcano alert levels, in order from lowest to highest, are (a) Green, Blue, Orange, Red; (b) Normal, Advisory, Watch, Warning; (c) Quiet, Active, Erupting, Over; (d) Watch, Warning, Normal, Advisory.
7. (6 pts) Diagram item. Draw a cross-section of a hillside showing a slump and a debris flow. Label the curved failure surface of the slump, the tilted block, the crescent scar at the top, the water-soaked flow in the valley, and an arrow showing where rain soaks in.
8. (5 pts) A cone of dry sand is 9 cm tall with a base 30 cm across. Find its angle of repose using these tangents: tan 25° = 0.47, tan 30° = 0.58, tan 32° = 0.62, tan 35° = 0.70. Then explain in one sentence what adding a lot of water would do to the slope.
9. (5 pts) Give three warning signs that a hillside may be about to fail, and name two things engineers or towns can do to reduce landslide danger.
10. (5 pts) A family of six packs water for three days at 4 liters per person per day. How many liters? If a hazard map at a scale of 1 to 25,000 shows their meeting place 8 cm from home, how far is the walk in kilometers, and how many minutes does it take at 5 km/h?
11. (5 pts) Match each hazard to its correct first action, and explain one of your choices: (1) earthquake, (2) tsunami after the shaking stops, (3) tornado warning, (4) flood warning for your street. Actions: go to the lowest inside room away from windows; leave early before roads close; Drop, Cover and Hold On; walk fast to high ground and stay for hours.
12. (5 pts) In three or four sentences, explain why the schoolchildren of Kamaishi survived the 2011 tsunami, and what Professor Katada meant when he said it was not a miracle.

UNIT PROJECT: OUR HOME HAZARD PLAN AND SAFE-HOUSE MODEL

Make a three-part capstone. First, a hazard map of your neighborhood with a scale bar, north arrow, shaded hazard zones (flood, slope, tsunami or other), your home, two meeting places and the routes to them, with the distances and walking times calculated. Second, your family plan and kit list, sized to your family with the water and food quantities worked out, contact cards made, and the record of at least three timed drills with a graph of the times. Third, a model building on your shake table, braced or isolated, with a short lab report (question, prediction, variables, data table, conclusion) comparing it with an unbraced tower.

Present the three parts to your family or co-op and lead a five-minute drill.

- **Hazard map**: Map is accurate for your real neighborhood, with scale, north arrow, correctly shaded hazard zones, meeting places and routes with distances and times calculated correctly.
- **Plan and kit**: Plan names hazards, actions, places, out-of-area contact and jobs; kit list is complete and quantities are computed for your family; at least three drills are timed and graphed.
- **Shake-table report**: The experiment has a clear question, prediction, independent and dependent variables, controls, a data table with three trials per tower and a conclusion that uses the words inertia and resonance correctly.
- **Presentation and care**: Work is neat and labeled; the drill is led clearly; the student can explain the science behind each part when asked.

Answer key

1. (b).
2. 15 × 0.1 = 1.5 s. The building’s period matches the ground’s, so each push arrives in time with its sway and the motion grows (resonance); it is in great danger of damage or collapse unless it has bracing, dampers or isolation.
3. Any two: base isolation (flexible rubber-and-steel bearings let the ground slide under the building); cross-bracing or shear walls (diagonals and stiff walls resist sideways force); tuned mass damper (a heavy weight tuned to swing against the building’s motion); ductile steel frames (bend without breaking); tying roof, floors and foundation together.
4. Earthquake swarms and harmonic tremor (seismometers); ground swelling or tilt (tiltmeters, GPS, satellite radar); gas release, especially sulfur dioxide (spectrometer); heat (thermometers in springs, infrared cameras or satellites).
5. Factor 10; rise of 3,600 ÷ 12 = 300 tons per day each day. A sudden drop with rising earthquakes can mean the vent has sealed and pressure is building, as at Pinatubo in late May 1991; it is a danger sign, not a sign of calm.
6. (b).
7. The drawing should show a block of soil that has slid down a curved (spoon-shaped) surface and tilted backward, with a crescent-shaped scar above it, and separately a wet flow of mud and rock running down a valley; a rain arrow entering the slope should be labeled. Full marks for correct labels on all five parts and a sensible hill shape.
8. Radius 15 cm; 9 ÷ 15 = 0.60, between tan 30° and tan 32°, so about 31 degrees. A lot of water fills the spaces between grains, adds weight, pushes the grains apart and lubricates

them, so the slope would fail at a lower angle and could flow.

9. Signs: new cracks in the ground or roads, doors and windows sticking, new springs or wet patches, tilted poles or trees, a bulge at the base of a slope, rumbling during heavy rain. Measures: drains to lower water in the slope, retaining walls and rock bolts, terraces or catch fences, replanting deep-rooted trees, mapping old slides and not building in their path, monitoring with tiltmeters and GPS.
10. 6 × 4 × 3 = 72 liters. 8 cm × 250 m = 2,000 m = 2 km. 2 ÷ 5 = 0.4 h = 24 minutes.
11. (1) Drop, Cover and Hold On; (2) walk fast to high ground and stay for hours; (3) lowest inside room away from windows; (4) leave early before roads close. Example explanation: in an earthquake most injuries come from falling objects and from running past windows and bricks, so you protect your head where you are.
12. The children had practiced for years and had learned three rules: do not trust the hazard map too much, do your best in any situation, and be the first to run so others follow. When the shaking stopped they left at once without waiting for orders, took the younger children with them, and climbed higher twice when the meeting points seemed unsafe; the wave later covered both earlier points. Nearly every child who was at school lived. Katada meant that it was practice and good decisions, not luck, that saved them, and any family can do the same.

UNIT 9 · OPTIONAL

Bonus: Field Lab

The whole year has been about an earth that moves: seismic waves through the core, plates and mountains, volcanoes and floods, erosion and the engineering that answers it. This bonus unit takes you outdoors to see the small, local versions of those great processes with your own eyes and measure them with your own hands. Four short field lessons send you into the yard, the neighborhood and the nearest roadcut with nails, a spade, a tape measure, a protractor and a notebook.

You will set erosion pins and catch the mud a storm carries off, as the first soil scientists did on their measured plots. You will dig a pit and read the soil’s horizons the way Vasily Dokuchaev read the black earth of Russia. You will walk your streets with a clipboard and draw a hazard map in the spirit of the geologists who mapped San Francisco’s shaking in 1906. And you will stand in front of a rock outcrop and read its layers from the bottom up like William Smith, keeping what you observe strictly apart from what anyone says it means.

Every lesson is lighter than the main units and built around a real place near you. The deliverable is a field notebook: dated tables, measured sketches to scale, a finished map and a measured outcrop drawing. “The earth is the LORD’s, and the fulness thereof” (Psalm 24:1), and the first step of keeping it is to look at it closely.

BEFORE YOU BEGIN

- Can measure length in millimeters and centimeters and convert between millimeters, centimeters and meters
- Can compute a rate (amount divided by time) and a percent (part divided by whole, times 100)
- Knows the words erosion, deposition, sediment and sedimentary rock from Unit 6
- Has an adult who can take them outdoors to a yard, a neighborhood walk and a roadcut or creek bank

MASTERY CHECKLIST

- I can set erosion pins, read them after rain and compute a soil-loss rate in millimeters per week.
- I can dig or find a soil face, measure and name its horizons, and compute percent sand, silt and clay from a jar test.
- I can draw a map of my neighborhood with a north arrow, scale bar and legend and mark its water, slope and falling hazards.
- I can convert map distances to real distances using a scale.
- I can measure and sketch a rock outcrop to scale, identify sandstone, shale and limestone by simple tests, and state the rule of superposition.
- I can keep observations and interpretations in separate columns and explain the difference using a roadcut sign as an example.

OPTIONAL BOOKS AND RESOURCES

- **USGS topoView (free topographic maps of the United States)** (https://ngmdb.usgs.gov/topoview/): Free. Zoom to your town, pick a historical or current topographic quadrangle, and download it as an image to use as the base map for Lesson 9.3. The 1:24,000 maps show contour lines, streams and floodplains.
- **FEMA Flood Map Service Center** (https://msc.fema.gov/portal/home): Free. Type in your address to see the official flood hazard zones for your street. Compare the 100-year zone with the floodplain you marked on your own map.
- **USDA Web Soil Survey** (https://websoilsurvey.nrcs.usda.gov/): Free. Outline your property or neighborhood on the map and read the soil scientists' description of the soil there, including its horizons and texture. Compare it with your own pit in Lesson 9.2.

UNIT 9 · LESSON 9.1 · 2 SESSIONS OF 45 MINUTES

9.1 Erosion Watch: Measuring Soil Loss in Your Own Yard

OBJECTIVES

- Set erosion pins and a splash board outdoors and record how much soil moves during real rain.
- Compute an erosion rate in millimeters per week from pin measurements and compare bare, grassy and mulched ground.
- Explain why plant cover slows erosion and name two ways farmers and gardeners keep soil in place.

Warm-up. Fill a cup with dry flour and tip it into a small heap on a plate. Now hold a spoon about 30 cm above the heap and let one drop of water fall from it. Look closely at the splash: how far did bits of flour fly? Try a second drop from 60 cm. Write down what you think a whole rainstorm does to a bare garden bed.

Video. Coming soon. Soil erosion by rain splash and runoff, erosion pins and runoff plots, contour plowing and cover crops; search USDA NRCS, USGS, SciShow Kids, Homeschool Pop (Alternate), Science Max and university extension channels.

KEY TERMS

erosion
The wearing away and carrying off of soil and rock by moving water, wind or ice.

runoff
Rain water that does not soak into the ground but flows across the surface, carrying soil with it.

splash erosion
The knocking loose of soil grains by the impact of raindrops. It is the first step of water erosion.

erosion pin
A nail or stake driven into the ground with its top at a known height, so that later measurements show whether soil was lost or gained.

sediment
Loose grains of soil, sand, silt or clay that water carries and later drops.

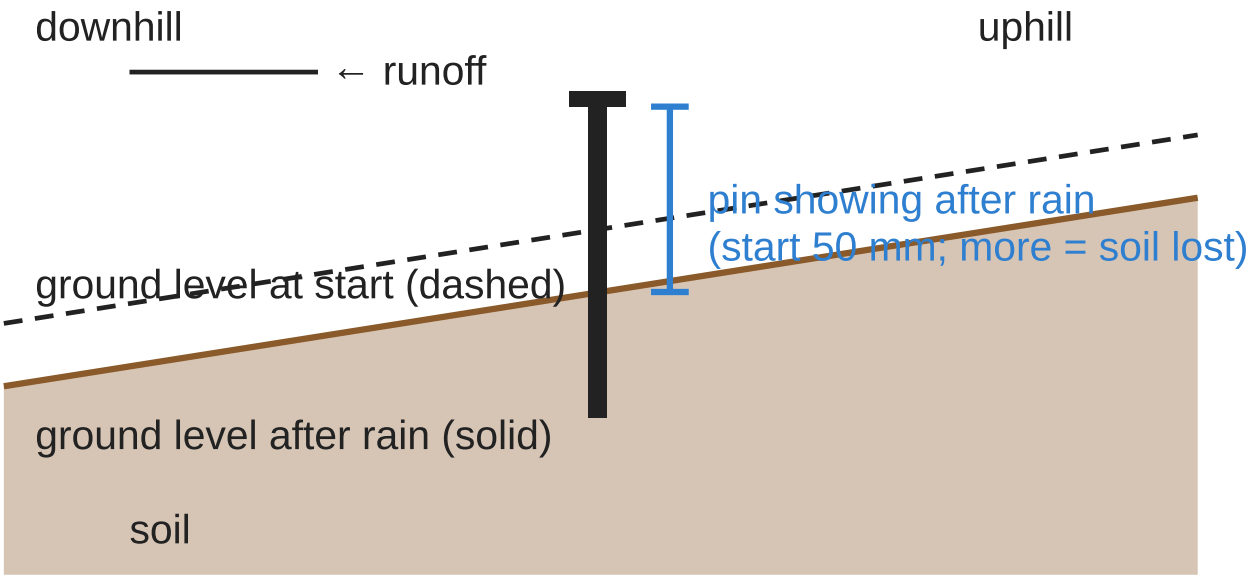
cover
Anything that shields the soil surface from rain and wind: grass, leaves, mulch, crop stubble or a growing crop.

CORE IDEAS

The story. In 1917, on a gentle slope at the University of Missouri in Columbia, two soil scientists named M. F. Miller and F. L. Duley did something no one in America had done before. They fenced off small, identical plots of ground on the same hillside and gave each one a different treatment: one was kept bare, one grew corn year after year, one grew wheat, one was left in grass sod. At the bottom of every plot they set a tank to catch whatever ran off in the rain. After each storm they measured the water in the tank and weighed the mud that had settled in it. They kept this up for years. The answer was plain and stayed plain: the bare plot and the corn plot lost soil many times faster than the plot under grass, though the rain, the slope and the soil were the same for all of them. The only thing that differed was the cover. Plots like these, copied all over the country in the 1930s, became the measuring sticks of soil conservation. Today you will build the simplest version of their experiment with nails, a ruler and a notebook.

How they figured it out. Water erosion begins before any water flows. A raindrop falling at full speed hits bare ground like a tiny hammer and throws soil grains up to a meter sideways. This is **splash erosion**, and on a slope more grains land downhill than uphill, so the whole surface creeps downward one storm at a time. Splashed clay then seals the surface so water cannot soak in, and the rain that cannot sink must run off. **Runoff** gathers into threads, threads into rills, and rills into gullies, each carrying **sediment** away. Cover stops this at the first step. A blade of grass or a dead leaf breaks the fall of the drop, roots hold the grains, and a rough, open surface lets water soak in instead of running. That is why Miller and Duley’s sod plot kept its soil. Scientists still measure the same way they did, only with finer tools: **erosion pins** driven flush with the ground and re-measured after rain, white splash boards that record how high mud flies, and jars of runoff that settle so the sediment can be measured.

Try it and see. Your own yard, a path, a ditch bank or the edge of a field is a laboratory. Choose three patches on the same slope: one bare, one grassy, one you cover with mulch or leaves. Set pins, mark the ground line, and come back after rain with a ruler. Where soil is lost the pin stands taller; where sediment piles up the mark is buried. Pin readings in millimeters over weeks turn into a rate, and a rate is what lets you compare. God gave Adam the garden “to dress it and to keep it” (Genesis 2:15), and keeping the ground means first finding out where it is going. The farmers of the 1930s learned to plow along the contour, plant strips of grass between strips of crop, and leave stubble on the field all winter. Every one of those cures was first proved on measured plots like the ones you are about to make.



An erosion pin. Drive the nail flush, or mark the ground line on it. After rain, the length of pin showing above the soil is the depth of soil lost.

PICTURE STUDY



View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm (The Oxbow), Thomas Cole, 1836 · Oil on canvas · Metropolitan Museum of Art, New York

Thomas Cole climbed Mount Holyoke in Massachusetts and painted the view just as a storm was clearing. Below him the Connecticut River loops back on itself in a great bend called an oxbow. On the left the hillside is wild forest under the rain; on the right the valley has been cleared into fields, pastures and haystacks, with smoke rising from farmhouses.

Cole painted himself as a tiny figure with an umbrella and an easel on the rocks near the bottom of the canvas. He was looking at the same question you will ask outdoors today: what happens to the land when the trees come off and the rain comes down?

Look closely

- Trace the river with your finger. Where does the water flow slowest, on the outside of the bend or the inside? Where do you think sediment is dropped?
- Compare the forested left half with the cleared right half. Which ground would splash and run off more in the storm that is passing?
- Find the fields on the far hillside. Are the plowed patches running up and down the slope or across it?
- Find the painter. Why do you think Cole made himself so small?

Talk about it

1. Cole painted this scene in 1836, when forests were being cleared for farms across New England. What would an erosion pin have shown on the cleared slopes compared with the wooded ones?
2. The oxbow bend has since been cut off from the river and is now a lake. How does a river cut off its own bend?
3. Cole shows storm and sunshine, wild and tame, in one picture. What do you think he wanted the viewer to feel about the land?

> **Safety first.** Work outdoors with a parent. Never step into a ditch, creek or storm drain while water is running, and stay off steep banks after heavy rain. Wear boots, wash your hands after handling soil, and ask before driving nails anywhere near buried pipes or wires.

EXPERIMENT: THE THREE-PATCH EROSION WATCH

Question: does cover change how much soil rain carries away? Prediction: the bare patch will lose the most soil, the mulched patch less, and the grassy patch least. What we change: the cover. What we keep the same: the slope, the soil, the rain and the time. What we measure: the length of pin showing above the ground, in millimeters, and the height of mud on a splash board.

You will set up three small plots and read them after every rain for at least three weeks. Real soil scientists run their plots for years, so the longer you keep your record, the better it gets.

You will need

- Nine long nails or thin stakes (at least 15 cm), three for each patch
- Permanent marker and a metric ruler
- Three white index cards or scraps of white plastic, and clothespins or small stakes to hold them upright

- A rain gauge (a straight-sided jar with a ruler taped to it will do)
- Mulch, straw or dead leaves for the covered patch
- Lab notebook, pencil, and a clear jar with a lid for runoff samples

Steps

1. With a parent, choose a gentle slope and mark three patches about 50 cm square side by side across the slope, so each gets the same rain and tilt. Leave one bare (scrape away the plants), leave one in grass, and cover one with a layer of mulch or leaves about 3 cm deep.
2. Push three nails into each patch, spaced out, until the top is exactly 5 cm above the ground. Measure with the ruler and write 50 mm as the starting reading for every pin. Give each pin a name, such as B1, B2, B3 for bare.
3. Stand a white card upright at the downhill edge of each patch with its bottom edge on the soil. Mark a line at the soil level.
4. Set the rain gauge in the open nearby, away from trees and roofs.
5. After each rain, read the gauge in millimeters and empty it. Measure every pin from the top of the nail to the soil, and write the date, the rain and the readings in a table. A larger number than 50 mm means soil was lost; a smaller number means sediment was added.
6. Look at the splash cards. Measure the highest mud spot above the soil line in millimeters, write it down, and wipe or replace the card.
7. If water puddles below the bare patch, scoop a jarful, cap it, and let it stand overnight. Measure the depth of sediment that settles compared with the depth of water.
8. After three weeks, average the three pins in each patch. Subtract 50 mm to find the soil lost, and divide by the number of weeks to get a rate in millimeters per week. Write one paragraph comparing the three patches with your prediction.

Tips

- Measure at the same spot on each pin every time, straight down to the soil, not to a leaf or clod.
- Frost, dogs and footprints also move pins. Note anything unusual in your record rather than quietly fixing it.
- If no rain comes, a watering can held 1 m up and poured at the same speed over each patch is a fair stand-in. Say so in the notebook.

Check your work

- I kept a dated table of rain, pin readings and splash heights for all three patches.
- I computed a soil-loss rate in millimeters per week for each patch.
- I can explain in one sentence why the covered patches lost less soil.

FIELD NOTEBOOK

1. Draw a cross-section of your slope with the three patches and the pins, and mark the ground level before and after the rain with two different lines.
2. Make a bar graph with three bars, one for each patch, showing millimeters of soil lost after three weeks.
3. Walk your street after a storm and sketch two places where you can see sediment that water dropped, such as a fan of sand at the bottom of a driveway or mud at a storm drain. Draw an arrow showing where it came from.

From history. Measured erosion plots spread quickly after the Missouri experiment. By 1933 the federal government had set up ten erosion experiment stations in different climates, each with plots of the same shape so that results could be compared from state to state. Decades of those plot records were later boiled down into a single formula for predicting soil loss from rain, slope, soil, cover and farming practice, still used by conservation planners today. The whole method grew from the simple idea you used: keep everything else the same, change one thing, and catch the mud.

WORKED EXAMPLES

Example 1. After four weeks, the three pins in the bare patch read 56 mm, 54 mm and 58 mm. The three pins in the grass patch read 51 mm, 50 mm and 51 mm. Every pin started at 50 mm. Find the soil lost and the erosion rate in millimeters per week for each patch, and tell how many times faster the bare patch eroded.

(Use the map or drawing “Exposed length above 50 mm equals soil lost.” shown earlier in this lesson.)

1. Average the bare pins: (56 + 54 + 58) ÷ 3 = 168 ÷ 3 = 56 mm. Soil lost = 56 − 50 = 6 mm.
2. Average the grass pins: (51 + 50 + 51) ÷ 3 = 152 ÷ 3 = 50.7 mm. Soil lost = 50.7 − 50 = 0.7 mm.
3. Rate for bare ground: 6 mm ÷ 4 weeks = 1.5 mm per week. Rate for grass: 0.7 mm ÷ 4 weeks = 0.175 mm per week, about 0.2 mm per week.
4. Compare: 1.5 ÷ 0.175 = 8.6, so the bare patch lost soil about 9 times faster than the grass.

Answer: Bare: 6 mm lost, 1.5 mm per week. Grass: about 0.7 mm lost, about 0.2 mm per week. The bare patch eroded roughly 9 times faster.

PRACTICE

1. EASY What is splash erosion, and why does cover stop it?
2. MEDIUM A student’s record for one patch is: Week 1, rain 12 mm, pin 50 mm; Week 2, rain 30 mm, pin 53 mm; Week 3, rain 4 mm, pin 53 mm; Week 4, rain 25 mm, pin 55

mm. (a) In which week was the most soil lost? (b) What pattern do you see between rain and soil loss? (c) What was the total soil lost over four weeks?

3. MEDIUM A jar of runoff from the bare patch holds 10 cm of water. After settling overnight the sediment at the bottom is 0.5 cm deep. What fraction and what percent of the jar is sediment?
4. HARD Design an experiment to test whether a steeper slope loses more soil. Name what you change, what you keep the same, what you measure, and one way to make the test fair.
5. CHALLENGE Miller and Duley's plots in Missouri had the same rain, slope and soil but different crops. Explain in three or four sentences why this design let them say that the cover caused the difference in soil loss, and why a comparison between two different farms could not.

COMMON MISTAKES

- Thinking erosion only happens in rivers and canyons. Most soil loss on farms and in yards starts with raindrops on bare ground.
- Reading a pin that has been buried by sediment as "no change." A reading under 50 mm means soil was added from uphill, which is deposition, and it is just as worth recording.
- Treating a single rainstorm as a rate. A rate needs a measured amount over a measured time, and several storms give a far better average than one.

> **Make it a game · Cover Up.** Set a plate of dry flour on the floor. Players take turns being "rain" with an eyedropper or spoon held at arm's length, trying to splash as much flour off the plate as possible in five drops. Then a "farmer" gets to cover the plate with one item from the kitchen (a paper towel, a sieve, a handful of oats) before the next player's five drops. Judge by how much flour leaves the plate. The best cover wins the round. Play three rounds and crown the best farmer.

> **Scripture.** "And surely the mountain falling cometh to nought, and the rock is removed out of his place. The waters wear the stones: thou washest away the things which grow out of the dust of the earth; and thou destroyest the hope of man." (Job 14:18–19, KJV)

Job knew that water wears stone and washes soil away. Three thousand years later your erosion pins measure the same thing, and the same God who made the rain gave us the sense to keep the ground covered.

Practice answers

1. Splash erosion is the knocking loose of soil grains by raindrops hitting bare ground. Cover such as grass, leaves or mulch breaks the fall of the drops so they never strike the soil at full speed.
2. (a) Week 2, when the pin reading rose 3 mm. (b) Soil was lost only in the weeks with heavy rain (30 mm and 25 mm); the dry week lost none. (c) $55 - 50 = 5$ mm.

3. 0.5 ÷ 10 = 1/20 = 5 percent of the depth is sediment.
4. Change: the slope angle (for example, trays of the same soil tilted at 5°, 15° and 25°). Keep the same: soil type, amount of soil, amount and speed of water, cover (all bare). Measure: the mass or depth of sediment caught in a pan at the bottom. Fair test: pour the same volume of water from the same height over each tray and repeat each slope at least twice.
5. Because everything except the cover was the same, any difference in soil caught in the tanks had to come from the cover; there was nothing else to blame. Two different farms differ in soil, slope, rain and farming at once, so a difference in erosion between them could have many causes. Changing one thing at a time, with everything else held constant, is what makes a cause-and-effect claim possible. The erosion pins in your yard work the same way: three patches on one slope under one rain.

9.2 Digging a Soil Pit: Reading the Horizons

OBJECTIVES

- Dig or find a soil face, identify its horizons by color, texture and roots, and measure each one in centimeters.
- Run a jar settling test and compute the percent of sand, silt and clay in a soil sample.
- Explain how soil forms from weathered rock and living things, and why topsoil is the layer worth protecting.

Warm-up. Take a spoonful of soil from the garden and a spoonful of sand from a sandbox or a bag. Wet each one and rub it between your thumb and finger. Which one feels gritty? Which one feels smooth or sticky? Try to roll each into a thin worm. Write down which one holds together and guess why.

Video. Coming soon. Soil horizons and soil profiles, how soil forms from rock, jar soil texture test, earthworms and soil; search USDA NRCS, Smithsonian, SciShow Kids, Homeschool Pop (Alternate), university extension and gardening channels.

KEY TERMS

soil
The loose top layer of the land, made of weathered rock grains mixed with air, water and living and once-living things.

horizon
A layer in the soil that differs from the layers above and below in color, texture or what it contains. Soil scientists letter them O, A, B, C and R from the top down.

topsoil (A horizon)
The dark upper layer rich in humus, roots and living things, where most plants feed.

subsoil (B horizon)
The layer below the topsoil, usually lighter or redder, where clay and minerals washed down from above collect.

parent material (C horizon)
The loose, partly weathered rock or sediment from which the soil above it formed.

humus
Dark, crumbly, decayed plant and animal matter that gives topsoil its color and holds water and nutrients.

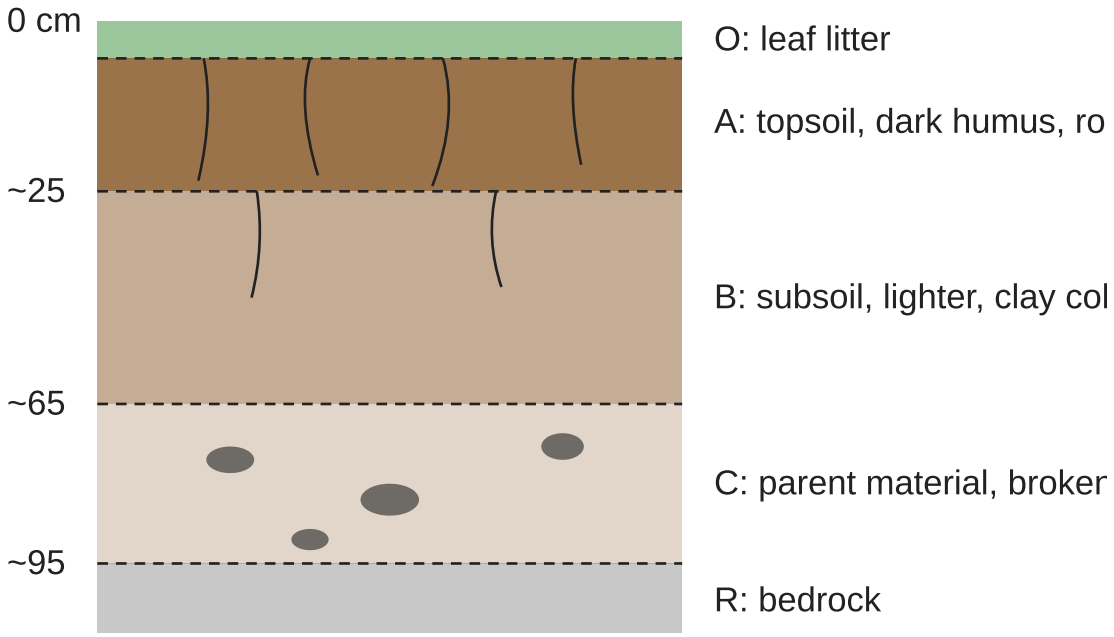
CORE IDEAS

The story. In 1877 a young Russian geologist named Vasily Dokuchaev was sent out across the steppes south of Moscow by a society of farmers and landowners in St. Petersburg. They wanted to know why the famous black earth of the steppe, the *chernozem*, grew such wheat,

and why it ended where it did. Dokuchaev did what geologists do: he dug. For years he traveled thousands of kilometers and cut pit after pit into the ground, and in every pit he saw the same thing from the top down: a black layer rich in roots, then a brown layer, then the pale rock or loess the whole thing rested on. He measured each layer and mapped where the black earth was thick and where it was thin. In 1883 he published *Russian Chernozem*, and in it he said something new. Soil was not just dirt or crumbled rock. It was a body of its own, with layers he called **horizons**, built over time by the climate, the plants and animals, the lie of the land and the rock beneath. Dokuchaev is remembered as the founder of soil science, and the lettered horizons you will measure today come from his school.

How they figured it out. Cut a clean face into the ground and the horizons show themselves. On top may be an **O horizon**, a mat of leaves and twigs not yet rotted. Below it is the **A horizon**, the **topsoil**, dark with **humus**, full of roots, worms and crumbs. Next comes the **B horizon**, the **subsoil**, often lighter, redder or yellower, denser, with clay that rain has carried down from above. Below that is the **C horizon**, the **parent material**: broken, weathered rock or sand or glacial till that has not yet become soil. Solid bedrock, if you reach it, is R. Not every soil has every horizon, and their thicknesses tell a story: deep, dark topsoil means long growth of grass or forest and little erosion; a thin A sitting right on B means the topsoil has been washed or blown away. The grains themselves can be sorted too. Shake soil in a jar of water and the heavy sand sinks in a minute, the silt in a few hours and the fine clay takes a day or more. The thickness of each band gives the percent of sand, silt and clay, and that mix, called texture, decides how a soil holds water and roots.

God’s handiwork. The topsoil of a field may be only 15 to 30 cm thick, yet nearly everything we eat grows in it. It is a made thing of astonishing design: rock crumbled by frost and roots and acids, mixed with the remains of countless plants and creatures, stirred by worms and insects and bacteria beyond counting, and held in place by the very roots it feeds. Scripture says God formed man “of the dust of the ground” (Genesis 2:7) and set him to dress and keep the garden. When you kneel at a soil pit with a tape measure, you are doing a small part of that keeping, because you cannot care for what you have never looked at.



A soil profile with typical horizons. Depths vary greatly from place to place; measure your own.

PICTURE STUDY



Man with a Hoe, Jean-François Millet, 1860–1862 · Oil on canvas · J. Paul Getty Museum, Los Angeles

Jean-François Millet grew up on a farm in Normandy and spent his life painting the people who worked the land. Here a laborer pauses, leaning on his hoe, in the middle of breaking rough ground into a field. The soil is stony and full of thistles; piles of weeds are burning behind him. Millet's painting shocked some viewers in Paris because the worker looks so worn, but Millet said he was simply painting the truth of labor he had known since boyhood.

Look at the ground as much as the man. Millet painted clods, stones and roots with real care, because he knew what it costs to turn hard ground into topsoil that will feed a family.

Look closely

- Look at the soil at the man’s feet. Is it loose and dark, or hard, pale and stony? Which horizon do you think his hoe has reached?
- Find the thistles and the smoke. What does the farmer do with weeds before he can plant?
- Compare the rough foreground with the smooth fields far away. What has to happen to the near ground to make it look like the far ground?
- Look at the man’s hands, back and face. What does the painting say about the work of making soil useful?

Talk about it

1. Genesis 3:19 says, “In the sweat of thy face shalt thou eat bread.” How does this picture show that verse?
2. If this field is plowed every year and left bare each winter, what would an erosion pin from Lesson 9.1 show over time?
3. Why might a farmer in Millet’s day have valued a deep, dark topsoil more than almost anything else he owned?

> **Safety first.** Dig only where a parent says it is safe, well away from buried pipes, cables, septic lines and tree roots, and never deeper than about 50 cm. Keep feet and hands clear of the spade blade, wear gloves and boots, and fill the pit back in when you are done. Wash your hands after handling soil, and leave any glass or sharp objects you dig up for an adult.

EXPERIMENT: THE SOIL PIT AND THE JAR TEST

Question: what layers lie under the grass, and what is the topsoil made of? Prediction: the top layer will be darkest and will have the most roots; the layers below will be lighter and harder. What we change: the depth. What we keep the same: the spot. What we measure: the thickness and color of each horizon in centimeters, and the percent of sand, silt and clay in the topsoil.

If you cannot dig, a fresh road cut, a creek bank, a construction trench viewed from a safe distance, or a deep hole from planting a tree all show a soil face.

You will need

- Spade or trowel, gloves and boots
- Metric tape measure or meter stick
- A trowel or old knife for smoothing the pit wall, and a spray bottle of water

- Two clear straight-sided jars with lids (about 1 liter), a spoonful of dish soap, and a ruler
- Lab notebook, pencil, colored pencils
- Hand lens, and a small bag for a topsoil sample

Steps

1. Choose a spot with a parent’s permission, lay a tarp or sheet beside it, and dig a pit about 40 to 50 cm deep and wide enough to see one straight wall. Put topsoil on one side of the tarp and deeper soil on the other so you can put them back in order.
2. Smooth one wall with the trowel from top to bottom. Mist it lightly with water so the colors show. Hold the tape against it with zero at the ground surface.
3. Find where the color or texture changes and mark each boundary with a nail or a pencil. Measure the depth of each boundary and write it down. Name the horizons O, A, B, C as best you can.
4. For each horizon, record its color (use words such as black, dark brown, yellow brown, gray), whether it is crumbly or dense, the number of roots in a 10 cm square, and any worms, stones or insects.
5. Take a handful of soil from the A horizon and a handful from the B horizon. Wet each and rub it. Gritty means sand, smooth and floury means silt, sticky and shiny means clay. Record what you feel.
6. Fill a jar about one third with topsoil, add water to about 2 cm below the top, add a squirt of dish soap, cap it and shake hard for two minutes. Set it where it will not be moved. Mark the sand line after 1 minute, the silt line after 2 hours, and the clay line after 2 days.
7. Measure the three bands with the ruler and compute the percent of each (band thickness divided by total thickness, times 100). Decide whether your topsoil is sandy, silty, clayey or a loam, a balanced mix.
8. Draw the pit wall to scale in your notebook with every horizon labeled and measured. Then fill the pit back in, deepest soil first, topsoil last, and tread it down.

Tips

- Colors are easiest to compare in shade with a damp wall; dry soil in sun looks paler than it is.
- If the jar stays cloudy after two days, that is clay still floating. Mark the line anyway and note the cloudiness.
- Lawn soil is often shallow and disturbed. A patch under old trees or at a fence line usually shows clearer horizons.

Check your work

- I measured and labeled at least three horizons and drew the pit wall to scale.
- I computed percent sand, silt and clay from my jar test.

- I can explain what the dark color of the A horizon comes from and why its thickness matters.

FIELD NOTEBOOK

1. Draw your soil pit wall to scale (1 cm on paper = 5 cm in the pit) with the horizons colored to match and labeled with depths.
2. Draw your settling jar after two days with the sand, silt and clay bands measured and labeled with their percents.
3. Draw one living thing you found in the pit (a worm, a beetle, a root, a fungus thread) with a hand lens, and write one sentence about what it does for the soil.

> **From history.** Charles Darwin’s last book, published in October 1881, was about earthworms. For more than forty years he had watched them at his home in Kent, counting castings, weighing what they brought up and tracking how a flat stone in his lawn slowly sank as worms dumped soil around it. He estimated that on a good field worms pass more than ten tons of dry earth per acre through their bodies each year, loosening, mixing and burying as they go. He called them one of the most important animals in the history of the world, and anyone who has dug a pit under an old pasture and found the topsoil crumbly, dark and riddled with burrows will understand why.

WORKED EXAMPLES

Example 1. After two days a jar test shows a settled column 6.0 cm tall: 3.0 cm of sand at the bottom, 2.1 cm of silt above it and 0.9 cm of clay on top. Find the percent of each and name the texture.

1. Sand: 3.0 ÷ 6.0 = 0.50, so 50 percent.
2. Silt: 2.1 ÷ 6.0 = 0.35, so 35 percent.
3. Clay: 0.9 ÷ 6.0 = 0.15, so 15 percent. Check: 50 + 35 + 15 = 100.
4. A soil with roughly half sand, a third silt and a little clay falls in the loam range on the soil texture chart used by the U.S. Department of Agriculture.

Answer: 50 percent sand, 35 percent silt, 15 percent clay: a loam, the balanced mix gardeners prize.

PRACTICE

1. EASY List the horizons O, A, B and C from the top down and say in a few words what each one is.
2. MEDIUM Two pits were measured on the same farm. Pit 1 (old pasture): A horizon 0–28 cm, B 28–70 cm. Pit 2 (field plowed up and down the slope for 40 years): A horizon 0–9 cm, B 9–55 cm. (a) How much thicker is the topsoil in the pasture? (b) What most likely

happened to the field's topsoil? (c) Which pit would you expect to find more earthworms in, and why?

3. MEDIUM In his 1881 book on earthworms, Charles Darwin estimated that worm castings bury objects on the surface of an English field at about 5 mm a year. At that rate, how many years would it take to bury a flat stone 10 cm thick? Show your work.
4. HARD Design an experiment to find out whether a mulch of leaves keeps topsoil moister than bare soil. Name the question, what you change, what you keep the same, what you measure and how often.
5. CHALLENGE Dokuchaev said that soil is formed by five things working together: parent rock, climate, living things, the lie of the land and time. Pick two of these and explain in three or four sentences how each one could make the soil in one pit differ from the soil in another pit nearby.

COMMON MISTAKES

- Thinking soil is just finely crushed rock. About half of a good topsoil by volume is air and water, and it is full of living things and humus; without them it is only dust.
- Reading the whole pit as one layer because it is all brown. Mist the wall and look for changes in shade, crumb size, density and roots; the boundaries are there.
- Thinking deeper is better. The thin dark A horizon on top is the layer plants feed from; subsoil brought up by deep digging grows poorly.

> **Make it a game · Horizon Relay.** Fill four cups with layers from your pit (leaves, dark topsoil, lighter subsoil, pebbly parent material) and cover them with paper. Players close their eyes, feel and smell one cup at a time with a parent's help, and race to name the horizon and its letter. Then shuffle the cups and build the pit in the right order, top to bottom, against the clock. Fastest correct stack wins, and anyone who puts the pebbles on top has to explain why that is wrong.

> **Scripture.** "And the LORD God formed man of the dust of the ground, and breathed into his nostrils the breath of life; and man became a living soul." (Genesis 2:7, KJV)

Scripture ties us to the soil from the first chapters. The dust God formed us from is the same ground that feeds us, and tending it well is part of the work He gave Adam in the garden.

Practice answers

1. O: leaf litter and undecayed plant matter. A: topsoil, dark with humus and roots. B: subsoil, lighter, with clay and minerals washed down from above. C: parent material, partly weathered rock or sediment.
2. (a) 28 − 9 = 19 cm thicker. (b) Much of the field's A horizon was eroded away by runoff on the plowed slope. (c) Pit 1, because the deep humus-rich topsoil holds more food and moisture for worms.
3. 10 cm = 100 mm. 100 mm ÷ 5 mm per year = 20 years.
4. Question: does leaf mulch slow the drying of topsoil? Change: cover (bare versus 3 cm of leaves) on two identical pots or garden squares. Keep the same: soil type, amount, sun,

watering at the start. Measure: soil moisture at 5 cm depth each day for a week, by weighing a scoop before and after drying or by using a moisture meter. Repeat with two pots of each kind to be sure.

5. Example: Living things: a pit under forest has a thick O horizon of leaves and a dark A horizon fed by roots and worms, while a pit in a bare, trampled yard has almost no O horizon and a thin A. Lie of the land: a pit at the bottom of a slope collects soil washed from above and has deep topsoil, while a pit on the steep slope loses soil and has thin topsoil over the B horizon. (Other correct pairs: parent rock such as sand versus clay giving different textures; climate such as wet versus dry affecting how much clay washes down.)

9.3 Local Hazard Map: Charting Where Water, Ground and Trees Could Go Wrong

OBJECTIVES

- Draw a scaled map of your neighborhood with a north arrow, a scale bar and a legend, and mark the natural hazards you find on a walk.
- Use a map scale to convert distances on paper to real distances in meters, and read a flood or topographic map for your area.
- Explain why the same earthquake, storm or flood does more harm in some places than others, using the 1906 San Francisco findings.

Warm-up. On a scrap of paper, draw your house from above as a rectangle. Now, from memory, add the nearest creek, ditch or low spot where water collects, the steepest slope, and the biggest tree that could reach your roof if it fell. Put a question mark next to anything you are not sure about. Those question marks are what today's walk is for.

Video. Coming soon. How hazard maps are made, flood plain maps, USGS topographic maps and contour lines, 1906 San Francisco earthquake ground shaking and made land; search USGS, FEMA, NOAA, Smithsonian, SciShow Kids and Homeschool Pop (Alternate).

KEY TERMS

hazard
A natural event or condition that could harm people or property: a flood, a landslide, a falling tree, strong shaking.

hazard map
A map that shows where a hazard is likely and how severe it could be, so people can plan, build and escape wisely.

scale
The ratio between a distance on the map and the real distance on the ground. On a 1:24,000 map, 1 cm stands for 24,000 cm, which is 240 m.

legend
The key on a map that explains what each symbol, color and pattern means.

floodplain
The low, flat land beside a stream that the stream spreads over when it floods.

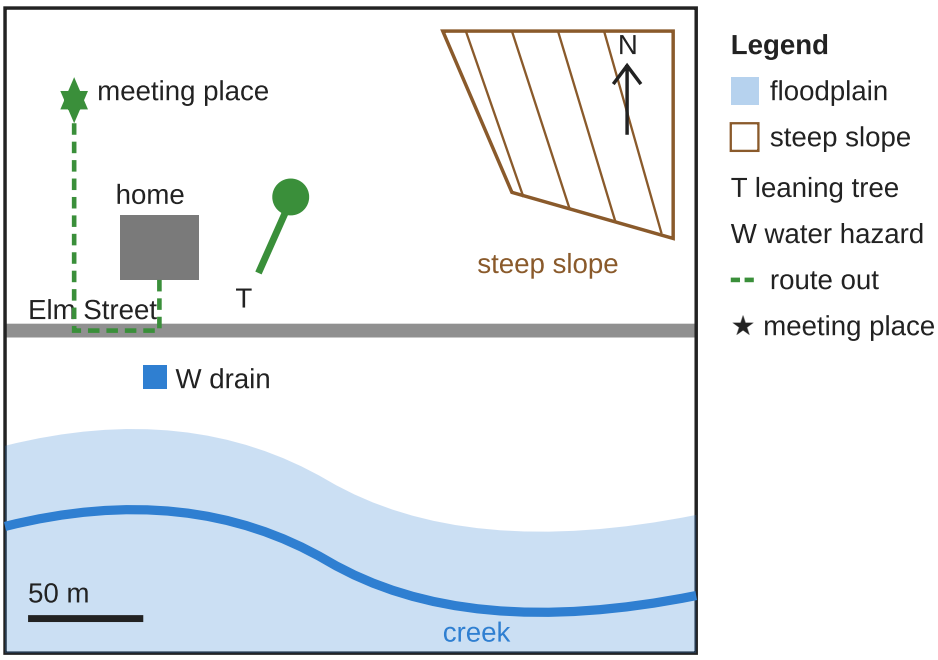
made land
Ground built by filling a marsh, pond or bay edge with loose dirt and rubble. It shakes far more in an earthquake than solid rock.

CORE IDEAS

The story. Three days after the earthquake of April 18, 1906, while San Francisco still smoldered, the governor of California appointed a commission of scientists to find out exactly what had happened. Its chairman was Andrew Lawson, a geologist at the University of California, and he put his people to work walking the state with notebooks. One of them, a young geologist named Harry Wood, went street by street through San Francisco, rating how hard the ground had shaken by the damage he saw: a cracked chimney here, a collapsed wall there, a house thrown off its foundation. When he colored his ratings onto a map of the city, the pattern was startling. The worst shaking did not follow the fault line and it did not follow the fire. It followed the ground. Buildings on the solid rock of the hills had mostly ridden out the quake. Buildings on **made land**, the old marshes and coves filled with loose dirt and rubble as the city grew, had been shaken to pieces, and in places the fill had turned almost to liquid. The commission's report, published in 1908, drew the lesson in plain words: the same earthquake is a different earthquake on different ground. It was one of the first true **hazard maps**, and when the Loma Prieta earthquake struck in 1989, the Marina District, built on fill, failed in just the way Wood's map foretold.

How they figured it out. A hazard map is a map of the land's weaknesses, and it is made by walking, measuring and recording, not guessing. Geologists today map four main things. *Ground type*: solid rock, firm old soil, soft young mud or fill. *Water*: the **floodplain** beside every stream and the low spots and storm drains where runoff gathers. Government flood maps mark the "100-year" zone, which means a place with about a 1-in-100 chance of flooding in any single year, not a place that floods once a century. *Slopes*: steep cut banks, bare hillsides and places where the ground already shows cracks or leaning trees. *Things that fall*: dead or leaning trees, loose walls, overhead lines. Every map needs three honest tools: a north arrow, a **scale** so distances can be measured, and a **legend** so anyone can read it. A map without a scale is only a picture.

Try it and see. Your neighborhood has a hazard map waiting to be drawn. Start with a base map: a printed street map, a tracing from an online map, or a drawing you pace out yourself at 1 cm to 10 m. Then walk it with a parent and look the way Wood looked. Where does water stand after rain? Which way does the street slope? Where is the ground soft, filled or dug up? Which trees lean toward the house? Where would you go, on foot, to be above any flood and clear of any slide? Mark it all with symbols, color your zones, and finish with the three things every family map needs: the meeting place, the route out and the nearest help. Psalm 46 says we need not fear "though the earth be removed" because God is our refuge, and the same God gave us eyes and maps so that we can be prudent as well as unafraid.



A neighborhood hazard map with the three honest tools: north arrow, scale bar and legend.

PICTURE STUDY



Cotopaxi, Frederic Edwin Church, 1862 · Oil on canvas · Detroit Institute of Arts

Frederic Edwin Church traveled twice to Ecuador, in 1853 and 1857, to see the great volcanoes of the Andes with his own eyes. Cotopaxi, nearly 5,900 m high, is one of the tallest active volcanoes in the world. Church painted it erupting, with its ash plume smearing the sunrise, a lake catching the red light, and a river plunging into a gorge below the viewer.

Cotopaxi is also one of the most dangerous volcanoes anywhere, not mainly for its lava but for its snowcap. When it erupts, melted snow and ice mix with ash into fast mudflows that race down the valleys toward towns such as Latacunga, which has been buried more than once. Today the valleys below Cotopaxi carry a hazard map on the ground itself: evacuation routes marked with signs pointing the way to high ground.

Look closely

- Find the plume. Which way is the wind carrying the ash? Which side of the mountain would you not want to live on?
- Find the snowcap. What would happen to it in an eruption, and where would the water go?
- Follow the river in the foreground down the gorge. Where does a mudflow travel: along ridges or along valleys?
- Church put the sun behind the haze. How does the light change the feeling of the picture: beauty, danger or both?

Talk about it

1. If you were drawing a hazard map of the land in this painting, which areas would you color most dangerous, and why?
2. Why do people live near a volcano like Cotopaxi at all? (Think about soil, water and the long quiet stretches between eruptions.)
3. How is a signed evacuation route on a street like the map you are making today?

> **Safety first.** Walk with a parent, stay on sidewalks and road edges facing traffic, and keep well back from creek banks, ditches, cliffs and construction sites. Never enter moving water or walk under a leaning tree. Mark hazards from a safe distance.

EXPERIMENT: OUR NEIGHBORHOOD HAZARD MAP

Question: where in our neighborhood could water, ground or falling things cause harm, and where is safe? Prediction: before the walk, mark on a sketch where you think the hazards are. What we change: nothing; this is a survey. What we keep the same: the area and the scale. What we measure: distances in paces converted to meters, and the location of every hazard we find.

You will end with a finished map, drawn to scale, that your whole family can read.

You will need

- A printed map of your neighborhood, or large paper and a ruler to draw your own
- Clipboard, pencil, colored pencils (blue, brown, red, green)
- A metric tape measure to find the length of your pace
- A compass or a compass app for the north arrow

- Access to a flood map or topographic map of your area, if a parent can print one (see the unit kits)
- Lab notebook

Steps

1. Measure your pace: walk ten normal steps beside a tape measure, divide the distance by ten, and write down the length of one pace in meters (for example, 0.6 m).
2. Make a base map. If you draw your own, choose a scale such as 1 cm = 10 m, draw your street as a line, and pace the distances between corners, converting paces to meters and meters to centimeters on paper. Add a north arrow using the compass and a scale bar 5 cm long labeled 50 m.
3. Walk the neighborhood with a parent. Mark with a blue W every place water stands or flows after rain: creeks, ditches, culverts, storm drains, low spots in the road. Shade the floodplain beside any stream light blue.
4. Mark with a brown S every steep slope, cut bank, bare hillside or place where the ground is cracked, slumped or filled. Hatch steep slopes in brown.
5. Mark with a red T every tree that is dead, leaning or close enough to fall on a house or road, and with a red L any loose wall, pole or overhead line near where people walk.
6. Mark with a green star the family meeting place on high, open ground, a green H for the nearest hospital or fire station, and draw the walking route from home to the meeting place in green.
7. At home, draw a clean copy. Put the legend in a box with every symbol and color explained. Write the date and your name as the surveyor.
8. Compare your map with an official flood map or topographic map if you have one. Note at least one thing the official map shows that you missed, and one thing you found that it does not show.

Tips

- Walk the route after a rain if you can; puddles and muddy flows show you exactly where water goes.
- A hazard is a could, not a will. Mark the leaning tree honestly, then let the family decide what to do about it.
- Keep the map simple enough that a younger brother or sister could follow the green route.

Check your work

- My map has a north arrow, a scale bar and a legend, and distances were paced and converted to meters.
- I marked water, slope and falling hazards with the correct symbols and colored the zones.
- I marked the meeting place, the route to it and the nearest help, and compared my map with an official one.

FIELD NOTEBOOK

1. Draw a cross-section of your street from the highest point to the lowest, marking where water would run and where it would pool.
2. Copy a small piece of a topographic map of your area and trace the contour lines in brown, then shade in blue the land that lies below the nearest stream’s floodplain line.
3. Draw three legend symbols of your own invention for hazards you found that had no standard symbol, and explain each in one sentence.

> **From history.** The most famous volcano hazard map in American history was drawn before the eruption it warned about. In 1978 two U.S. Geological Survey geologists, Dwight Crandell and Donal Mullineaux, published a study of the old ash, mudflow and lava deposits around Mount St. Helens in Washington. From that record they mapped the zones most at risk and wrote that the volcano was the one in the Cascade Range most likely to erupt again, perhaps before the end of the century. On May 18, 1980, it did. Because of their map and the monitoring it prompted, most of the land around the mountain had already been closed, and the warning saved many lives.

WORKED EXAMPLES

Example 1. On a USGS topographic map at a scale of 1:24,000, the distance from a house to the edge of the creek’s floodplain measures 3.5 cm. On the student’s own map, drawn at 1 cm = 10 m, the same distance should be how long? First find the real distance.

(Use the map or drawing “Always check a scale bar before measuring distances on a map.” shown earlier in this lesson.)

1. At 1:24,000, 1 cm on the map is 24,000 cm on the ground. 24,000 cm = 240 m, so 1 cm = 240 m.
2. Real distance: 3.5 cm × 240 m per cm = 840 m.
3. On the student’s map, 1 cm = 10 m, so 840 m ÷ 10 m per cm = 84 cm. That is too long for a sheet of paper, so the student should choose a smaller scale, such as 1 cm = 50 m: 840 ÷ 50 = 16.8 cm.
4. Check by going backward: 16.8 cm × 50 m per cm = 840 m.

Answer: The floodplain edge is 840 m from the house. At 1 cm = 10 m that would be 84 cm on paper, so a scale of 1 cm = 50 m (giving 16.8 cm) fits the page better.

PRACTICE

1. EASY Name the three things every usable map must have, and say what each one is for.
2. MEDIUM After an earthquake, surveyors counted damaged buildings in three parts of a town. Rock hills: 200 buildings, 10 badly damaged. Old firm soil: 300 buildings, 30 badly damaged. Filled marsh: 100 buildings, 40 badly damaged. (a) Find the percent badly damaged in each area. (b) Which ground type was most dangerous, and how

many times worse was it than the rock hills? (c) Why is percent a fairer comparison than the raw counts?

3. MEDIUM A flood map marks your street inside the 100-year flood zone. A neighbor says, “It flooded in 2015, so we are safe for the next ninety years.” Explain why the neighbor is wrong.
4. HARD On your map at 1 cm = 25 m, the walking route from home to the meeting place measures 14 cm. (a) How far is it in meters? (b) If you walk at 1.2 m per second, how many minutes does it take? Round to the nearest tenth.
5. CHALLENGE Design a kitchen-table test to show why made land shakes worse than rock. Name what you build, what you change, what you keep the same and what you measure.

COMMON MISTAKES

- Thinking danger from an earthquake depends only on distance from the fault. Ground type matters as much, which is why soft fill far from a fault can suffer more than rock right beside it.
- Reading “100-year flood” as one flood per hundred years. It is a 1 percent chance every year, and years are independent.
- Drawing a map without a scale bar. Without it, no one can tell whether the creek is 20 m or 200 m from the house.

Make it a game · Map Scout. Spread your finished hazard map on the table. A parent names a spot on it (“the storm drain by the Smiths’ driveway”). You must say, in order, which direction it is from your house, how far in meters using the scale bar, and what symbol it carries. Three correct in a row earns a point. Then switch: you name a spot and a younger sibling finds it. The first scout to five points plans the family’s next walk.

Scripture. “Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah.” (Psalm 46:2–3, KJV)

The psalm does not promise that the ground will never shake or the waters never rise. It promises that God is our refuge when they do. A hazard map is one of the ordinary means He gives us to be wise, and trust in Him is what keeps wisdom from turning into fear.

Practice answers

1. A north arrow (to orient the map), a scale or scale bar (to measure real distances) and a legend (to explain the symbols and colors).
2. (a) Rock: 10 ÷ 200 = 5 percent. Firm soil: 30 ÷ 300 = 10 percent. Fill: 40 ÷ 100 = 40 percent. (b) The filled marsh, 40 ÷ 5 = 8 times worse than the rock hills. (c) The areas had different numbers of buildings, so raw counts would make the firm soil (30 damaged) look worse than the fill (40 damaged out of far fewer).

3. The 100-year zone means about a 1-in-100 chance of flooding in any single year. Each year is a fresh chance; a flood in one year does not use up the risk for the years after. Two such floods can happen a few years apart.
4. (a) 14 × 25 = 350 m. (b) 350 ÷ 1.2 = 291.7 seconds, which is about 4.9 minutes.
5. Build two small “ground” trays: one of a firm wood board, one of a pan of loose wet sand or gelatin. Stand an identical tower of blocks on each. Change: only the ground type. Keep the same: the tower, and the shaking (slide both trays together on the same table, pushed the same way for the same time). Measure: how long until each tower falls, or how far the top block moves in a set number of shakes. Repeat three times and compare. The loose, wet material should move more and topple the tower sooner.

9.4 Visiting a Rock Outcrop: Reading Layers Like William Smith

OBJECTIVES

- Sketch a rock outcrop to scale, measure its layers in centimeters and record the color, grain size and hardness of each.
- Use simple field tests (fingernail, coin, steel nail, vinegar) to tell sandstone, shale and limestone apart.
- State the principle of superposition and explain the difference between observing the order of layers and interpreting their age.

Warm-up. Stack five different things on a table one at a time: a book, a plate, a towel, a magazine, a cutting board. Ask a family member who did not watch to come in and tell you which one you put down first and which one last. How did they know? Write the rule in one sentence. You have just stated the first rule of reading rock layers.

Video. Coming soon. How to read rock layers at a roadcut, sedimentary rocks sandstone shale limestone identification, William Smith and the first geological map, principle of superposition; search USGS, Smithsonian, SciShow Kids, Homeschool Pop (Alternate), Science Max and geology field-trip channels.

KEY TERMS

outcrop
A place where bedrock shows at the surface, with no soil over it: a cliff, a roadcut, a creek bank or a quarry wall.

stratum (plural strata)
A single layer of sedimentary rock, usually laid down by water or wind, with a surface above and below that separates it from its neighbors.

superposition
The rule that in an undisturbed stack of layers, the layer on the bottom was laid down first and the layer on top last.

sandstone
Rock made of sand grains cemented together. You can see or feel the grains, and quartz sandstone will scratch glass.

shale
Rock made of mud and clay pressed into thin sheets. It is soft, splits into flakes, and often smells earthy when breathed on.

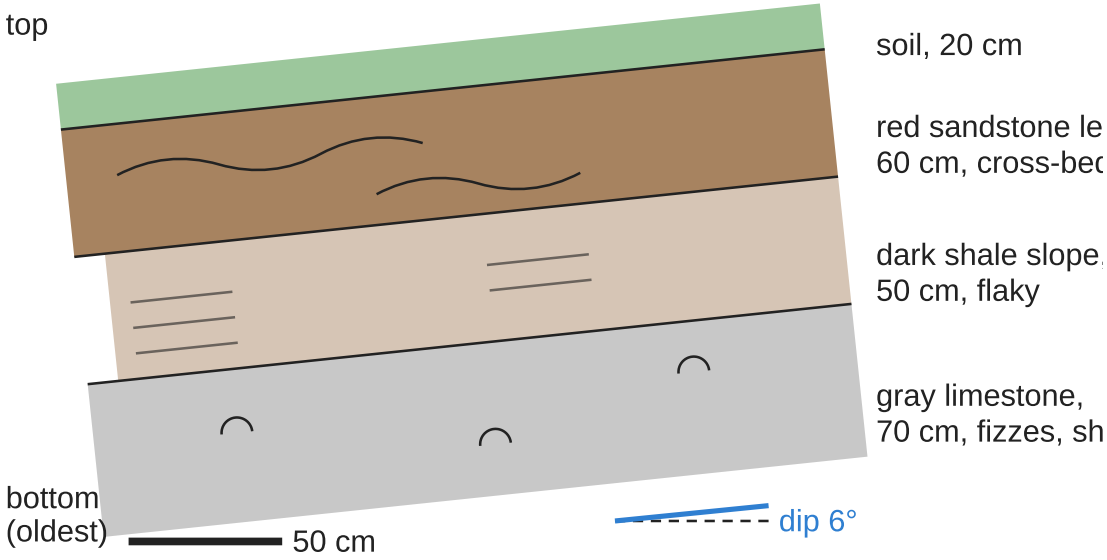
limestone
Rock made mostly of the mineral calcite, often from shells. It is scratched by a steel nail, not by a fingernail, and it fizzes in vinegar.

CORE IDEAS

The story. In 1793 a young surveyor named William Smith, the son of a village blacksmith, was hired to survey the route of a canal to carry coal across the hills of Somerset in England. Digging began two years later, in 1795. Cutting a canal means slicing open the ground for kilometers, and Smith, who had been peering into coal pits and quarries since boyhood, walked every meter of the fresh cuts. He noticed something the quarrymen half knew and no one had written down: the layers came in the same order everywhere. A red marl, then a gray lias, then a yellow oolite, and so on up the hill, always in the same sequence, each one tilted gently toward the east. More than that, each layer held its own fossils, so that a shell from one bed could tell you which bed it was even on the far side of the county. On a June evening in 1799, at a dinner in Bath, Smith dictated his *Order of the Strata* to two friends, and in 1815 he published the first geological map of an entire nation, England and Wales colored layer by layer. People called him “Strata Smith.” Everything he did began with the same act you will do today: standing in front of an **outcrop** with a notebook, looking hard, and writing down what is really there.

How they figured it out. An outcrop is read from the bottom up, because of the rule of **superposition**: in an undisturbed stack, the lowest **stratum** was laid down first and the highest last. Stand back first and sketch the whole face, then come close and work layer by layer. Measure each one with a tape. Note its color, whether it stands out as a ledge (hard) or wears back as a slope (soft), and whether it breaks in blocks, flakes or crumbs. Then test it. A fingernail scratches hardness up to about 2.5, a copper coin about 3, a steel nail or knife blade about 5.5. **Shale** is soft, flaky and dull; **limestone** resists a fingernail but yields to a nail, and a drop of vinegar makes it fizz with tiny bubbles because its calcite reacts with the acid; **sandstone** is gritty, and if its grains are quartz it will scratch glass and shrug off the nail. Look at the boundary between layers: is it knife-sharp and flat, or wavy and gullied? Look for fossils, ripple marks, cross-bedding and cracks. Hold a protractor against a tilted layer, hang a string with a washer from its center, and read the dip, the angle the layer makes with level. Smith needed nothing more than these tools, and neither do you.

The big idea. There is a line to keep clear in your notebook, and good geologists keep it clear in theirs. On one side go *observations*: this layer is 60 cm thick, gray, fizzes, has shell fossils, and lies under a 40 cm bed of red sandstone with a sharp flat contact. Anyone can repeat those. On the other side go *interpretations*: what laid the layers down, how fast, and how long ago. The order of the layers is a fact you can see. The years assigned to them are a reading of the facts, and readings depend on assumptions. The sign at a roadcut will often give an age in millions of years; the “Thinking About Time” box below shows how to read it. Your job at the outcrop is to be the kind of witness Smith was: measure first, draw carefully, and let the rock speak before anyone tells you what it says.



A measured field sketch of an outcrop. Hard layers stand out as ledges; soft ones wear back as slopes.

⏳ Thinking About Time

What the sign says. What the sign says: a roadcut or park sign often names each layer with a museum word and a number, such as “Ordovician limestone, deposited about 450 million years ago,” or “Pennsylvanian sandstone, about 300 million years old.” Those ages come from assuming that such layers built up at roughly the slow rates seen on today’s sea floors, and from radiometric dates on certain volcanic minerals, which assume known starting amounts and no gain or loss of atoms over time.

What we observe. What we observe: the layers lie in a definite order, with the lowest laid down first. Many are flat-lying sheets that can be traced for hundreds of kilometers. The contacts between them are often knife-sharp and flat, with little sign of the gullying, soil and roots that would mark a surface exposed to weather for a long time. Fossils are buried whole, sometimes in great numbers, in a way that today’s slow burial rarely produces.

How Christians read it. How Christians read it: creation geologists read most fossil-bearing layers as laid down rapidly, in the year of the Flood described in Genesis 7–8 and the centuries just after, when “all the fountains of the great deep” were broken up and the waters covered the mountains. Wide, flat, sharply bounded sheets of sediment and whole buried creatures fit fast-moving water. The order of the layers is the same under either reading; what differs is the time assigned to it. Reading the sign accurately, naming its assumptions and stating this view beside it is what you are learning to do.

Try it. At your outcrop, run a finger along the contact between two layers. Is it flat and sharp, or weathered, uneven and marked by old root holes and cracks? Write down

> which, and what it suggests about how long the lower surface waited before the next layer came.
>
> *Genesis 7:11*

PICTURE STUDY



The Grand Canyon of the Yellowstone, Thomas Moran, 1872 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C. (lent by the U.S. Department of the Interior)

In 1871 Thomas Moran joined Ferdinand Hayden’s government survey of the Yellowstone country, sketching in watercolor as the party rode. Back east he painted this enormous canvas, more than two meters tall and well over three meters wide, of the canyon where the Yellowstone River has cut through rock stained yellow and orange by hot water. In 1872 Congress bought the painting and hung it in the Capitol, the same year it made Yellowstone the first national park.

The two tiny men on the point in the foreground, often said to be Hayden and a companion, are doing what you will do today: standing in front of a great outcrop, looking. Moran was careful to paint the rock as it really weathered, in pinnacles, ledges and crumbling slopes, because the men of the survey would see the picture and know if he had cheated.

Look closely

- Find the hard ledges that stick out and the softer slopes that have crumbled back. Which parts of the canyon wall would you test with a nail first?
- Look at the colors. The yellows and oranges come from iron minerals in rock altered by hot water. Can you see where the colors change?

- Find the waterfall in the distance. What does the river do to the canyon with every year of flow?
- Find the two men. Why do you think Moran painted them so small?

Talk about it

1. If you were Hayden with a notebook, what three observations would you write first about the canyon walls?
2. Moran’s painting helped persuade Congress to protect Yellowstone. How can careful observation and honest drawing be a way of keeping God’s creation?
3. What is the difference between what Moran could see in the rock and what a sign might say about how old it is?

> **Safety first.** Visit outcrops only with a parent. At a roadcut, park well off the road, face traffic, and stay off the pavement. Never climb the face or stand under loose, overhanging rock, and do not hammer; look, touch and test the rocks that have already fallen to the base. Wear sturdy shoes and safety glasses if any chipping is done by an adult, and collect only where it is allowed.

EXPERIMENT: THE MEASURED OUTCROP

Question: what layers make up this outcrop, in what order, and what kind of rock is each? Prediction: sketch the face from a distance and guess which layers are hard and which soft before you test them. What we change: nothing; this is a survey. What we keep the same: the same tests on every layer. What we measure: the thickness of each layer in centimeters, its hardness against three tools, its reaction to vinegar, and the dip angle.

Good outcrops to ask about: roadcuts on highways and country roads, creek and river banks, old quarry edges in parks, sea cliffs and the cut behind a parking lot. A parent should choose the spot.

You will need

- Lab notebook, pencil, colored pencils, clipboard
- Metric tape measure (3 m or longer)
- A copper coin, a steel nail, a small piece of glass with taped edges (for an adult to use) and your fingernail
- Small dropper bottle of white vinegar
- Protractor and a 30 cm string with a washer tied on for measuring dip
- Hand lens, and a pencil or hammer to lay against the rock for scale in photos
- Small bags and a marker for labeling any samples you are allowed to take

Steps

1. Stand back far enough to see the whole face. Draw its outline on a full notebook page, then draw every layer boundary you can see. Number the layers from the bottom up,

because the bottom is oldest.

2. Hold the tape vertically against the face (or against a fallen block of each layer) and measure the thickness of each layer. Write the thickness beside its number. If the face is too tall, measure the lowest meter and estimate the rest by comparing.
3. For each layer, write its color when dry and when wet (use the dropper), and whether it stands out as a ledge or wears back as a slope.
4. Test the hardness of a loose piece of each layer: can a fingernail scratch it? a coin? a steel nail? Record yes or no for each tool. An adult may test whether the rock scratches glass.
5. Put one drop of vinegar on a fresh surface of each layer and watch closely with the hand lens for tiny bubbles. Limestone fizzes; sandstone and shale usually do not. Record the result.
6. Rub a piece of each layer between your fingers. Gritty with visible grains means sandstone; smooth, flaky and dull means shale; smooth but hard and fizzing means limestone. Write your best name for each layer.
7. Measure the dip. Lay the straight edge of the protractor along a layer boundary, hang the string from its center, and read the angle between the string and the 90° mark. Zero means the layers are level. Record the angle and the direction the layers tilt down toward.
8. Look at each contact between layers and note whether it is sharp and flat, wavy or gullied. Record any fossils, ripple marks or cross-bedding. Finish with a clean, to-scale drawing with a scale bar and every layer labeled with thickness, rock name and hardness.

Tips

- Weathered rock surfaces lie. Test a freshly broken face on a fallen piece, not the crusty outside.
- Vinegar is a weak acid and fizzes slowly; scratch a little powder from the rock first and the bubbles show better.
- Photograph each layer with a pencil beside it for scale, and write the layer number on a slip of paper in the photo.

Check your work

- I drew the outcrop to scale, numbered the layers from the bottom up and measured each thickness in centimeters.
- I tested every layer with fingernail, coin, nail and vinegar and named each rock.
- I can state the rule of superposition and tell an observation from an interpretation.

FIELD NOTEBOOK

1. Draw your outcrop to scale with a scale bar, each layer colored to match and labeled with thickness, rock name and hardness result.

2. Draw one hand-lens view of the grains or fossils in your most interesting layer, with the magnification noted.
3. Make a two-column page, “What I observed” and “What I think it means,” with at least three entries in each column, and keep them strictly apart.

> **From history.** William Smith’s great 1815 map, nearly 2.6 m tall and hand-colored layer by layer, nearly ruined him. He had spent everything on surveying and printing, others copied his work, and in 1819 he was sent to debtors’ prison for a time. Only in 1831, when he was over sixty, did the Geological Society of London award him its first Wollaston Medal and call him the father of English geology. His nephew John Phillips, whom he had raised and trained, carried his methods on. The lesson Smith left is a field lesson: walk the ground, measure what is there, and draw it honestly, whatever anyone says.

WORKED EXAMPLES

Example 1. A roadcut is 4.5 m tall. A student’s drawing of it is 15 cm tall. (a) What is the scale of the drawing? (b) A sandstone ledge measures 6 cm thick on the drawing. How thick is the real ledge? (c) What percent of the outcrop’s height is sandstone?

(Use the map or drawing “Every measured sketch needs a scale.” shown earlier in this lesson.)

1. (a) Convert to the same unit: 4.5 m = 450 cm. Scale = 15 cm : 450 cm = 1 : 30. One centimeter on paper stands for 30 cm of rock.
2. (b) Real thickness = 6 cm × 30 = 180 cm = 1.8 m.
3. (c) 1.8 m ÷ 4.5 m = 0.40, so 40 percent of the face is sandstone.
4. Check: 40 percent of 15 cm on the drawing is 6 cm, which matches.

Answer: (a) 1:30. (b) 1.8 m. (c) 40 percent.

PRACTICE

1. EASY State the rule of superposition in your own words, and give the one condition it depends on.
2. MEDIUM Three layers were tested at an outcrop. Layer 1 (bottom): fingernail no, coin yes, nail yes, vinegar fizzes, shell fossils. Layer 2: fingernail yes, splits in thin flakes, no fizz. Layer 3 (top): fingernail no, coin no, nail no, gritty grains, no fizz. (a) Name each rock. (b) Which layer would form a ledge and which a slope? (c) Which layer was deposited first?
3. MEDIUM An outcrop has four layers measured from the bottom: 120 cm, 45 cm, 90 cm and 25 cm. (a) What is the total height in meters? (b) The second layer is shale. What fraction of the outcrop is shale, as a percent, rounded to the nearest whole number?
4. HARD Design a jar experiment to see how a mix of sand, silt and clay settles into layers in still water, and say what you would compare with what you saw at the outcrop.

5. CHALLENGE A sign at the roadcut reads, “These limestone beds were deposited about 450 million years ago.” In four or five sentences, separate what the sign observes from what it interprets, name one assumption behind the number, and state how a creation geologist reads the same beds.

COMMON MISTAKES

- Testing the weathered outside of a rock. Crusts are softer and duller than fresh rock, so break or find a fresh face first.
- Thinking all layers are level. Many strata are tilted or even folded, and the dip you measure is part of the story of what has happened since they were laid down.
- Writing an interpretation in the observation column. “Gray, fizzes, 60 cm, shells” is an observation; “formed slowly on a quiet sea floor” is a reading of it.

Make it a game · Strata Smith Says. Build a stack of six layers in a clear box from kitchen materials: flour, brown sugar, oats, cocoa, crushed crackers, rice. A parent then asks questions in the voice of Strata Smith: “Which layer went down first?” “What was laid down between the oats and the cocoa?” “If I find oats, what lies right under them?” Each right answer scores a point; a wrong one means you must say the rule of superposition aloud. Then a sibling rebuilds the stack in secret with one layer changed, and you must spot it.

Scripture. “In the six hundredth year of Noah’s life, in the second month, the seventeenth day of the month, the same day were all the fountains of the great deep broken up, and the windows of heaven were opened.” (Genesis 7:11, KJV)

Genesis gives the Flood a date in Noah’s life, the way a field notebook gives a date to a measurement. The waters that broke from the deep and fell from heaven moved sediment on a scale no one alive has seen, and many Christians read the great stacks of layered rock, like the one you measured, as part of their record.

Practice answers

1. In a stack of sedimentary layers, the bottom layer was laid down first and the top layer last. It holds only if the layers have not been overturned or disturbed since they formed.
2. (a) Layer 1 limestone, Layer 2 shale, Layer 3 sandstone. (b) The sandstone (3) and limestone (1) form ledges; the soft shale (2) wears back as a slope. (c) Layer 1, the bottom, by superposition.
3. (a) 120 + 45 + 90 + 25 = 280 cm = 2.8 m. (b) 45 ÷ 280 = 0.161, about 16 percent.
4. Fill a clear jar two thirds with water, add a mixed handful of sand, silt (fine dust) and clay, cap and shake, then set it still. Change: nothing after shaking, or repeat with faster and slower pouring. Keep the same: the mix and the jar. Measure: the order and thickness of the bands that form and how long each takes to settle (sand in a minute, silt in hours, clay in a day or more). Compare the sharp, flat boundaries and the sorting by grain size with the contacts and grain sizes you recorded at the outcrop, and note that the whole stack formed in one event from one jar of muddy water.

5. The sign observes that these are limestone beds lying in a certain order with certain fossils; that can be checked by anyone with a nail and vinegar. The age is an interpretation. One assumption is that the beds built up at about the slow rates of lime mud seen on today’s sea floors (another is that radiometric clocks on nearby volcanic layers started at known amounts and never gained or lost atoms). A creation geologist reads the same beds as laid down rapidly by the waters of the Flood and its aftermath, pointing to the sharp flat contacts, the wide continuous sheets and the whole buried fossils. The order of the layers is the same under both readings; the time assigned is what differs.

Unit 9 review

Answer each question. Show your work for calculations and use complete sentences for explanations. Bring your field notebook; you may use your own data where a question asks for it. The review is worth 60 points.

1. (10 pts) Three erosion pins in a bare patch started at 50 mm above the soil. After six weeks they read 59 mm, 56 mm and 59 mm. (a) What was the average soil loss? (b) What is the erosion rate in millimeters per week? (c) Give one reason the grass patch beside it lost less.
2. (10 pts) Diagram item: draw a soil pit wall in cross-section with the O, A, B and C horizons labeled from top to bottom. Beside each, write one feature you would use to recognize it in the field.
3. (10 pts) A jar test settles into 2.4 cm of sand, 1.2 cm of silt and 0.4 cm of clay. Find the percent of each (round to the nearest whole percent) and say whether this soil is sandy, silty or clayey.
4. (10 pts) Multiple choice. In the 1906 San Francisco earthquake, the buildings that were damaged most stood on: (a) the solid rock of the hills; (b) the fault line itself; (c) made land, where marshes and coves had been filled with loose dirt; (d) the highest ground in the city. Choose one and explain in a sentence why that ground type shakes the way it does.
5. (10 pts) On a map at 1:24,000, the distance from a house to a creek is 2.5 cm. (a) What is the real distance in meters? (b) The same house is in the 100-year flood zone. Explain in one or two sentences what that zone means.
6. (10 pts) At a roadcut, Layer 1 (bottom) fizzes in vinegar and is scratched by a steel nail but not a fingernail; Layer 2 is flaky and scratched by a fingernail; Layer 3 (top) is gritty, is not scratched by the nail, and does not fizz. (a) Name the three rocks. (b) Which layer was laid down first, and what rule tells you? (c) The sign says the beds are “about 450 million years old.” In two or three sentences, tell which part of the sign is observation and which is interpretation, and how a creation geologist reads the beds.

Unit project: my field notebook: four sites, measured

Assemble a field notebook with one section for each lesson: the erosion-watch table and bar graph with a computed rate for each patch; the soil pit drawing to scale with horizons measured and the jar-test percents; the finished neighborhood hazard map with north arrow, scale bar, legend, meeting place and route; and the measured outcrop sketch with every layer’s thickness, rock name, hardness tests and dip.

Finish with a one-page summary titled “What I observed and what I think it means,” in two columns, drawing on all four sites. Date every page and name the place.

- **Measurement**: Every site has real measurements in metric units: pin readings, horizon depths, paced distances and layer thicknesses, with correct rates and percents computed from them.

- **Drawing**: The pit, the map and the outcrop are drawn to a stated scale with a scale bar, labels and a legend where needed, and are neat enough for someone else to read.
- **Reasoning**: Observations and interpretations are kept in separate columns, and the summary explains at least one conclusion from the data and one claim from a sign or map that is an interpretation.
- **Care**: Pages are dated and named, safety steps were followed, the pit was filled in, and nothing was taken from a site without permission.

Answer key

1. (a) Average reading (59 + 56 + 59) ÷ 3 = 58 mm; soil lost = 58 − 50 = 8 mm. (b) 8 ÷ 6 = 1.3 mm per week. (c) Grass breaks the fall of raindrops, its roots hold the grains, and the rough surface lets water soak in instead of running off.
2. The drawing shows four bands in order from the top: O (leaf litter and undecayed plant matter), A (dark topsoil, humus, many roots and worms), B (lighter, redder or yellower subsoil, denser, clay collects here), C (pale, partly weathered rock or sediment, few roots). Any correct feature for each earns credit.
3. Total 4.0 cm. Sand 2.4 ÷ 4.0 = 60 percent; silt 1.2 ÷ 4.0 = 30 percent; clay 0.4 ÷ 4.0 = 10 percent. It is a sandy soil (a sandy loam on the texture chart).
4. (c). Loose, wet fill shakes much harder than rock and can even lose its strength and flow during strong shaking, so buildings on it suffer far more than those on bedrock.
5. (a) 2.5 × 24,000 = 60,000 cm = 600 m. (b) The house has about a 1-in-100 chance (1 percent) of flooding in any given year; it does not mean a flood only once every hundred years.
6. (a) Layer 1 limestone, Layer 2 shale, Layer 3 sandstone. (b) Layer 1, by the rule of superposition: in an undisturbed stack the bottom layer was laid down first. (c) The rock types, order, thickness and fossils are observations anyone can check; the age is an interpretation that depends on assumptions such as slow, steady deposition and radiometric clocks with known starting amounts. A creation geologist reads the beds as laid down rapidly by the Flood and its aftermath, pointing to sharp flat contacts, wide continuous sheets and whole buried fossils; the order of layers is the same under both readings.