

SCHOOL LAUNCH • SCIENCE • HIGH SCHOOL

HIGH SCHOOL GEOLOGY

A one-credit high school geology course with lab: minerals and rocks, plate tectonics, rivers and glaciers, caves, fossils and rock layers, the Flood and the Ice Age, mining and gems, maps and the great geologists, and a Field Lab on the ground where you live.

First edition

"The earth is the LORD's, and the fulness thereof; the world, and they that dwell therein." (Psalm 24:1, KJV)

COURSE GUIDE

A one-credit high school geology course for families. The student reads one lesson a week, studies a picture, learns three words, answers five questions, and does one hands-on activity. The year ends with a four-lesson Field Lab in which the student writes a real field report on the place they live. A parent who has never studied geology can teach it; every lesson has a “For Families” note with the background a parent needs.

The course teaches geology as the study of God’s earth: “The earth is the LORD’s, and the fulness thereof; the world, and they that dwell therein” (Psalm 24:1, KJV). Students learn the observations every geologist agrees on, the standard names and figures they will meet in museums and on exams, and how Christians of good faith read that evidence.

Museum signs and textbooks give ages in millions of years and use period names such as Cambrian and Jurassic. This course teaches those as **museum words**: the student must know them for the SAT, ACT, CLT and AP Environmental Science, and for any museum visit. Wherever they appear, the lesson adds a **Thinking About Time** box in three parts:

- **What the sign says:** the standard claim.
- **What we observe:** the layers, fossils, and measured rates themselves.
- **How Christians read it:** both readings stated fairly. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6–9. Other Christians hold an older earth and read the days of Genesis 1 differently. Scripture is never treated as myth, and no reader is sneered at.

The habit the course drills, lesson after lesson, is separating what is **observed** from what is **inferred**.

WHO IT IS FOR

Students aged 14 and up (grades 9–12). No earlier geology is required. The math is arithmetic, percentages, rates and exponents; half-life questions use $(\frac{1}{2})^n$. A parent who has never studied geology can teach the course from the For Families notes.

HOW TO USE THIS COURSE

A 600–900 word reading.

A Thinking About Time box when museum ages come up.

Three key vocabulary words.

A picture study: a public-domain painting, engraving or photograph on Wikimedia Commons.

Five comprehension questions with answers, including data-reading and calculation questions in the style of the ACT and SAT.

One hands-on activity with cheap materials and a safety line where needed.

An Exam Connection note: where the lesson meets the SAT, ACT, CLT or AP Environmental Science.

A For Families note.

SCOPE AND SEQUENCE

Unit 1: Minerals and Rocks (1–4)

Mineral properties and the Mohs scale; igneous, sedimentary and metamorphic rocks; the rock cycle.

Unit 2: The Restless Earth: Plate Tectonics, Earthquakes, and Volcanoes (5–8)

Earth's interior and plate tectonics; earthquakes; volcanoes and Mount St. Helens 1980; mountain building.

Unit 3: Weathering, Erosion, Rivers, and Glaciers (9–12)

Weathering and soil; rivers and floods; glaciers; deserts, wind and coasts.

Unit 4: Groundwater, Caves, and the Water Beneath Our Feet (13–16)

Aquifers and wells; caves and karst; hot springs and geysers; floods, water quality and stewardship.

Unit 5: Fossils and Reading Rock Layers (17–20)

How fossils form; Steno's principles and cross-sections; the geologic column and index fossils; relative and radiometric dating.

Unit 6: The Flood, Catastrophe, and the Ice Age (21–24)

Uniformitarianism and catastrophism; the Flood of Genesis and Flood geology; the Grand Canyon; the Ice Age.

Unit 7: Earth's Riches: Mining, Gems, and Energy (25–28)

Ores and mining; gems; coal, oil and gas; building stone, salt and stewardship.

Unit 8: Maps, Field Geology, and the Great Geologists (29–32)

Topographic maps; geologic maps and cross-sections; Steno and Hutton; Buckland and Agassiz.

Unit 9: Field Lab: Doing Geology Where You Live (33–36)

The geologist's kit and notebook; reading your local landscape; experiments on rates; the capstone field report.

MATERIALS

- **Safety glasses:**
- **a hand lens (10x):**
- **a steel nail:**
- **a copper penny:**
- **an unglazed tile:**
- **a magnet:**
- **white vinegar:**
- **a small hammer:**
- **clear jars and plastic boxes:**
- **sand and gravel:**
- **modeling clay:**
- **plaster of Paris:**
- **Epsom salt:**
- **a notebook and pencil:**
- **Maps:** : A free USGS topographic map and state geologic map of your home area (links in Unit 8 and the Field Lab). No kit purchase is required; a rock and mineral study set (about 15–30 specimens) is helpful but optional.

GRADING

Weekly: comprehension questions (50 points) and activity write-up (50 points). Each unit ends with a short test built from its questions. The Field Lab report and presentation are the final exam and count for one quarter of the year. One high school science credit with lab. Transcript name: Geology (with lab).

- Comprehension questions (weekly): 30%
- Hands-on activity write-ups (weekly): 30%
- Unit tests: 15%
- Field Lab report and presentation (final exam): 25%
- Transcript name: Geology (with lab). One high school science credit.

A NOTE TO PARENTS

Scripture is quoted from the King James Version only, word for word. Historical sources are quoted exactly or marked as paraphrase. Facts and figures follow the U.S. Geological Survey, the National Park Service, and standard textbooks; where estimates vary, the lesson gives the range. It avoids partisan politics, identity ideology, and climate alarmism, and it teaches stewardship of resources plainly, from Genesis 2:15.

Exam preparation. ACT Science: reading data tables, graphs and conflicting-viewpoint passages (Units 2, 3, 5, 6, 8). **SAT and CLT:** exponential decay and percent problems (half-life, Unit 5), scientific reading passages, vocabulary. **AP Environmental Science:** earth

systems, plate tectonics, soil, the hydrologic cycle, groundwater, mining, fossil fuels, geologic hazards (Units 2, 3, 4, 7).

CONTENTS

Unit 1: Minerals and Rocks

- 1.1 What a Mineral Is
- 1.2 Igneous Rocks
- 1.3 Sedimentary Rocks
- 1.4 Metamorphic Rocks and the Rock Cycle

Unit 2: The Restless Earth: Plate Tectonics, Earthquakes, and Volcanoes

- 2.1 Earth's Interior and Plate Tectonics
- 2.2 Earthquakes
- 2.3 Volcanoes
- 2.4 Mountains and the Shape of the Land

Unit 3: Weathering, Erosion, Rivers, and Glaciers

- 3.1 Weathering and Soil
- 3.2 Rivers and Streams
- 3.3 Glaciers
- 3.4 Deserts, Wind, and Coasts

Unit 4: Groundwater, Caves, and the Water Beneath Our Feet

- 4.1 Groundwater and Aquifers
- 4.2 Caves and Karst
- 4.3 Hot Springs, Geysers, and Geothermal Energy
- 4.4 Floods, Water Quality, and Stewardship

Unit 5: Fossils and Reading Rock Layers

- 5.1 How Fossils Form
- 5.2 Steno's Principles and Reading Rock Layers
- 5.3 The Geologic Column and Index Fossils
- 5.4 Dating Methods, Relative and Radiometric

Unit 6: The Flood, Catastrophe, and the Ice Age

- 6.1 Uniformitarianism and Catastrophism
- 6.2 The Flood of Genesis and Flood Geology
- 6.3 The Grand Canyon as a Case Study
- 6.4 The Ice Age

Unit 7: Earth's Riches: Mining, Gems, and Energy

- 7.1 Ores and Mining
- 7.2 Gems and Precious Stones
- 7.3 Coal, Oil, and Natural Gas
- 7.4 Building Stones, Salt, and Stewardship

Unit 8: Maps, Field Geology, and the Great Geologists

- 8.1 Topographic Maps and Landforms
- 8.2 Geologic Maps and Cross-Sections
- 8.3 The Founders: Nicolaus Steno and James Hutton
- 8.4 The Founders: William Buckland and Louis Agassiz

Unit 9: Field Lab: Doing Geology Where You Live

9.1 The Geologist's Kit and the Field Notebook

9.2 Reading Your Local Landscape

9.3 Catastrophe and Calm: Experiments on Rates

9.4 The Geology Field Report (Capstone)

★ quarter path ·  Thinking About Time box

MINERALS AND ROCKS

Every mountain, every pebble in a creek, every brick and countertop and sidewalk is built from minerals, and minerals are built from a short list of elements arranged in patterns. This unit begins with what a mineral is and how a careful person tells one from another with nothing more than a fingernail, a penny, a nail, and a tile. Then it moves through the three great families of rock, igneous, sedimentary, and metamorphic, and the cycle that turns one into another. Along the way you will meet the men who first worked these things out, and you will learn to separate what geologists observe from what they infer. “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter.” (Proverbs 25:2, KJV)

BEFORE YOU BEGIN

- No earlier geology needed; comfortable with fractions, percentages and basic algebra
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 1.1, What a Mineral Is, and define mineral, streak, cleavage.
- I can explain the main ideas of Lesson 1.2, Igneous Rocks, and define intrusive, felsic, columnar jointing.
- I can explain the main ideas of Lesson 1.3, Sedimentary Rocks, and define lithification, clastic, cross-bedding.
- I can explain the main ideas of Lesson 1.4, Metamorphic Rocks and the Rock Cycle, and define metamorphism, foliation, parent rock.

1.1 WHAT A MINERAL IS

Video. Videos coming.

KEY VOCABULARY

mineral

A naturally occurring, inorganic solid with a definite chemical composition and an orderly crystal structure.

streak

The color of a mineral's powder, found by rubbing it on an unglazed porcelain tile; more reliable than surface color.

cleavage

A mineral's tendency to break along flat planes of weak atomic bonding; contrasted with fracture, which is irregular or curved breakage.

CORE IDEAS

Pick up a handful of gravel and you are holding a crowd of minerals. Most people call all of it "rock," but a geologist makes a sharp distinction. A rock is a mixture, like a fruitcake. A mineral is one ingredient, like a single raisin. To be called a mineral, a substance must pass a five-part test. It must be **naturally occurring**, so a lab-grown diamond does not strictly count even though it is chemically identical to a mined one. It must be **inorganic**, which rules out coal and amber, since those come from living things. It must be a **solid**, so water is not a mineral but ice is. It must have a **definite chemical composition**, meaning it can be written as a formula: quartz is always SiO_2 , halite is always NaCl . And it must have an **orderly crystal structure**, atoms stacked in a repeating pattern. Glass fails this last test; its atoms are jumbled, so obsidian, volcanic glass, is a rock but not a mineral.

Telling minerals apart. Color is the first thing anyone notices and the least reliable. Quartz alone comes clear, white, pink, purple, yellow, smoky brown, and black, depending on tiny impurities. So geologists lean on properties that do not change.

Streak is the color of a mineral's powder, found by dragging it across an unglazed porcelain tile. Hematite can look silvery gray or dull red on the outside, but its streak is always reddish brown.

Luster is how light bounces off the surface. The big split is metallic versus nonmetallic. Nonmetallic lusters are described with everyday words: glassy, pearly, silky, waxy, dull, earthy.

Hardness is resistance to scratching. In 1812 the German mineralogist Friedrich Mohs arranged ten minerals so that each scratches the ones below it: 1 talc, 2 gypsum, 3 calcite, 4 fluorite, 5 apatite, 6 orthoclase feldspar, 7 quartz, 8 topaz, 9 corundum, 10 diamond. The scale is a ranking, not a measurement. Diamond at 10 is not twice as hard as apatite at 5; in

absolute terms it is many times harder than corundum at 9. The useful part is that common objects fit between the steps: a fingernail is about 2.5, a copper penny about 3.5, a steel nail or a piece of window glass about 5.5, and a streak plate about 7.

Cleavage is the tendency to break along flat planes where the atomic bonds are weakest. Mica peels into sheets because it has one perfect cleavage. Halite breaks into little cubes: three cleavages at right angles. Calcite also has three, but not at right angles, so it breaks into slanted blocks called rhombs. Quartz has no cleavage at all; it breaks along curved, shell-like surfaces, which is called conchoidal **fracture**.

Specific gravity compares a mineral's weight to the weight of an equal volume of water. Quartz is 2.65, so it weighs 2.65 times as much as the same volume of water. Galena, the lead ore, is about 7.5. Gold is 19.3, which is why a prospector's pan works: gold sinks while sand washes away.

The acid test identifies calcite. A drop of white vinegar on calcite fizzes as the acid breaks the mineral apart and releases carbon dioxide gas. Vinegar is weak, so the fizz may be faint; scratching the surface to make a little powder, or warming the vinegar, makes it easier to see.

The rock-formers. Of the several thousand known minerals, fewer than a dozen make up nearly all of the earth's crust. **Quartz** is SiO_2 , hardness 7, glassy, with no cleavage; it survives weathering and ends up as most of the sand on beaches. **Feldspar** is the most abundant mineral group in the crust, roughly half of it by volume, hardness 6, usually white or pink, with two cleavages close to right angles. **Mica** comes as colorless muscovite and black biotite, both splitting into thin flexible sheets. **Calcite** is CaCO_3 , hardness 3, the stuff of limestone and marble, and it fizzes. **Hornblende** is a dark green to black mineral of the amphibole family, common in granite and in many dark rocks. **Olivine** is olive green, forms at very high temperature, makes up much of the earth's mantle, and when gem quality is called peridot. **Halite** is rock salt, NaCl , which forms cubes and is the only mineral this course will ever let you taste, and then only a store-bought specimen you know is salt.

The building block. Most of these are silicates, and all silicates share one piece: a silicon atom surrounded by four oxygen atoms at the corners of a tiny pyramid called the silicon-oxygen tetrahedron. Tetrahedra can sit alone, as in olivine; link in single chains, as in pyroxene; in double chains, as in hornblende; in flat sheets, as in mica; or in a three-dimensional framework, as in quartz and feldspar. The structure explains the behavior. Mica cleaves into sheets because its tetrahedra are bonded in sheets. Quartz has no cleavage because its framework has no weak direction.

Job described mining long before mineralogy had a name: "As for the earth, out of it cometh bread: and under it is turned up as it were fire. The stones of it are the place of sapphires: and it hath dust of gold." (Job 28:5-6, KJV) To search out such a matter with a tile and a nail is a small but real exercise of that honor.

PICTURE STUDY



Mineralien und Gesteine (Minerals and Rocks), color plate from Meyers Konversations-Lexikon, 4th edition, Bibliographisches Institut, Leipzig, about 1885-1890,

Figure 1, top left, is a cluster of free-standing quartz crystals from Herkimer, New York; count the six sides on each prism. Compare the grainy granite in figure 13 with the banded gneiss in figure 19 and the conglomerate in figure 21, three rock types you will meet in the next three lessons.

Look closely

Talk about it

HANDS-ON ACTIVITY: A KITCHEN MOHS KIT

You will need

- Safety glasses
- A fingernail
- A copper penny dated before 1982 if you can find one
- A steel nail
- A small piece of glass with taped edges or a glass jar
- An unglazed porcelain tile or the unglazed bottom ring of a coffee mug
- White vinegar
- And any rocks or minerals you have on hand plus household items such as a piece of chalk
- A crystal of rock salt
- A chip of granite or marble
- And a piece of tile

Steps

1. Make a chart with columns for the specimen, whether a fingernail scratches it, whether a penny scratches it, whether a nail scratches it, whether it scratches glass, and whether the streak plate scratches it.
2. Test each specimen in order from softest tool to hardest, pressing firmly and wiping away powder to see whether a true groove was cut.
3. Assign each specimen a hardness range such as “between 3.5 and 5.5.” Then drag each across the tile and record the streak color, and finish with a drop of vinegar on each to see which fizz.

Check your work

- A scratch leaves a groove you can feel with a fingernail; a mark that wipes off is powder from the softer tool, not a scratch. Safety line: wear safety glasses, keep glass edges taped, and never strike or break rocks near other people.

PRACTICE

1. List the five parts of the definition of a mineral, and name one common substance that fails each part.
2. Why do geologists trust streak more than color?
3. Use the Mohs table. A student finds that a mineral scratches a steel nail and a piece of glass, but a streak plate scratches the mineral. Between what two Mohs numbers does its hardness lie, and which rock-forming mineral from this lesson is the best fit?
4. A specimen has a mass of 53 grams and, when lowered into a measuring cup, raises the water level by 20 milliliters. Calculate its specific gravity and say which mineral in this lesson it matches.
5. Explain, using the silicon-oxygen tetrahedron, why mica splits into sheets but quartz does not.

Exam connection. ACT Science passages often present a table of mineral properties and ask you to identify an unknown, exactly as in question 3, and SAT Math uses ratio problems like the specific gravity calculation in question 4. AP Environmental Science expects you to know that minerals are the raw material of mining and soil, which this course returns to in later units.

For families. At the table, ask which objects in the kitchen are minerals, which are rocks, and which are neither: table salt, a glass, a ceramic plate, an ice cube, a pencil lead. Before the activity, decide together where rock testing happens so chips do not end up in food or on the floor, and agree that nothing unknown goes in anyone’s mouth. Scholars still debate the exact count of mineral species, which rises every year as new ones are approved, so treat any number above five thousand as a round figure.

Practice answers

1. Naturally occurring (a lab-grown diamond fails), inorganic (coal or amber fails), solid (water fails), definite chemical composition (a mixture like granite fails), orderly crystal structure (glass or obsidian fails).
2. Surface color changes with small impurities and weathering, so one mineral can show many colors, while the powder color is fixed by the mineral's own composition. Hematite may look gray or red, but its streak is always reddish brown.
3. Harder than 5.5 and softer than 7, so between about 5.5 and 7. Feldspar, at 6, is the best fit among the rock-formers listed.
4. Specific gravity equals mass divided by the mass of the displaced water. Twenty milliliters of water has a mass of 20 grams, so $53 \div 20 = 2.65$, which matches quartz.
5. In mica the tetrahedra are bonded into flat sheets, with weaker bonds between the sheets, so the mineral splits along those planes. In quartz the tetrahedra form a three-dimensional framework with no weak direction, so it has no cleavage and breaks with conchoidal fracture.

1.2 IGNEOUS ROCKS

Video. Videos coming.

KEY VOCABULARY

intrusive

Igneous rock that cooled slowly underground and therefore has large, visible crystals; granite and gabbro are examples.

felsic

Igneous rock rich in feldspar and silica, light in color and low in iron and magnesium; the opposite is mafic.

columnar jointing

The pattern of long five- or six-sided columns produced when a thick body of lava shrinks as it cools.

CORE IDEAS

Deep beneath the ground, rock can grow hot enough to melt. Molten rock underground is called **magma**. The moment it breaks the surface it is renamed **lava**. The distinction matters because the two cool in completely different ways, and the way a melt cools decides what kind of rock it becomes. Rocks that form from cooled melt are **igneous**, from the Latin word for fire.

Slow and fast. Magma that cools underground, surrounded by warm rock, loses its heat over a long time. Atoms have leisure to find their places, and the crystals grow large enough to see without a lens. The result is an **intrusive** igneous rock with a coarse, salt-and-pepper texture. Granite is the familiar example; look at a granite countertop and you can pick out the pink or white feldspar, the glassy gray quartz, and the black specks of mica and hornblende.

Lava that erupts at the surface meets cold air or water and freezes quickly. Crystals have no time to grow, so the rock is fine-grained, and the individual minerals are too small to see. This is an **extrusive** igneous rock. If cooling is nearly instant, as when lava meets water or the melt is especially stiff, no crystals form at all and the result is obsidian, a natural glass that breaks with razor edges. If the lava is frothy with gas, the bubbles are frozen in place and the rock is pumice, so full of holes that it floats. The rule is simple and testable: crystal size records cooling rate.

Because of this, igneous rocks come in matched pairs, one intrusive and one extrusive, with the same minerals but different textures. Granite and rhyolite are the same recipe cooled slow and fast. Gabbro and basalt are another pair. Sometimes a magma cools slowly for a while, grows a few big crystals, then erupts and freezes the rest; the result, big crystals in a

fine background, is called porphyritic, and the plate you studied last lesson shows two examples.

Light and dark. The second thing to notice is composition. **Felsic** rocks are rich in feldspar and silica, light in color, and relatively low in iron and magnesium: granite and rhyolite, with roughly 70 percent silica. **Mafic** rocks are rich in magnesium and iron, dark in color, and lower in silica, roughly 50 percent: gabbro and basalt. Diorite and andesite sit in between. Composition also controls how a volcano behaves. Silica-rich melt is stiff and traps gas, so felsic volcanoes tend to explode; mafic lava runs like syrup and builds broad, gentle shields.

Where to see it happening. The island of Hawaii is the best place on earth to watch basalt being made. Kilauea erupted almost continuously from 1983 to 2018, and in 2018 lava from its lower east rift zone buried roads and destroyed about seven hundred homes. Hawaiian lava comes in two textures: pahoehoe, smooth and ropy, and aa, a rubble of sharp clinkers. Iceland sits on the Mid-Atlantic Ridge, where new basalt crust is built, and eruptions like Fagradalsfjall in 2021 drew visitors who could stand a safe distance from a fresh lava flow. Yellowstone's lava is the felsic kind: thick rhyolite flows and welded ash cover the plateau, and the heat that powers its geysers comes from magma still below. Granite, by contrast, is seen only after the rock above it has been stripped away. Yosemite's El Capitan and Half Dome, Pikes Peak in Colorado, and Stone Mountain in Georgia are all granite that cooled underground and was later uncovered.

Columns. When a thick body of lava cools, it shrinks, and the shrinking cracks it into long columns, most of them with five or six sides, like mud cracks running straight down into the rock. This is **columnar jointing**. Devils Tower in Wyoming rises 867 feet from its base, and its sides are a bundle of such columns, some several feet across. It was the first national monument, proclaimed by Theodore Roosevelt in 1906. The Giant's Causeway on the coast of County Antrim, Northern Ireland, is a pavement of about forty thousand basalt columns stepping down into the sea. Both are good places to practice separating observation from inference: the columns and their geometry are observed; the age on the sign is inferred.

Order of crystallization. In the 1920s the Canadian-American geologist Norman L. Bowen melted rocks in the laboratory and cooled them slowly. He found that minerals do not all crystallize at once. Olivine forms first, at the highest temperature, followed by pyroxene, hornblende, and biotite; among the feldspars the calcium-rich kinds come first and the sodium- and potassium-rich kinds later; quartz forms last, at the lowest temperature. This is why olivine and quartz are almost never found together in the same rock, and why early-formed crystals can settle out and change the composition of what remains. Keep the simple version: as a melt cools, minerals crystallize in order.

"He looketh on the earth, and it trembleth: he toucheth the hills, and they smoke." (Psalm 104:32, KJV) Nothing in geology is more plainly visible than a hill that smokes, and nothing better rewards a patient observer.



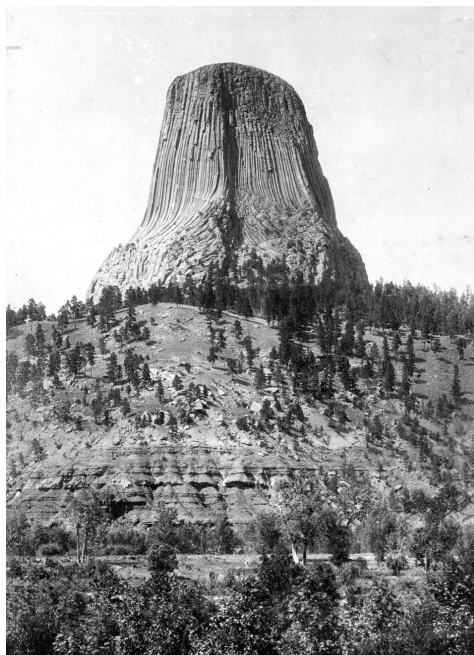
Thinking About Time

What the sign says. The National Park Service sign at Devils Tower gives its age as about 50 million years, and signs at the Giant's Causeway say the columns formed about 60 million years ago.

What we observe. A mass of igneous rock with columnar jointing, standing above softer sedimentary layers that have worn away around it. The columns show it cooled from a melt and shrank; the geometry is measured, not assumed. No one observed the eruption, the cooling, or the stripping away of the cover.

How Christians read it. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6-9, and would place the intrusion and the rapid erosion of the softer rock around it within and after the Flood year. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the long ages inferred from radiometric methods. Both agree that "In the beginning God created the heaven and the earth." (Genesis 1:1, KJV) The columns are observation; the millions are inference, and the student should be able to say which is which.

PICTURE STUDY



Devils Tower, on the west bank of the Belle Fourche River, Wyoming, Nathaniel H. Darton, U.S. Geological Survey, 1900,

Follow the vertical columns from the summit down to the apron of broken column fragments at the base, then look at the horizontal sedimentary beds in the bluff at the bottom of the photograph; the tower is igneous, the bluff is not.

Look closely

Talk about it

HANDS-ON ACTIVITY: FAST COOLING VERSUS SLOW COOLING

You will need

- Safety glasses
- 2 cups of sugar
- 1 cup of water
- A saucepan
- Two clean glass jars
- Two pencils
- Two pieces of cotton string
- A kitchen towel
- And a refrigerator
- Or substitute Epsom salt dissolved in hot water for a quicker version

Steps

1. An adult heats the water and stirs in the sugar until no more dissolves and the liquid is clear.
2. Pour half into each jar.
3. Hang a string from a pencil into each jar without touching the bottom.
4. Put jar 1 in the refrigerator to cool fast.
5. Wrap jar 2 in the towel and leave it in a warm, still spot to cool slowly.
6. Check both every day for a week and sketch what you see.

Check your work

- The slow-cooled jar grows fewer, larger, better-formed crystals; the fast-cooled jar grows many small ones or a crust. Relate this to granite and rhyolite. Safety line: hot sugar syrup sticks to skin and burns badly, so only an adult handles the pan, and let the jars cool before anyone touches them.

PRACTICE

1. What is the difference between magma and lava, and why does it matter for the rock that forms?
2. Use the table to name each rock. | Specimen | Crystal size | Color and composition | |---|---| | A | coarse, crystals easily seen | light, mostly feldspar and quartz | | B | fine, no visible crystals | dark, iron- and magnesium-rich | | C | coarse, crystals easily seen | dark, iron- and magnesium-rich | | D | fine, no visible crystals | light, mostly feldspar and quartz |
3. Why does pumice float, and what does that tell you about the lava it came from?
4. Devils Tower rises 867 feet above its base. Using 1 foot = 0.3048 meter, how tall is that in meters, rounded to the nearest meter?
5. Explain, using Bowen's finding, why a geologist would be surprised to find olivine and quartz together in one rock.

Exam connection. ACT Science regularly builds a passage around a classification table like the one in question 2, and AP Environmental Science Unit 4 on earth systems expects you to connect volcano type to magma composition and to the plate setting of Hawaii, Iceland, and Yellowstone.

For families. Ask everyone at dinner where the family has seen igneous rock: a granite counter or curb, a pumice stone in the bathroom, a lava rock in a gas grill. The age of Devils Tower and the exact way its columns formed, whether as the neck of a volcano or as an intrusion that never reached the surface, are both still discussed by geologists; the sign gives one view. For the activity, plan on a week of patience and keep the slow-cooling jar somewhere it will not be bumped.

Practice answers

1. Magma is molten rock underground; lava is the same melt once it reaches the surface. Magma cools slowly and grows large crystals; lava cools fast and forms fine-grained or glassy rock.
2. A is granite, B is basalt, C is gabbro, D is rhyolite.
3. Pumice is full of gas bubbles frozen in place, so its overall density is less than water. The lava was frothy with dissolved gas escaping as it erupted, which is typical of stiff, silica-rich melt.
4. $867 \times 0.3048 = 264.3$, so about 264 meters.
5. Olivine crystallizes first at the highest temperatures and quartz last at the lowest. By the time a melt is cool enough to form quartz, the olivine has either settled out or reacted with the remaining melt to form other minerals, so the two rarely coexist.

1.3 SEDIMENTARY ROCKS

Video. Videos coming.

KEY VOCABULARY

lithification

The process by which loose sediment becomes solid rock through compaction and cementation.

clastic

Sedimentary rock made of broken pieces of older rock, classified by grain size; conglomerate, sandstone, siltstone, and shale.

cross-bedding

Layers tilted within a bed, left by the moving face of a ripple or dune; records the direction of the current or wind.

CORE IDEAS

Most of the rock you can see from a car window is sedimentary. These are rocks made from pieces of older rocks, from minerals that settled out of water, or from the remains of living things. Because they form in layers at the surface, they are the rocks that hold fossils, coal, oil, and most of the world's drinking water. They also carry the record that geologists argue about most, so it pays to learn their language carefully.

From mountain to mud. The story has four steps. **Weathering** breaks rock down where it sits. Mechanical weathering is force: water freezes in a crack and pries it wider, roots push, heat expands and cold shrinks. Chemical weathering is reaction: rainwater slowly dissolves calcite, oxygen rusts iron minerals, and feldspar rots into clay. **Transport** moves the loose material by water, wind, ice, or gravity, rounding the grains and sorting them by size as it goes. **Deposition** happens when the carrying power drops: a river slows, a wind dies, a wave spends itself, and the load settles. Then comes **lithification**, which turns loose sediment into stone. Compaction squeezes the water out as more layers pile on; cementation glues the grains together with minerals carried in groundwater, usually calcite, silica, or iron oxide. Iron oxide cement is why so much sandstone in the American Southwest is red.

Three families. **Clastic** rocks are made of broken pieces, and they are named by grain size using the scale published by Chester K. Wentworth in 1922. Gravel is anything larger than 2 millimeters, from granules through pebbles and cobbles to boulders above 256 millimeters. Sand runs from 1/16 millimeter to 2 millimeters. Silt is 1/256 to 1/16 millimeter, too fine to see as grains but gritty between the teeth. Clay is anything finer. Cemented gravel with rounded pieces is conglomerate; with sharp, angular pieces it is breccia, which tells you the pieces did not travel far. Sand makes sandstone, silt makes siltstone, and clay makes shale, which splits into thin flaky sheets.

Chemical rocks precipitate from water. When seawater or a desert lake evaporates, halite and gypsum crystallize out as rock salt and rock gypsum; thick salt beds under Michigan, Kansas, and the Gulf Coast formed this way. Some limestone is chemical too, like the travertine terraces at Mammoth Hot Springs in Yellowstone.

Organic rocks are built from living things. Coal is compressed plant matter from swamps. Fossil limestone, such as the shell hash called coquina in Florida, is made of skeletons of sea creatures. Chalk is a very fine limestone made of countless plates from microscopic floating algae called coccoliths. The white cliffs of Dover on the English Channel are chalk standing up to about 350 feet high, pure white except for dark bands of flint nodules, and the same chalk runs under the Channel and across northern France.

What the layers record. Sedimentary rocks keep **structures** that tell how they were laid down. **Bedding** is the basic layering; each bed marks a change in what was being delivered. **Cross-bedding** is a set of layers tilted inside a flat bed, the frozen downstream face of a migrating ripple or dune, and it records the direction the current or wind was moving. **Ripple marks** are the ridged surface of a bed; symmetrical ripples record waves moving back and forth, asymmetrical ripples record a one-way current. **Mud cracks** are polygons that form when wet mud dries and shrinks, so they record a surface exposed to air. Reading these is observation: a geologist measures a cross-bed and says which way the current ran. Saying how long the whole stack took to form is inference.

The Coconino question. High in the walls of the Grand Canyon runs a pale cream-colored cliff several hundred feet thick called the Coconino Sandstone. It is almost pure quartz sand, well sorted, with grains that look frosted, and it is full of sweeping cross-beds larger than a house. Fossils are scarce except for trackways of small four-footed animals walking up the slopes. The standard reading, found on every park sign, is that the Coconino was a vast desert of wind-blown dunes. The evidence given is the size of the cross-beds, the frosted rounded grains, fine wind-ripple laminations, and a few surfaces that look like raindrop pits. A different reading, held by many Christian geologists and discussed in peer-reviewed journals, is that the sand was laid down under water as great sand waves moved by strong currents. Its supporters point out that the cross-beds dip at gentler angles than the slip faces of modern dry dunes, that laboratory experiments by Leonard Brand in the late 1970s found the trackways looked most like those made by animals walking on sand under shallow water, and that the formation contains thin dolomite beds and mica flakes that are unusual for a desert. Geologists who hold the desert view answer each point in turn. The honest summary is that the sand, the sorting, the cross-beds, and the tracks are all observed; dry dunes and underwater sand waves are both inferences, and you should be able to state the evidence for each.

Scripture gives Christians a frame for water that moves sediment on a grand scale: “the same day were all the fountains of the great deep broken up, and the windows of heaven were opened.” (Genesis 7:11, KJV)



Thinking About Time

What the sign says. Signs at the Grand Canyon label the Coconino Sandstone Permian, about 280 million years old, and the Dover chalk is labeled Cretaceous, deposited over millions of years at a rate often given as a few centimeters per thousand years, based on the slow settling of plankton measured on today's sea floors.

What we observe. Layers, grain sizes, cross-beds, tracks, and present-day rates of settling in calm water. We also observe that deposition can be very fast. On June 12, 1980, a pyroclastic flow at Mount St. Helens laid down about 25 feet of finely laminated deposit in a single afternoon, and the U.S. Geological Survey documented that eruptions there built up as much as 600 feet of new material in places, which streams later cut into canyons within a few years. One violent event made many thin layers in hours.

How Christians read it. Many Christian families understand the thick, widespread sedimentary layers of the continents within a young earth and the Flood of Genesis 6–9, taking Mount St. Helens as a small model of what moving water and sediment can do quickly. Other Christians hold an older earth and accept the slow rates on the sign as the usual case, while allowing that catastrophes punctuate the record. Both readings honor the same text: “Thou coveredst it with the deep as with a garment: the waters stood above the mountains.” (Psalm 104:6, KJV) The layers are observation; the rate, and so the time, is inference.

PICTURE STUDY



Pegwell Bay, Kent: a Recollection of October 5th 1858, William Dyce, about 1858–1860,

Dyce painted the chalk cliffs of the Kent coast with a geologist's care: trace the horizontal bedding and the dark flint bands in the cliff face, then notice the fallen chalk blocks and the wave-cut platform the figures are standing on, the cliff being weathered into fresh sediment before your eyes.

Look closely

Talk about it

HANDS-ON ACTIVITY: THE SEDIMENT JAR

You will need

- A clear jar with a tight lid
- About a quart
- A handful each of gravel
- Coarse sand
- Fine sand or silt from a garden
- And clay or potting soil
- Water
- A ruler
- A notebook

Steps

1. Add the sediments to the jar in any order, fill with water to within an inch of the top, screw the lid on tightly, and shake hard for thirty seconds.
2. Set it down and watch.
3. Time how long the water takes to clear.
4. After an hour, and again the next day, measure the thickness of each layer with the ruler and draw the jar.
5. Shake once more and let it settle again.

Check your work

- The gravel lands first, then sand, then silt, with the clay clouding the water for hours; one shaking produces several distinct layers, graded from coarse at the bottom to fine at the top. Count the layers after the second shaking and compare them with the first. Safety line: use a plastic jar if a young sibling is helping, and wipe up spills, since wet clay is slippery.

PRACTICE

1. Name the four steps that turn a mountain into sedimentary rock, and say what happens at each.
2. Use the Wentworth table to classify each sediment and name the rock it would become.
| Size class | Grain diameter | |---|---| | gravel | larger than 2 mm | | sand | 1/16 mm to 2 mm | | silt | 1/256 mm to 1/16 mm | | clay | smaller than 1/256 mm | Sample X: grains 0.5 mm across. Sample Y: grains 0.01 mm across. Sample Z: angular pieces 30 mm across.
3. What is the difference between conglomerate and breccia, and what does that difference tell you?

4. A bed of sandstone shows symmetrical ripple marks on its upper surface and mud cracks on the shale just above. Explain what each structure records.
5. State one piece of evidence for the wind-blown dune reading of the Coconino Sandstone and one piece for the underwater reading, and label each as observation or inference.

Exam connection. Grain-size tables like the one in question 2 are standard ACT Science material, and AP Environmental Science Unit 4 treats soil formation, weathering, and erosion directly; Unit 6 covers coal as a sedimentary fuel. SAT Reading sometimes pairs a science passage with a cliff or canyon diagram that must be read for bedding order.

For families. The sediment jar is a good dinner-table experiment: ask how many layers one shaking made, and whether a stranger seeing the jar could tell it was shaken once or several times. The Coconino debate is a live one and a good place to practice disagreeing well; a parent might read the park sign and the alternative aloud and ask the student to list what both sides agree is actually there. Potting soil can carry mold, so wash hands after the activity.

Practice answers

1. Weathering breaks rock down in place; transport carries and sorts the pieces by water, wind, ice, or gravity; deposition drops them when the carrying power falls; lithification turns the sediment to rock by compaction and cementation.
2. X is sand and becomes sandstone. Y is silt, since $1/256$ mm is about 0.004 mm and $1/16$ mm is about 0.0625 mm, so it becomes siltstone. Z is gravel, and because the pieces are angular it becomes breccia.
3. Conglomerate has rounded pieces; breccia has angular ones. Rounding takes travel, so breccia pieces were deposited close to where they broke off.
4. Symmetrical ripples record waves moving back and forth in shallow water; mud cracks record wet mud that dried in the air. Together they say the spot was under shallow water, then exposed.
5. For dunes: frosted, well-rounded, well-sorted quartz grains and large cross-beds, which are observations; “desert” is the inference. For water: cross-beds that dip more gently than modern dry dune faces and trackways resembling those made under water in experiments, which are observations; “sand waves under a current” is the inference.

1.4 METAMORPHIC ROCKS AND THE ROCK CYCLE

Video. Videos coming.

KEY VOCABULARY

metamorphism

The change of an existing rock into a new rock by heat, pressure, and chemically active fluids, without melting.

foliation

The layered or striped texture of a metamorphic rock produced when flat or elongated minerals line up across the direction of pressure.

parent rock

The original rock from which a metamorphic rock formed; shale is the parent of slate, limestone or marble.

CORE IDEAS

Take a rock that already exists and bury it deep, squeeze it, heat it almost to melting, and soak it in hot fluids, and it will change into something new without ever becoming liquid. That change is **metamorphism**, from Greek words meaning change of form, and the product is a **metamorphic rock**. The rock it came from is called the **parent rock**. The key idea is that metamorphism happens in the solid state. If the rock melts, it stops being metamorphic and starts over as magma, and whatever cools from that melt is igneous.

Three agents. Heat makes atoms mobile, so old minerals rearrange into new ones that are stable at the higher temperature. The temperatures involved run from roughly 150 to 200 degrees Celsius at the low end up to around 800 degrees, close to the melting point of many rocks. Pressure comes from the weight of overlying rock and from the sideways squeeze of colliding plates. When pressure is stronger in one direction than another, flat and needle-shaped minerals such as mica and hornblende rotate until they lie across the push, and the rock takes on a layered, striped, or flaky look called **foliation**. Hot, chemically active fluids, mostly water carrying dissolved ions, speed up the reactions and carry material in and out.

Two settings. **Contact metamorphism** happens where magma intrudes cooler rock. The intruded rock is baked in a halo around the magma body, and because the main agent is heat rather than directed pressure, the products are usually not foliated. **Regional metamorphism** happens over hundreds of square miles where mountain ranges are being built, with both deep burial and directed pressure, and its products are foliated.

Foliated and non-foliated. The classic foliated sequence starts with shale. Low-grade metamorphism turns shale into **slate**, dense and fine-grained, splitting into thin flat sheets. A little more heat and pressure makes **phyllite**, with a silky sheen from tiny mica flakes. More still makes **schist**, in which the mica flakes are big enough to see and glitter, often with

garnet crystals. At high grade the minerals separate into light and dark bands and the rock is **gneiss**, which can also form directly from granite. Increase the heat beyond that and the rock begins to melt.

The non-foliated rocks are made from parents with only one main mineral, so there is nothing to line up. Limestone, which is calcite, recrystallizes into **marble**: the fossils are destroyed, the calcite grains grow into an interlocking sugary mosaic, and it still fizzes in vinegar. Sandstone, which is quartz, becomes **quartzite**, so tightly fused that it breaks through the grains instead of around them. Remember the four pairs: shale to slate, limestone to marble, sandstone to quartzite, granite to gneiss.

Rock that built a civilization. Slate splits into thin, waterproof, fireproof sheets, which made it the roofing stone of Wales, Pennsylvania, and Vermont; a good slate roof lasts a century. Marble carves cleanly and takes a polish. The quarries at Carrara in the Apuan Alps of Italy have been worked since Roman times, and from a single block of Carrara marble Michelangelo cut the Pietà in 1498 and 1499, the sculpture of Mary holding the body of Christ that now stands in St. Peter's Basilica. In America, the Vermont Marble Company at Proctor, and the quarry at Danby, Vermont, supplied marble for buildings across the country, including the exterior of the Jefferson Memorial in Washington, and Colorado's Yule marble clads the Lincoln Memorial.

The rock cycle. Now the three families come together. Igneous rock weathers into sediment; sediment lithifies into sedimentary rock; burial and pressure turn sedimentary rock into metamorphic rock; metamorphic rock melts into magma; magma cools into igneous rock. But every arrow can be skipped or reversed. Metamorphic rock can be uplifted and weathered straight to sediment. Igneous rock can be metamorphosed without ever being sediment. Draw it yourself: three boxes labeled igneous, sedimentary, and metamorphic, with magma and sediment as way stations, and label each arrow with the process: melting, cooling, weathering and erosion, deposition, lithification, heat and pressure, uplift.

Hutton and the question he raised. The man who first saw this cycle clearly was James Hutton, a Scottish farmer, physician, and natural philosopher, who lived from 1726 to 1797. At Siccar Point on the Scottish coast in 1788 he found nearly vertical beds of old rock planed off and covered by nearly horizontal younger beds, and he reasoned that the lower rocks had been laid down, hardened, tilted, raised, worn away, and buried again. The observation was sound and it is still taught. But Hutton drew a larger inference, and he ended his 1788 *Theory of the Earth* with it: "The result, therefore, of our present enquiry is, that we find no vestige of a beginning,—no prospect of an end." That sentence is philosophy, not geology. Christians have answered it from Scripture: "In the beginning God created the heaven and the earth." (Genesis 1:1, KJV) And of the earth's end: "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." (Psalm 102:25-26, KJV) The rock cycle is real; the rocks are recycled; but the cycle had a Maker, a start, and will have a finish. "The present is the key to the past" is a slogan later writers used to sum up Hutton's idea; it was not his sentence.

Thinking About Time

What the sign says. Museum signs describe metamorphic rocks like the Vishnu Schist at the bottom of the Grand Canyon as “Precambrian,” well over a billion years old, and Hutton’s line is often quoted as the birth of deep time.

What we observe. Banded, folded, recrystallized rock whose minerals record high temperature and directed pressure; unconformities where tilted rock is overlain by flat rock; and in the laboratory, the temperatures and pressures at which those minerals form. No one has observed how long a given rock spent at those conditions.

How Christians read it. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6–9, and hold that the heat and pressure of catastrophic burial and rapid mountain building can metamorphose rock far faster than the slow rates the sign assumes. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the long ages as the best inference from radiometric dating. Both reject Hutton’s “no vestige of a beginning,” because Scripture declares a beginning. The folds are observation; the duration is inference.

PICTURE STUDY



Workmen at Carrara, John Singer Sargent, watercolor, 1911,

Three quarrymen carry the heavy ropes used to lower marble blocks down the mountain; notice how Sargent lets the white of the paper stand for the blinding white of the marble quarry behind them.

Look closely

Talk about it

HANDS-ON ACTIVITY: ROCK CYCLE IN A BAG

You will need

- Safety glasses
- Old crayons in three or four colors with the paper removed
- A vegetable peeler or cheese grater
- Aluminum foil
- A zip-top freezer bag
- A bowl of hot tap water
- A bowl of ice water
- And tongs

Steps

1. Grate the crayons into shavings; this loose pile is your sediment.
2. Fold a square of foil around a spoonful of mixed shavings and press down hard with your palm for a minute; open it and you have a crumbly “sedimentary rock” of pressed layers.
3. Seal that pressed cake inside the freezer bag, press the air out, and hold the bag in the hot tap water with tongs for two or three minutes while squeezing it gently through the bag; open it to find a “metamorphic rock” with the colors smeared and folded but not fully blended.
4. Finally, put the cake in a small foil boat, set the boat on the surface of the hot water until it melts completely, then slide it into the ice water; the solid that forms is your “igneous rock,” one color throughout.

Check your work

- In the sedimentary stage you can still pick out individual shavings; in the metamorphic stage the shavings are deformed and the colors streak like foliation; in the igneous stage all trace of the original grains is gone. Safety line: hot tap water can scald, so an adult fills the bowl, nothing goes on the stove or in the microwave, and use tongs rather than fingers.

PRACTICE

1. What are the three agents of metamorphism, and why is melting excluded?
2. Complete the table. | Parent rock | Metamorphic rock | Foliated? | |---|---|---| | shale | ? | ? | | limestone | ? | ? | | sandstone | ? | ? | | granite | ? | ? |
3. Explain why marble and quartzite are not foliated while slate and schist are.
4. A block of Carrara marble measures 2 meters by 1 meter by 1 meter. Marble has a density of about 2.7 metric tons per cubic meter. What is the mass of the block?

5. What did Hutton observe at Siccar Point, what did he infer, and which part do Christians answer from Scripture?

Exam connection. The rock cycle is a stock diagram on the ACT Science test and in AP Environmental Science Unit 4, where you may be asked to identify the process on each arrow; the parent-rock table in question 2 is the kind of matching item the CLT and SAT Reading science passages reward.

For families. Ask where metamorphic rock appears in daily life: a marble windowsill or cutting board, a slate chalkboard or roof, the quartzite countertop sold as a harder alternative to marble. Hutton is a good evening conversation: a parent can read his closing sentence aloud and ask the student whether it is something a person could see in a rock. Geologists still discuss how fast metamorphism can happen under the right conditions; that is a question of rates, which the student should recognize by now as inference. The crayon activity is messy; grate over newspaper, and keep foil away from the microwave.

Practice answers

1. Heat, pressure, and chemically active fluids. Metamorphism happens in the solid state; if the rock melts, the melt is magma and the rock that cools from it is igneous, not metamorphic.
2. Shale becomes slate, foliated. Limestone becomes marble, non-foliated. Sandstone becomes quartzite, non-foliated. Granite becomes gneiss, foliated.
3. Marble and quartzite form from parents that are nearly all one mineral, calcite or quartz, which grows as roughly equal-sized grains with no flat shape to line up. Shale contains clay that recrystallizes into mica, a flat mineral that rotates to lie across the pressure, producing foliation.
4. Volume is $2 \times 1 \times 1 = 2$ cubic meters; $2 \times 2.7 = 5.4$ metric tons, about 5,400 kilograms.
5. He observed tilted older beds planed off and covered by flat younger beds. He inferred a cycle of deposition, uplift, erosion, and renewed deposition, which is accepted, and went further to infer that the earth shows no sign of a beginning or an end. Christians answer the second inference with Genesis 1:1 and Psalm 102:25–26, which declare both a beginning and an end.

UNIT 1 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) List the five parts of the definition of a mineral, and name one common substance that fails each part.
2. (5 pts) Why do geologists trust streak more than color?
3. (5 pts) Use the Mohs table. A student finds that a mineral scratches a steel nail and a piece of glass, but a streak plate scratches the mineral. Between what two Mohs numbers does its hardness lie, and which rock-forming mineral from this lesson is the best fit?
4. (5 pts) A specimen has a mass of 53 grams and, when lowered into a measuring cup, raises the water level by 20 milliliters. Calculate its specific gravity and say which mineral in this lesson it matches.
5. (5 pts) Explain, using the silicon-oxygen tetrahedron, why mica splits into sheets but quartz does not.
6. (5 pts) What is the difference between magma and lava, and why does it matter for the rock that forms?
7. (5 pts) Use the table to name each rock. | Specimen | Crystal size | Color and composition | |---|---|---| | A | coarse, crystals easily seen | light, mostly feldspar and quartz | | B | fine, no visible crystals | dark, iron- and magnesium-rich | | C | coarse, crystals easily seen | dark, iron- and magnesium-rich | | D | fine, no visible crystals | light, mostly feldspar and quartz |
8. (5 pts) Why does pumice float, and what does that tell you about the lava it came from?
9. (5 pts) Devils Tower rises 867 feet above its base. Using 1 foot = 0.3048 meter, how tall is that in meters, rounded to the nearest meter?
10. (5 pts) Explain, using Bowen's finding, why a geologist would be surprised to find olivine and quartz together in one rock.
11. (5 pts) Name the four steps that turn a mountain into sedimentary rock, and say what happens at each.
12. (5 pts) Use the Wentworth table to classify each sediment and name the rock it would become. | Size class | Grain diameter | |---|---| | gravel | larger than 2 mm | | sand | 1/16 mm to 2 mm | | silt | 1/256 mm to 1/16 mm | | clay | smaller than 1/256 mm | Sample X: grains 0.5 mm across. Sample Y: grains 0.01 mm across. Sample Z: angular pieces 30 mm across.
13. (5 pts) What is the difference between conglomerate and breccia, and what does that difference tell you?
14. (5 pts) A bed of sandstone shows symmetrical ripple marks on its upper surface and mud cracks on the shale just above. Explain what each structure records.
15. (5 pts) State one piece of evidence for the wind-blown dune reading of the Coconino Sandstone and one piece for the underwater reading, and label each as observation or

inference.

16. (5 pts) What are the three agents of metamorphism, and why is melting excluded?
17. (5 pts) Complete the table. | Parent rock | Metamorphic rock | Foliated? | |---|---|---| | shale | ? | ? | | limestone | ? | ? | | sandstone | ? | ? | | granite | ? | ? |
18. (5 pts) Explain why marble and quartzite are not foliated while slate and schist are.
19. (5 pts) A block of Carrara marble measures 2 meters by 1 meter by 1 meter. Marble has a density of about 2.7 metric tons per cubic meter. What is the mass of the block?
20. (5 pts) What did Hutton observe at Siccar Point, what did he infer, and which part do Christians answer from Scripture?

Answer key

1. Naturally occurring (a lab-grown diamond fails), inorganic (coal or amber fails), solid (water fails), definite chemical composition (a mixture like granite fails), orderly crystal structure (glass or obsidian fails).
2. Surface color changes with small impurities and weathering, so one mineral can show many colors, while the powder color is fixed by the mineral's own composition. Hematite may look gray or red, but its streak is always reddish brown.
3. Harder than 5.5 and softer than 7, so between about 5.5 and 7. Feldspar, at 6, is the best fit among the rock-formers listed.
4. Specific gravity equals mass divided by the mass of the displaced water. Twenty milliliters of water has a mass of 20 grams, so $53 \div 20 = 2.65$, which matches quartz.
5. In mica the tetrahedra are bonded into flat sheets, with weaker bonds between the sheets, so the mineral splits along those planes. In quartz the tetrahedra form a three-dimensional framework with no weak direction, so it has no cleavage and breaks with conchoidal fracture.
6. Magma is molten rock underground; lava is the same melt once it reaches the surface. Magma cools slowly and grows large crystals; lava cools fast and forms fine-grained or glassy rock.
7. A is granite, B is basalt, C is gabbro, D is rhyolite.
8. Pumice is full of gas bubbles frozen in place, so its overall density is less than water. The lava was frothy with dissolved gas escaping as it erupted, which is typical of stiff, silica-rich melt.
9. $867 \times 0.3048 = 264.3$, so about 264 meters.
10. Olivine crystallizes first at the highest temperatures and quartz last at the lowest. By the time a melt is cool enough to form quartz, the olivine has either settled out or reacted with the remaining melt to form other minerals, so the two rarely coexist.
11. Weathering breaks rock down in place; transport carries and sorts the pieces by water, wind, ice, or gravity; deposition drops them when the carrying power falls; lithification turns the sediment to rock by compaction and cementation.
12. X is sand and becomes sandstone. Y is silt, since $1/256$ mm is about 0.004 mm and $1/16$ mm is about 0.0625 mm, so it becomes siltstone. Z is gravel, and because the pieces are angular it becomes breccia.
13. Conglomerate has rounded pieces; breccia has angular ones. Rounding takes travel, so breccia pieces were deposited close to where they broke off.
14. Symmetrical ripples record waves moving back and forth in shallow water; mud cracks record wet mud that dried in the air. Together they say the spot was under shallow water, then exposed.

15. For dunes: frosted, well-rounded, well-sorted quartz grains and large cross-beds, which are observations; “desert” is the inference. For water: cross-beds that dip more gently than modern dry dune faces and trackways resembling those made under water in experiments, which are observations; “sand waves under a current” is the inference.
16. Heat, pressure, and chemically active fluids. Metamorphism happens in the solid state; if the rock melts, the melt is magma and the rock that cools from it is igneous, not metamorphic.
17. Shale becomes slate, foliated. Limestone becomes marble, non-foliated. Sandstone becomes quartzite, non-foliated. Granite becomes gneiss, foliated.
18. Marble and quartzite form from parents that are nearly all one mineral, calcite or quartz, which grows as roughly equal-sized grains with no flat shape to line up. Shale contains clay that recrystallizes into mica, a flat mineral that rotates to lie across the pressure, producing foliation.
19. Volume is $2 \times 1 \times 1 = 2$ cubic meters; $2 \times 2.7 = 5.4$ metric tons, about 5,400 kilograms.
20. He observed tilted older beds planed off and covered by flat younger beds. He inferred a cycle of deposition, uplift, erosion, and renewed deposition, which is accepted, and went further to infer that the earth shows no sign of a beginning or an end. Christians answer the second inference with Genesis 1:1 and Psalm 102:25–26, which declare both a beginning and an end.

THE RESTLESS EARTH: PLATE TECTONICS, EARTHQUAKES, AND VOLCANOES

The ground under your feet feels like the most solid thing in the world, but it is not standing still. Whole continents creep along at the speed your fingernails grow, mountains rise and wear down, and now and then the earth lurches or a mountain explodes. This unit looks inside the planet, follows the great plates across its surface, and then studies the two most dramatic things the restless earth does: earthquakes and volcanoes. Along the way you will meet real people, real dates, and real numbers, and you will learn to tell what geologists have measured from what they have inferred. “In his hand are the deep places of the earth: the strength of the hills is his also” (Psalm 95:4, KJV).

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 2.1, Earth’s Interior and Plate Tectonics, and define lithosphere, subduction, seafloor spreading.
- I can explain the main ideas of Lesson 2.2, Earthquakes, and define epicenter, moment magnitude (M_w), Modified Mercalli intensity.
- I can explain the main ideas of Lesson 2.3, Volcanoes, and define viscosity, pyroclastic flow, lahar.
- I can explain the main ideas of Lesson 2.4, Mountains and the Shape of the Land, and define anticline, batholith, isostasy.

2.1 EARTH'S INTERIOR AND PLATE TECTONICS

Video. Videos coming.

KEY VOCABULARY

lithosphere

The rigid outer shell of the earth, crust plus uppermost mantle, about 100 kilometers thick, broken into plates.

subduction

The sinking of one plate beneath another at a convergent boundary, producing a trench and a line of volcanoes.

seafloor spreading

The making of new ocean crust at a mid-ocean ridge as plates move apart, recorded by magnetic stripes.

CORE IDEAS

A planet in layers. If you could slice the earth like an apple, you would find it built in layers. The outer skin is the **crust**. Under the oceans it is thin, about 7 kilometers, and made of dark, heavy basalt. Under the continents it is about 35 kilometers thick, up to 70 beneath great mountain ranges, and made mostly of lighter, granite-like rock. Its base is a boundary called the Moho, found in 1909 by the Croatian scientist Andrija Mohorovičić.

Below the crust lies the **mantle**, about 2,900 kilometers of hot, dense rock, solid yet able to flow very slowly, as a glacier flows while staying ice. Beneath it is the core, mostly iron with some nickel. The **outer core** is liquid, and its churning produces the earth's magnetic field. The **inner core**, about 1,220 kilometers in radius, is solid because of the crushing pressure at the center, roughly 6,371 kilometers below your feet.

How do we know?. No one has been there; the deepest hole ever drilled, in Russia's Kola Peninsula, reached only about 12 kilometers.

The main tool is the earthquake. A large quake sends two kinds of waves through the body of the earth. P waves push and pull like sound and travel through solid or liquid. S waves shake side to side and cannot travel through liquid at all. Seismographs more than about 104 degrees away from a quake record P waves but no S waves. This "S-wave shadow zone" is the fingerprint of a liquid layer deep inside: the outer core. In 1936 the Danish seismologist Inge Lehmann noticed faint P waves bouncing off something inside that liquid, and so the solid inner core was found.

Two other clues agree. The earth as a whole weighs about 5.5 grams per cubic centimeter, but surface rocks weigh only 2.7 to 3.0, so something far heavier must lie inside. Iron meteorites, leftover building material of the solar system, show what that heavy stuff is likely made of.

Lithosphere and asthenosphere. The crust plus the cool, rigid top of the mantle forms the **lithosphere**, about 100 kilometers thick, broken into a dozen large plates and several small ones. Beneath it lies the **asthenosphere**, a hotter, weaker zone of the mantle that yields and flows, and the plates ride on it.

Wegener's bold idea. In 1912 a German meteorologist named Alfred Wegener gave lectures, and in 1915 published a book, arguing that the continents had once been joined and had drifted apart. He pointed to the way South America and Africa fit like puzzle pieces, to matching fossils such as the fern *Glossopteris* and the small reptile *Mesosaurus* on both sides of the Atlantic, to mountain belts that line up across the ocean, and to scratches left by ancient ice in places now near the equator. That is a paraphrase of his argument.

Most geologists rejected it. Wegener could not explain what force could push a continent through solid ocean floor, and physicists showed the rocks were far too strong for that. He died on the Greenland ice sheet in 1930, his idea still unwelcome.

Seafloor spreading. The answer came from the ocean floor. Sonar surveys after the Second World War revealed a mountain chain running down the middle of the Atlantic, with a rift valley along its crest. In 1962 the American geologist Harry Hess proposed that new ocean floor is made at these ridges and carried away on both sides, while old floor sinks back into the mantle at deep trenches. The continents do not plow through the ocean floor; they ride along with it.

In 1963 Fred Vine and Drummond Matthews supplied the proof. The earth's magnetic field has flipped many times, and cooling lava records its direction. Ship surveys found stripes of normal and reversed magnetism in mirror image on either side of the ridge. By the late 1960s geologists had a unified theory: **plate tectonics**.

Three kinds of boundary. At a **divergent** boundary, plates pull apart and new crust forms. The Mid-Atlantic Ridge is the great example; in Iceland it rises above the sea, and you can walk the rift at Thingvellir. At a **convergent** boundary, plates push together. Where ocean floor meets a continent, the denser ocean plate sinks in subduction, making a trench offshore and volcanoes onshore: the Andes and the Cascades. Where two continents meet, neither sinks, and the crust crumples upward: India pushing into Asia built the Himalaya. At a **transform** boundary, plates slide past one another. The San Andreas Fault, where the Pacific plate grinds northwest past the North American plate, is the famous case.

Some volcanoes sit far from any boundary. The Hawaiian Islands lie over a **hot spot**, a fixed plume of heat under the moving Pacific plate, which carries each island away to the northwest as a new one forms behind it; Kauai is worn and quiet while the Big Island still erupts.

Museum words and measured rates. Today satellites measure the plates directly. GPS stations show them moving about 2 to 10 centimeters a year, roughly the rate your fingernails grow. A museum sign will add that "the Atlantic opened over 180 million years." Notice the arithmetic: 3 centimeters a year times 180 million years is about 5,400 kilometers, close to the width of the ocean. The box below explains what that number does

and does not settle. “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding” (Job 38:4, KJV).

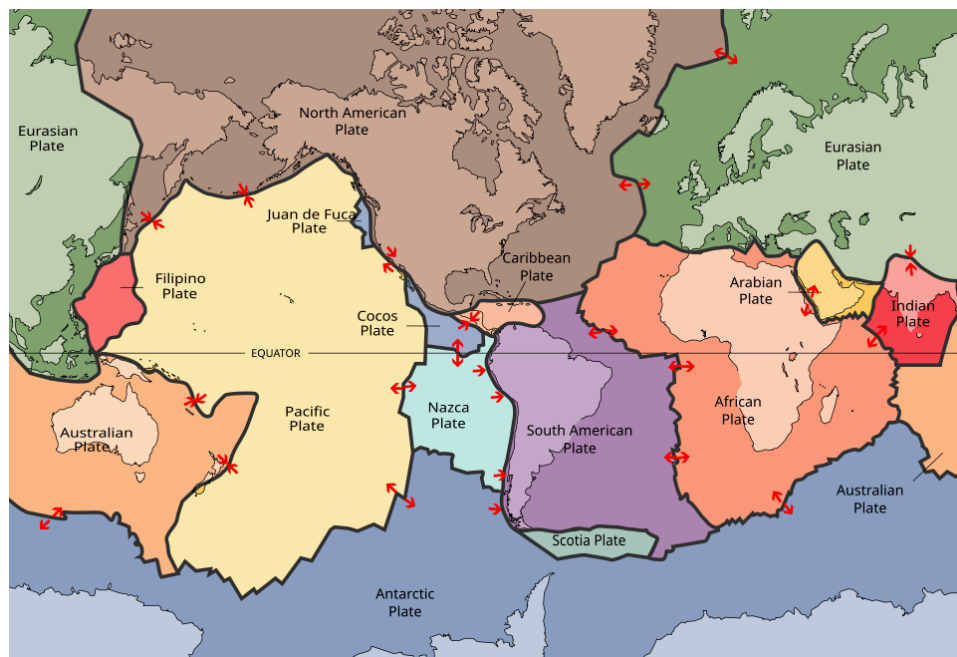
Thinking About Time

What the sign says. “The Atlantic Ocean began to open about 180 million years ago, during the Jurassic, and is still widening today.”

What we observe. GPS instruments measure plates moving about 2 to 10 centimeters a year right now. The seafloor shows symmetric magnetic stripes, youngest at the ridge and older toward the continents. The 180-million-year figure comes from dividing the ocean’s width by today’s rate, and from radiometric ages of seafloor rock, which rest on assumptions about starting amounts and constant decay.

How Christians read it. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6–9, and some Christian geologists propose that the plates moved rapidly during the Flood year, when “all the fountains of the great deep” were “broken up” (Genesis 7:11, KJV), and have slowed to a crawl since. Other Christians hold an older earth, accept the slow timescale, and read the days of Genesis 1 differently. Both groups agree on what is measured today; they differ on whether that rate was always the same.

PICTURE STUDY



Tectonic plates of the world, United States Geological Survey map, 1996,

Find the Mid-Atlantic Ridge, the trench along the west coast of South America, the Himalaya where India meets Asia, and the San Andreas Fault. Notice how the arrows show plates

spreading apart at ridges and colliding at trenches, and how the Pacific is ringed by convergent boundaries.

Look closely

Talk about it

HANDS-ON ACTIVITY: GRAHAM-CRACKER PLATES

You will need

- Graham crackers
- A tub of frosting
- A plate
- A cup of water
- A butter knife

Steps

1. Spread a thick layer of frosting on the plate; this is the soft asthenosphere.
2. Set two graham crackers side by side on it, touching.
3. Divergent: slowly push the crackers apart and watch the frosting well up between them, just as magma rises at a ridge.
4. Convergent: dip one end of each cracker in water for a few seconds so it softens, then push the two soft ends together and watch them buckle and fold upward like the Himalaya.
5. For subduction, push a dry cracker against a soft one and slide the dry one underneath.
6. Transform: set two dry crackers edge to edge and slide them past one another; listen and feel for the sticking and jerking.

Check your work

- The frosting rises where plates part, crumples where soft plates collide, and the dry crackers catch and jerk when they slide, which is exactly how earthquakes happen along the San Andreas.

PRACTICE

1. Name the four main layers of the earth from the outside in, and say which one is liquid.
2. Explain why the S-wave shadow zone tells geologists that the outer core is liquid.
3. Give three lines of evidence Wegener used for continental drift, and say why most geologists rejected his idea anyway.
4. Match each example to its boundary type: Iceland, the Andes, the Himalaya, the San Andreas Fault.
5. Calculation. A GPS station shows the Pacific plate moving 7 centimeters a year past the North American plate along the San Andreas Fault. At that rate, how many years would it take to move 1 kilometer? How far would it move in 100 years?

Exam connection. Plate tectonics is a named topic in AP Environmental Science, Unit 4, Earth Systems, where students are asked to match boundary types to landforms and hazards. ACT Science passages often give a table of plate speeds or seafloor ages and ask students to read a trend, exactly the skill in Question 5.

For families. Ask at the table: how can anyone describe a place no one has seen? Talk about the difference between measuring (GPS rates today, the shadow zone) and inferring (what the rate was long ago). The one real debate among Christians is over timescale, not over whether the plates move; speak of both views with respect. The activity is messy and edible, so cover the table.

Practice answers

1. Crust, mantle, outer core, inner core. The outer core is liquid.
2. S waves cannot travel through liquid. Seismographs more than about 104 degrees from an earthquake record no S waves, so a liquid layer must lie in the path through the deep earth, blocking them.
3. Any three: the fit of the coastlines of South America and Africa, matching fossils such as *Glossopteris* and *Mesosaurus*, matching mountain belts and rock layers across the Atlantic, and ancient glacial evidence in places now near the equator. He was rejected because he could not explain what force moved the continents through solid ocean floor.
4. Iceland, divergent. The Andes, convergent, oceanic plate under continental plate. The Himalaya, convergent, continent against continent. The San Andreas Fault, transform.
5. 1 kilometer is 100,000 centimeters; 100,000 divided by 7 is about 14,300 years. In 100 years it moves 700 centimeters, which is 7 meters, about 23 feet.

2.2 EARTHQUAKES

Video. Videos coming.

KEY VOCABULARY

epicenter

The point on the earth's surface directly above the focus, the underground spot where the fault first breaks.

moment magnitude (M_w)

The scale, used by the USGS, that measures the total energy released by an earthquake; each whole step is about 32 times the energy.

Modified Mercalli intensity

A scale from I to XII describing how strong the shaking felt and what it damaged at a particular place.

CORE IDEAS

Why the ground breaks. Rock is stiff, but not perfectly rigid. Push on it long enough and it bends a little, storing energy like a drawn bow. When the strain grows greater than the rock can hold, it snaps along a **fault** and the two sides spring back unbent. That snap is the earthquake. The American geologist Harry Fielding Reid worked this out in 1910 from fences and roads bent and then broken by the 1906 San Francisco earthquake, and called it **elastic rebound**.

Faults come in three kinds. In a normal fault the crust is pulled apart and one block slides down the break. In a reverse fault, called a thrust fault when the break is gently tilted, the crust is squeezed and one block rides up over the other. In a strike-slip fault the blocks slide past each other sideways, like the San Andreas. The spot underground where the rock first breaks is the **focus**; the point on the surface directly above it is the **epicenter**.

Waves and the instrument that catches them. An earthquake sends out three families of waves. P waves travel fastest, about 6 kilometers a second in the crust, pushing and pulling the ground along the direction of travel. S waves come next, about 3.5 kilometers a second, shaking the ground from side to side. Surface waves arrive last, rolling along the top, and do most of the damage to buildings.

A **seismograph** records the shaking. The old kind hung a heavy weight on a spring with a pen attached; when the ground shook, the frame moved while the weight, by inertia, stayed nearly still, and the pen drew a wiggling line on a turning drum.

Finding the epicenter. Because P waves outrun S waves, the gap between their arrivals grows with distance, like two runners of different speeds pulling apart. For nearby earthquakes a simple rule works: each second of P-to-S lag means roughly 8 kilometers.

Here is why: a P wave takes $\frac{1}{6}$ of a second to cross a kilometer and an S wave takes $\frac{1}{3.5}$, a difference of about 0.12 seconds per kilometer, and 1 divided by 0.12 is about 8.

Worked example. Station A records the S wave 10 seconds after the P wave, so the quake is about 80 kilometers away. Station B has a 20-second lag, about 160 kilometers; Station C, 30 seconds, about 240 kilometers. One station alone gives only a distance, a circle on the map. Draw A's circle with a compass, then B's; they cross at two points. C's circle picks the right one. Three circles, one epicenter.

How big? Magnitude and intensity. Two numbers describe an earthquake. **Magnitude** measures the energy released at the source, one number per quake. The USGS now uses the moment magnitude scale, M_w , in place of the older Richter scale. Each whole step up means about 10 times the ground motion on a seismogram and about 32 times the energy. So a magnitude 7 releases about 32 times the energy of a 6 and about 1,000 times that of a 5.

Intensity measures the shaking felt at a particular place. The Modified Mercalli scale runs from I, not felt, through VI, felt by everyone with some plaster cracked, to XII, total destruction. One earthquake has one magnitude but many intensities, strongest near the epicenter and fading with distance.

Earthquakes that changed history. On November 1, 1755, All Saints' Day, the churches of Lisbon, Portugal, were full when the ground heaved at about 9:40 in the morning. The quake, estimated at magnitude 8.5 or greater, threw down the city; a tsunami swept into the harbor, and fires burned for days. Estimates of the dead range from ten thousand to several times that.

Between December 16, 1811 and February 7, 1812, three great shocks, each estimated near magnitude 7 to 7.5, struck near New Madrid, Missouri. The Mississippi reportedly ran backward for a time, Reelfoot Lake in Tennessee was born, and church bells reportedly rang as far away as Boston, though that story is often repeated and poorly documented.

At 5:12 in the morning on April 18, 1906, the San Andreas Fault broke along nearly 300 miles. The quake is estimated at magnitude 7.9; fires then burned for three days, and about 3,000 people died. On Good Friday, March 27, 1964, a magnitude 9.2 earthquake under Prince William Sound shook Alaska for over four minutes, the strongest ever recorded in North America; tsunamis killed most of its 131 victims, some in Oregon and California. The largest earthquake ever measured, magnitude 9.5, struck Chile on May 22, 1960, and its tsunami crossed the Pacific to Hawaii and Japan.

Tsunamis and safe buildings. When the seafloor jumps, it shoves the whole column of water above it, and a **tsunami** races outward at the speed of a jet airliner. In the open ocean it is a low swell a ship may not notice; near shore it slows, piles up, and arrives as a wall of water. If the sea suddenly draws back, run for high ground.

Earthquakes rarely kill people; collapsing buildings do. Engineers now build steel frames that flex, brace walls in both directions, set buildings on bearings that let the ground move underneath, and bolt heavy things down. The psalmist, who knew the ground could move,

wrote, “God is our refuge and strength, a very present help in trouble. Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea” (Psalm 46:1-2, KJV).

PICTURE STUDY



Looking Down Sacramento Street, San Francisco, April 18, 1906, Arnold Genthe, 1906,

Genthe took this photograph on the morning of the earthquake, with a borrowed camera. Look at the people standing in the street watching the smoke rise from downtown, the cable-car tracks running down the hill, and the fallen brick on the right. Notice that most of the houses are still standing; the fire that followed did more damage than the shaking.

Look closely

Talk about it

Safety first. Dry spaghetti snaps into sharp pieces, so keep it away from eyes and sweep up afterward.

HANDS-ON ACTIVITY: SHAKE TABLE AND SPAGHETTI TOWERS

You will need

- A shallow box lid or baking sheet
- Four or five marbles
- A second lid or tray
- Two large rubber bands
- Dry spaghetti
- Mini marshmallows
- A ruler

- A stopwatch

Steps

1. Set the marbles on the lower tray and rest the upper lid on them so it rolls freely; loop the rubber bands around both trays to hold the upper lid loosely centered.
2. This is your shake table.
3. Build two towers of spaghetti and marshmallows, each 30 centimeters tall, one with plain upright legs and one braced with diagonal pieces.
4. Set one at a time on the table and shake the top lid side to side with a steady rhythm, counting seconds until the tower falls or leans.
5. Then try a wider base, a lighter top, or a tower taped to the lid.

Check your work

- Diagonal bracing and a wide base matter more than extra height, and a heavy top makes a tower fail faster, just as engineers find in real buildings.

PRACTICE

1. What is elastic rebound, and who worked it out from which earthquake?
2. What is the difference between magnitude and intensity? Which one can have many values for a single earthquake?
3. Data reading. Three stations record the following P-to-S lag times: Station X, 15 seconds; Station Y, 25 seconds; Station Z, 40 seconds. Using the rule of about 8 kilometers per second of lag, how far is the epicenter from each station? Why do you need all three?
4. Calculation. About how many times more energy does a magnitude 8 earthquake release than a magnitude 6?
5. Explain why the 1964 Alaska earthquake killed more people by water than by shaking.

Exam connection. ACT Science regularly uses seismic travel-time tables or P-and-S graphs and asks students to find a distance or compare stations, the skill in Question 3. SAT Math includes exponential comparisons like Question 4. AP Environmental Science lists earthquakes and tsunamis under geologic hazards in Unit 4.

For families. Ask whether your family has an earthquake plan and where you would meet. Scholars still debate the exact magnitudes of the New Madrid and Lisbon quakes, since no instruments existed; the numbers come from reports of damage and felt area. The shake table is safe and loud; younger siblings will want turns.

Practice answers

1. Rock bends under strain, stores energy, and then snaps along a fault and springs back to its unbent shape, releasing the energy as an earthquake. Harry Fielding Reid described it in 1910 from the 1906 San Francisco earthquake.

2. Magnitude measures energy released at the source and is one number per quake. Intensity measures the shaking felt at a particular place and is different from place to place, so one quake has many intensities.
3. X, about 120 kilometers; Y, about 200 kilometers; Z, about 320 kilometers. One station gives only a circle of possible locations, two circles cross at two points, and the third circle shows which crossing is the real epicenter.
4. Two whole steps, so about 32 times 32, which is roughly 1,000 times the energy.
5. The quake occurred under Prince William Sound and shifted the seafloor, sending tsunamis along the coast and across the Pacific. Most of the 131 deaths came from these waves, including some in Oregon and California, while the shaking struck a thinly settled region.

2.3 VOLCANOES

Video. Videos coming.

KEY VOCABULARY

viscosity

The resistance of a fluid to flowing; in magma it rises with silica content and decides whether an eruption oozes or explodes.

pyroclastic flow

A fast, ground-hugging avalanche of hot gas, ash, and rock fragments, the deadliest product of an explosive eruption.

lahar

A volcanic mudflow of ash and water that races down river valleys, often triggered by melted snow or heavy rain.

CORE IDEAS

What makes a volcano gentle or deadly. A volcano is a vent where molten rock, called **magma** underground and lava in the open air, reaches the surface. Whether it oozes or explodes depends mostly on silica and gas. Silica, the stuff of quartz, links into chains inside molten rock and stiffens it. Basalt magma, about 50 percent silica, runs like warm syrup; rhyolite magma, about 70 percent, is as stiff as cold tar. The stiffness of a fluid is its **viscosity**. Gas, mostly water vapor and carbon dioxide, is the other ingredient. In runny magma, bubbles escape easily and the lava flows out. In stiff magma, gas stays trapped under pressure until the whole mass shatters, like a shaken soda bottle opened too fast.

Three shapes of mountain. A shield volcano is built of thin, runny basalt flows that spread far before cooling, a broad, gentle dome like a shield laid face up. Mauna Loa in Hawaii is the greatest: about 4,170 meters above the sea and about 9,000 above the seafloor. A composite volcano, or stratovolcano, is the classic cone, built of alternating layers of stiff lava and ash. Mount Rainier in Washington, 4,392 meters, and Mount Fuji in Japan, 3,776 meters, are composite volcanoes. A cinder cone is a small, steep hill of loose fragments thrown out of a single vent. On February 20, 1943, a Mexican farmer named Dionisio Pulido watched a crack open in his cornfield and begin to smoke. Within a week Paricutin was over 100 meters tall; by the time it fell quiet in 1952 it stood about 424 meters and had buried two villages, leaving only a church tower above the lava.

What comes out. Lava is the least of it. Volcanoes also throw out **ash**, fine shattered rock that can circle the globe; pumice, rock so frothy it floats; and bombs, blobs of lava that harden in flight. Deadliest is the pyroclastic flow, a ground-hugging avalanche of hot gas and ash moving at over 100 miles an hour at several hundred degrees. Lahars are mudflows of ash and water from melted snow, crater lakes, or rain; they follow river valleys for tens of miles and bury whatever lies in them.

Three famous eruptions. In AD 79 Mount Vesuvius buried the Roman towns of Pompeii and Herculaneum. Pliny the Younger, then seventeen, watched from across the bay and years later wrote two letters to the historian Tacitus describing it. In paraphrase: a cloud rose from the mountain shaped like a tall pine tree, with a trunk and spreading branches; his uncle, the naturalist Pliny the Elder, sailed toward the eruption to study it and rescue friends, and died on the shore at Stabiae. The eruption is traditionally dated August 24, though some recent evidence points to autumn.

On August 26 and 27, 1883, the island volcano Krakatoa, between Java and Sumatra, blew itself apart. The explosion was heard about 3,000 miles away, tsunamis as high as 100 feet killed about 36,000 people on nearby coasts, and ash in the upper air gave the world vivid red sunsets for months.

Mount St. Helens, May 18, 1980. The third eruption was watched by scientists with instruments, so it deserves detail. Mount St. Helens in Washington began stirring in March 1980, and over seven weeks its north face swelled into a bulge that grew about five feet a day. At 8:32 on Sunday morning, May 18, a magnitude 5.1 earthquake shook the bulge loose. The north side of the mountain slid away in the largest landslide in recorded history, and the magma inside, suddenly uncorked, burst sideways in a **lateral blast** that flattened forest across about 230 square miles. USGS geologist David Johnston, watching from a ridge six miles north, keyed his radio and called, "Vancouver! Vancouver! This is it!" He was never found. Fifty-seven people died. A column of ash rose fifteen miles in fifteen minutes, and the mountain lost about 1,300 feet of its height.

What followed matters as much. Within hours, the avalanche, pyroclastic flows, and mudflows had laid down deposits hundreds of feet thick in places, up to about 600 feet in the North Fork Toutle River valley, some of them finely layered, thin bed upon thin bed, each laid in moments by a passing surge. Then on March 19, 1982, a small eruption melted snow in the crater, and the mudflow that followed cut through the 1980 deposits, carving a canyon system up to about 100 feet deep in a single day. Some writers have nicknamed it the "Little Grand Canyon of the Toutle River." The blast had also swept Spirit Lake with a wave hundreds of feet high and left a mat of thousands of uprooted trees floating on it; over the years many sank upright, trunks standing on the lake floor, where they are slowly being buried.

A ring, a caldera, and the watchers. Most of the world's volcanoes stand along the edges of the Pacific plate, the **Ring of Fire**, where ocean floor sinks and melts beneath continents and island arcs. Yellowstone is different: a hot spot under North America that has blown out enormous calderas, collapsed basins where a mountain once stood. The present caldera is about 45 by 30 miles, and a museum sign dates its last great eruption to "640,000 years ago." Today the USGS runs volcano observatories in Hawaii, the Cascades, Alaska, Yellowstone, and California, measuring earthquakes, ground swelling, and gas, and issuing warnings. "He looketh on the earth, and it trembleth: he toucheth the hills, and they smoke" (Psalm 104:32, KJV).

Thinking About Time

What the sign says. Signs at Mount St. Helens explain that thick, layered deposits and deep canyons normally take thousands of years to form, and that Yellowstone's last caldera eruption was "640,000 years ago."

What we observe. At Mount St. Helens, deposits hundreds of feet thick, some finely layered, were laid down in hours on May 18, 1980, and a canyon system up to about 100 feet deep was cut through them in one day on March 19, 1982. These rates were measured by people who were there. Whether the earth's older layers and canyons formed quickly or slowly is an inference, not an observation; no one watched them form.

How Christians read it. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6-9, and point to Mount St. Helens as proof that layering and canyon cutting do not require long ages, only enough water and energy. Other Christians hold an older earth, agree that catastrophes can work fast, and hold that most of the record still reflects slow processes over long ages, reading the days of Genesis 1 differently. Both sides agree about what happened at Mount St. Helens; the debate is over how much of the rest of the earth it explains.

PICTURE STUDY



Mount St. Helens eruption, May 18, 1980, Austin Post, USGS, 1980,

Austin Post, a USGS glaciologist and aerial photographer, took this from an airplane the afternoon of the eruption. Look at the vast column of ash boiling up from the open crater, the gray plain where the north face of the mountain used to be, and the dark lines of flattened timber on the ridges.

Look closely

Talk about it

Safety first. Vinegar is the only acid used; wipe up spills so no one slips.

HANDS-ON ACTIVITY: VISCOSITY RACE

You will need

- A cookie sheet
- Three books
- Honey
- Pancake syrup
- Water
- Three spoons
- A stopwatch
- A ruler
- Masking tape

Steps

1. Prop one end of the cookie sheet on the books to tilt it, and mark a start line and a finish line 20 centimeters apart with tape.
2. At the same moment, spoon equal amounts of honey, syrup, and water onto the start line and time each to the finish.
3. Record the times in a table.
4. Then warm the honey jar in a bowl of hot tap water for five minutes and race again.

Check your work

- Honey is the stiff, high-silica rhyolite; syrup is the andesite of a composite volcano; water is runny basalt like Mauna Loa. Warming the honey lowers its viscosity just as hotter magma flows more easily. If you want a cinder cone, pile damp sand around a film canister or small cup, add two spoons of baking soda, pour in vinegar, and watch the “eruption.” Label it honestly: it is a gas-pressure demonstration, not the chemistry of real magma.

PRACTICE

1. Why does magma with more silica tend to erupt explosively?
2. Match each volcano to its type: Mauna Loa, Mount Rainier, Parícutin. Describe the shape of each type.
3. What did David Johnston say on the radio on May 18, 1980, and what did the lateral blast do to the forest?
4. Explain, using the dates, why Mount St. Helens matters to the debate about how fast geology can work.

5. Calculation. Paricutin grew from a crack to about 424 meters in roughly nine years. Mount St. Helens lost about 1,300 feet, about 400 meters, of height in a few minutes. If Paricutin had grown at a steady rate, about how many meters a year did it add, and how does that compare with Mount St. Helens?

Exam connection. AP Environmental Science Unit 4 covers volcanoes as a geologic hazard and the Ring of Fire as a consequence of subduction. ACT Science passages often give a table of silica content against eruption type or lava speed and ask students to find the pattern, as in the viscosity race.

For families. Talk about the people in these stories: Pliny the Elder sailing toward the danger, David Johnston staying at his post. Scholars still debate the exact date of the AD 79 eruption and the death toll at Krakatoa, and the depth figures for the Toutle River canyons vary between sources. Before the activity, know that honey on a cookie sheet is a sticky cleanup; hot water for warming the jar should be tap-hot, not boiling.

Practice answers

1. Silica makes magma stiff, or viscous, so gas bubbles cannot escape easily. Pressure builds until the magma shatters, throwing out ash and fragments instead of flowing out as lava.
2. Mauna Loa, shield volcano, broad and gentle. Mount Rainier, composite volcano, a tall layered cone. Paricutin, cinder cone, a small steep hill of loose fragments.
3. "Vancouver! Vancouver! This is it!" The blast flattened forest across about 230 square miles north of the mountain.
4. On May 18, 1980, deposits hundreds of feet thick, some finely layered, were laid down in hours. On March 19, 1982, a mudflow cut a canyon system up to about 100 feet deep through them in one day. Both were watched and measured, showing that thick layers and canyons can form quickly when enough energy and water are present.
5. About 424 divided by 9, roughly 47 meters a year, with most of the growth in the first year. Mount St. Helens lost about the same height in minutes that Paricutin gained in nine years, which shows that volcanoes can change faster than almost anything else on earth.

2.4 MOUNTAINS AND THE SHAPE OF THE LAND

Video. Videos coming.

KEY VOCABULARY

anticline

An upward arch of folded rock layers, with the oldest layers in the center; a syncline is the matching downward trough.

batholith

A huge body of granite that cooled slowly underground from magma and was later exposed by uplift and erosion, as in the Sierra Nevada.

isostasy

The floating balance of the crust on the denser mantle, by which mountains have deep roots like icebergs and rise as they erode.

CORE IDEAS

Bent rock. Stand in a road cut in Pennsylvania or the Appalachian valleys of Virginia and you may see rock layers that were once flat now arched like the roof of a barn or sagging like a hammock. Rock that is squeezed slowly, deep in the crust where it is warm and under pressure, bends rather than breaks. An upward arch is an **anticline**; a downward trough is a **syncline**. Put your hands flat on a tablecloth and slide them together, and you will make a row of them. Where the squeezing is intense, folds lie over on their sides or are pushed one on top of another along thrust faults, and the result is a long chain of parallel ridges and valleys, the Valley and Ridge of the Appalachians.

Broken rock. Nearer the surface, cold rock breaks instead of bending. When the crust is stretched, it cracks into blocks along normal faults, and the blocks tilt and drop, leaving the high edges standing as mountains and the dropped blocks as basins. Nevada and western Utah are made of this: the **Basin and Range**, with dozens of north-south ranges separated by dry basins, like a set of books tilted on a shelf. The Teton Range in Wyoming is the most dramatic fault-block range in America. On its east side the Teton fault drops the valley of Jackson Hole while the range rises, so Grand Teton, 13,775 feet, stands straight up out of the flat floor with no foothills at all.

Volcanic and dome mountains. Some mountains are simply volcanoes: Rainier, Shasta, Hood, and the whole Cascade chain are built of lava and ash, one eruption on another. Dome mountains form another way. Magma pushes up from below without breaking through, lifting the overlying layers into a blister. Erosion then strips the top, leaving a core of old crystalline rock surrounded by rings of upturned sedimentary layers, oldest in the middle. The Black Hills of South Dakota, where Mount Rushmore is carved into the granite core, are the classic dome.

Three American ranges. The Appalachians run from Alabama to Newfoundland and are old, worn, and rounded. Their highest point, Mount Mitchell in North Carolina, is 6,684 feet, and their folded layers tell of a great collision. A museum sign will say they rose “about 300 million years ago, when Africa collided with North America to form Pangaea.” The Rockies are higher and sharper; Mount Elbert in Colorado reaches 14,440 feet, and the signs give the uplift as “about 80 to 55 million years ago.” The Sierra Nevada of California is different again: a single huge block of granite, a **batholith**, that cooled slowly underground from many bodies of magma and was later tilted up along faults on its east side, so the range rises gently from the west and drops like a wall to the east. Mount Whitney, 14,505 feet, is the highest peak in the lower forty-eight states. Yosemite Valley, with Half Dome and El Capitan, was cut into this granite by rivers and then widened and polished by glaciers.

Why mountains float. Why do mountains stand so high and not sink? The answer is **isostasy**. The crust floats on the denser mantle the way an iceberg floats on the sea. An iceberg shows only about a tenth of itself above water; the rest is a deep root below. Mountains likewise have deep roots of light crust that reach far down into the mantle, which is why the crust is up to 70 kilometers thick under the Himalaya. As erosion wears a range down, its root rises to compensate, like an iceberg rising as it melts, so a mountain range is slow to disappear. The idea was proposed in the 1850s after surveyors in India found that the Himalaya pulled a plumb line sideways less than their bulk predicted.

How mountains are read. How do geologists know which range is older? They cannot watch mountains grow, but they can observe three things. First, the layers: folded and faulted strata tell that the rock was squeezed. Second, the cut: valleys, canyons, and worn-down summits show how much has been removed. Third, the comparison: the Appalachians are lower, rounder, and more deeply eroded than the Rockies, which in turn are more worn than the still-rising Himalaya. From these observations, geologists infer an order: Appalachians first, Rockies later, Himalaya latest. The order is agreed by nearly everyone. The absolute ages on the signs are a separate inference, and the box below takes it up.

Mountains in Scripture. The Bible speaks of mountains as the plainest proof of God’s strength. “In his hand are the deep places of the earth: the strength of the hills is his also. The sea is his, and he made it: and his hands formed the dry land” (Psalm 95:4–5, KJV). Isaiah pictures the Creator as a surveyor who “weighed the mountains in scales, and the hills in a balance” (Isaiah 40:12, KJV). And Psalm 104 describes the waters that once “stood above the mountains” fleeing at God’s rebuke: “They go up by the mountains; they go down by the valleys unto the place which thou hast founded for them” (Psalm 104:6, 8, KJV). Many readers have taken that verse to describe mountains rising and valleys sinking as the Flood waters drained; others read it as poetry about the water itself. Either way, the mountains are his.

Thinking About Time

What the sign says. “The Appalachians formed about 300 million years ago and were once as tall as the Alps; the Rockies rose about 80 to 55 million years ago; the Sierra

Nevada granite cooled about 100 million years ago.”

What we observe. Folded, faulted, and eroded strata. The Appalachians are lower, rounder, and more deeply cut than the Rockies, and the Rockies more than the Himalaya, which GPS shows still rising a few millimeters a year. From degree of erosion geologists infer a relative order, old to young. The million-year figures come from radiometric dating of the rocks and from assuming erosion rates measured today held in the past.

How Christians read it. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6–9. Some Christian geologists place the main uplift of the mountains late in the Flood year, as the waters drained, and cite Psalm 104:8, “They go up by the mountains; they go down by the valleys.” Other Christians hold an older earth, accept the long timescale for the ranges, and read the days of Genesis 1 differently. The relative order, Appalachians before Rockies before Himalaya, is agreed by all; the absolute ages are where the readings differ.

PICTURE STUDY



The Tetons and the Snake River, Ansel Adams, 1942,

Adams took this for the National Park Service during a government project to photograph the parks. Look at how the Tetons rise straight out of the flat valley floor with no foothills: that sharp front is the line of the Teton fault. Follow the Snake River’s curves across the dropped block of Jackson Hole, and notice the storm light that Adams waited for.

Look closely

Talk about it

Safety first. A butter knife only, and cut away from your hand.

HANDS-ON ACTIVITY: FOLDING LAYERS AND MEASURING A HILL

Materials. Three or four colors of modeling clay or a stack of folded bath towels, two heavy books, a protractor, a drinking straw, a piece of string, a washer or nut, tape.

Steps for folding. Flatten each color of clay into a thin sheet and stack them, or lay towels in a stack. Set a book at each end and push the books slowly together. Watch the layers rise into an anticline and sag into a syncline; push harder to make the folds lean over. Cut the fold across with a butter knife and look at the layers end-on, the way a road cut shows them.

Steps for the clinometer. Tape the straw along the straight edge of the protractor, tie the string through the center hole, and hang the washer from it. Sight through the straw at the top of a nearby hill; where the string crosses the scale is the angle. Measure your distance to the base of the hill by pacing. The hill's height above your eye is the distance times the tangent of the angle, which any calculator gives.

What to notice. The first folds are gentle; keep pushing and they tighten and lean, as in the Appalachians.

You will need

Steps

PRACTICE

1. What is the difference between an anticline and a syncline, and in which kind of mountain range are they common?
2. How did the Teton Range form, and why does it have no foothills on its east side?
3. Explain the iceberg analogy for isostasy, and say why a mountain range is slow to wear away.
4. Data reading. The table gives the highest peak of three ranges: Appalachians, Mount Mitchell, 6,684 feet; Rockies, Mount Elbert, 14,440 feet; Sierra Nevada, Mount Whitney, 14,505 feet. By how many feet does Mount Elbert exceed Mount Mitchell? Which is higher, Whitney or Elbert, and by how much? Does height alone prove which range is oldest?
5. In the mountain story, what do all geologists agree on, and where do Christian readings differ?

Exam connection. AP Environmental Science Unit 4 asks students to connect plate boundaries to mountain building and to read cross-sections of folded and faulted strata. ACT Science and SAT Math use elevation tables and simple trigonometry of the sort in Question 4 and the clinometer activity. The CLT's science readings sometimes draw on classic geological writing about landforms.

For families. Ask which of the three American ranges your family has seen, and what shape it had. Scholars agree on the relative order of the ranges but give the Appalachians' museum age in several stages, so you will see different numbers on

different signs. Before the clinometer activity, practice sighting a rooftop first; a steady arm and a patient helper make the angle much easier to read.

Practice answers

1. An anticline is an upward arch of folded layers; a syncline is a downward trough. They are common in folded ranges such as the Valley and Ridge of the Appalachians.
2. It is a fault-block range. Along the Teton fault, the range block rose while the valley block, Jackson Hole, dropped, so the mountains stand directly above the flat valley floor.
3. The crust floats on the denser mantle as an iceberg floats on the sea, with most of its bulk below as a root. As erosion removes rock from the top, the root rises to keep the balance, so the range stays high for a long time.
4. Elbert exceeds Mitchell by 7,756 feet. Whitney is higher than Elbert by 65 feet. Height alone does not prove age; geologists also look at how rounded and eroded the range is and how its layers are folded and faulted.
5. Nearly all agree on the relative order, Appalachians before Rockies before Himalaya, from the degree of erosion and the folded and faulted layers. Christian readings differ on absolute ages: some place mountain uplift late in the Flood year, citing Psalm 104:8, and others accept the long timescale.

UNIT 2 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) Name the four main layers of the earth from the outside in, and say which one is liquid.
2. (5 pts) Explain why the S-wave shadow zone tells geologists that the outer core is liquid.
3. (5 pts) Give three lines of evidence Wegener used for continental drift, and say why most geologists rejected his idea anyway.
4. (5 pts) Match each example to its boundary type: Iceland, the Andes, the Himalaya, the San Andreas Fault.
5. (5 pts) Calculation. A GPS station shows the Pacific plate moving 7 centimeters a year past the North American plate along the San Andreas Fault. At that rate, how many years would it take to move 1 kilometer? How far would it move in 100 years?
6. (5 pts) What is elastic rebound, and who worked it out from which earthquake?
7. (5 pts) What is the difference between magnitude and intensity? Which one can have many values for a single earthquake?
8. (5 pts) Data reading. Three stations record the following P-to-S lag times: Station X, 15 seconds; Station Y, 25 seconds; Station Z, 40 seconds. Using the rule of about 8 kilometers per second of lag, how far is the epicenter from each station? Why do you need all three?
9. (5 pts) Calculation. About how many times more energy does a magnitude 8 earthquake release than a magnitude 6?
10. (5 pts) Explain why the 1964 Alaska earthquake killed more people by water than by shaking.
11. (5 pts) Why does magma with more silica tend to erupt explosively?
12. (5 pts) Match each volcano to its type: Mauna Loa, Mount Rainier, Paricutin. Describe the shape of each type.
13. (5 pts) What did David Johnston say on the radio on May 18, 1980, and what did the lateral blast do to the forest?
14. (5 pts) Explain, using the dates, why Mount St. Helens matters to the debate about how fast geology can work.
15. (5 pts) Calculation. Paricutin grew from a crack to about 424 meters in roughly nine years. Mount St. Helens lost about 1,300 feet, about 400 meters, of height in a few minutes. If Paricutin had grown at a steady rate, about how many meters a year did it add, and how does that compare with Mount St. Helens?
16. (5 pts) What is the difference between an anticline and a syncline, and in which kind of mountain range are they common?
17. (5 pts) How did the Teton Range form, and why does it have no foothills on its east side?
18. (5 pts) Explain the iceberg analogy for isostasy, and say why a mountain range is slow to wear away.

19. (5 pts) Data reading. The table gives the highest peak of three ranges: Appalachians, Mount Mitchell, 6,684 feet; Rockies, Mount Elbert, 14,440 feet; Sierra Nevada, Mount Whitney, 14,505 feet. By how many feet does Mount Elbert exceed Mount Mitchell? Which is higher, Whitney or Elbert, and by how much? Does height alone prove which range is oldest?
20. (5 pts) In the mountain story, what do all geologists agree on, and where do Christian readings differ?

Answer key

1. Crust, mantle, outer core, inner core. The outer core is liquid.
2. S waves cannot travel through liquid. Seismographs more than about 104 degrees from an earthquake record no S waves, so a liquid layer must lie in the path through the deep earth, blocking them.
3. Any three: the fit of the coastlines of South America and Africa, matching fossils such as *Glossopteris* and *Mesosaurus*, matching mountain belts and rock layers across the Atlantic, and ancient glacial evidence in places now near the equator. He was rejected because he could not explain what force moved the continents through solid ocean floor.
4. Iceland, divergent. The Andes, convergent, oceanic plate under continental plate. The Himalaya, convergent, continent against continent. The San Andreas Fault, transform.
5. 1 kilometer is 100,000 centimeters; 100,000 divided by 7 is about 14,300 years. In 100 years it moves 700 centimeters, which is 7 meters, about 23 feet.
6. Rock bends under strain, stores energy, and then snaps along a fault and springs back to its unbent shape, releasing the energy as an earthquake. Harry Fielding Reid described it in 1910 from the 1906 San Francisco earthquake.
7. Magnitude measures energy released at the source and is one number per quake. Intensity measures the shaking felt at a particular place and is different from place to place, so one quake has many intensities.
8. X, about 120 kilometers; Y, about 200 kilometers; Z, about 320 kilometers. One station gives only a circle of possible locations, two circles cross at two points, and the third circle shows which crossing is the real epicenter.
9. Two whole steps, so about 32 times 32, which is roughly 1,000 times the energy.
10. The quake occurred under Prince William Sound and shifted the seafloor, sending tsunamis along the coast and across the Pacific. Most of the 131 deaths came from these waves, including some in Oregon and California, while the shaking struck a thinly settled region.
11. Silica makes magma stiff, or viscous, so gas bubbles cannot escape easily. Pressure builds until the magma shatters, throwing out ash and fragments instead of flowing out as lava.
12. Mauna Loa, shield volcano, broad and gentle. Mount Rainier, composite volcano, a tall layered cone. Paricutin, cinder cone, a small steep hill of loose fragments.
13. "Vancouver! Vancouver! This is it!" The blast flattened forest across about 230 square miles north of the mountain.
14. On May 18, 1980, deposits hundreds of feet thick, some finely layered, were laid down in hours. On March 19, 1982, a mudflow cut a canyon system up to about 100 feet deep through them in one day. Both were watched and measured, showing that thick layers and canyons can form quickly when enough energy and water are present.
15. About 424 divided by 9, roughly 47 meters a year, with most of the growth in the first year. Mount St. Helens lost about the same height in minutes that Paricutin gained in nine years,

which shows that volcanoes can change faster than almost anything else on earth.

16. An anticline is an upward arch of folded layers; a syncline is a downward trough. They are common in folded ranges such as the Valley and Ridge of the Appalachians.
17. It is a fault-block range. Along the Teton fault, the range block rose while the valley block, Jackson Hole, dropped, so the mountains stand directly above the flat valley floor.
18. The crust floats on the denser mantle as an iceberg floats on the sea, with most of its bulk below as a root. As erosion removes rock from the top, the root rises to keep the balance, so the range stays high for a long time.
19. Elbert exceeds Mitchell by 7,756 feet. Whitney is higher than Elbert by 65 feet. Height alone does not prove age; geologists also look at how rounded and eroded the range is and how its layers are folded and faulted.
20. Nearly all agree on the relative order, Appalachians before Rockies before Himalaya, from the degree of erosion and the folded and faulted layers. Christian readings differ on absolute ages: some place mountain uplift late in the Flood year, citing Psalm 104:8, and others accept the long timescale.

WEATHERING, EROSION, RIVERS, AND GLACIERS

In Unit 2 you learned how rock is made. In this unit you will learn how rock is unmade, and how the pieces are carried away and laid down somewhere else. Water, ice, and wind do nearly all of this work, and every landscape you have ever seen, from a cornfield in Iowa to the cliffs of Yosemite, is their handiwork. Scripture speaks of these same agents plainly: “The waters wear the stones” (Job 14:19, KJV). Four lessons follow: weathering and soil, rivers, glaciers, and the deserts and coasts where wind and waves rule.

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 3.1, Weathering and Soil, and define weathering, hydrolysis, soil horizon.
- I can explain the main ideas of Lesson 3.2, Rivers and Streams, and define drainage basin, competence, base level.
- I can explain the main ideas of Lesson 3.3, Glaciers, and define firn, striations, till.
- I can explain the main ideas of Lesson 3.4, Deserts, Wind, and Coasts, and define deflation, loess, longshore drift.

3.1 WEATHERING AND SOIL

Video. Videos coming.

KEY VOCABULARY

weathering

The breakdown of rock at or near the surface, either mechanically, into smaller pieces of the same material, or chemically, into new minerals.

hydrolysis

A chemical reaction between water and a mineral such as feldspar that produces clay.

soil horizon

A distinct layer in a soil profile, named O, A, E, B, C, or R from the surface downward.

CORE IDEAS

No rock at the surface of the earth lasts unchanged. Granite that formed deep underground is cool, wet, and exposed to air once it reaches the surface, and it begins to come apart. Geologists call this breakdown **weathering**. Weathering happens in place; when the broken pieces are carried away by water, ice, or wind, that is **erosion**. Job describes both in one breath: “And surely the mountain falling cometh to nought, and the rock is removed out of his place. The waters wear the stones: thou wastest away the things which grow out of the dust of the earth” (Job 14:18-19, KJV).

Mechanical weathering. Mechanical weathering breaks rock into smaller pieces without changing what the rock is made of.

Frost wedging is the most powerful kind in cold climates. Water seeps into a crack, freezes, and expands by about nine percent. The ice pushes the crack walls apart. The next day it melts, water seeps deeper, and the cycle repeats. Over many winters the rock splits; the talus piles at the foot of mountain cliffs are mostly frost work.

Exfoliation happens when a large body of rock that formed under great pressure is uncovered. Freed from the weight above it, the rock expands slightly and cracks in sheets parallel to its surface, like the layers of an onion. Half Dome in Yosemite and Stone Mountain in Georgia show this.

Root wedging is a tree doing what ice does, more slowly. Roots grow into cracks and widen them as they thicken.

Salt crystal growth works in deserts and along seacoasts. Salty water soaks into pores, dries, and leaves crystals that grow and pry grains loose.

Abrasion is rock grinding rock. Sand carried by wind sandblasts the base of a cliff; cobbles in a stream knock against each other until they are round.

Chemical weathering. Chemical weathering changes the minerals themselves into new substances. It needs water, and it goes fastest where it is warm and wet.

Dissolution. Rain picks up carbon dioxide from the air and from soil, and becomes a weak acid, carbonic acid. Limestone, which is calcium carbonate, dissolves slowly in it. This is how Mammoth Cave in Kentucky was hollowed out, how sinkholes open in Florida, and why the lettering on old marble gravestones grows faint while granite stones nearby stay sharp.

Oxidation. Iron in minerals combines with oxygen and water to make rust. The red soil of Georgia and the red cliffs of Sedona are iron oxide.

Hydrolysis. Water reacts with feldspar, the most common mineral in granite, and turns it into soft clay. The quartz grains are left behind as sand. This is why granite in a wet climate crumbles into gritty soil.

What controls the rate. Two things matter most: climate and rock type. Warm, wet places speed chemical weathering; cold places with many freeze-and-thaw days speed frost wedging; dry deserts are slow at both. Quartz resists nearly everything. Limestone dissolves in Kentucky but stands up as the rim of the Grand Canyon, because Arizona is dry. Surface area matters too: a rock cut by many cracks weathers faster than a solid block.

Soil. Soil is weathered rock mixed with decayed plants and animals, water, and air. The rock it comes from is the **parent material**. A pit in a field shows layers, called **horizons**, named with letters.

- **O horizon:** leaf litter and other organic matter at the top.
- **A horizon:** topsoil, dark with **humus**, the decayed organic matter that holds water and feeds plants.
- **E horizon:** a pale layer from which clay and iron have been washed downward.
- **B horizon:** subsoil, where that clay and iron collect; often reddish or sticky.
- **C horizon:** partly weathered parent material.
- **R horizon:** solid bedrock.

Soil is also described by its **texture**, the mix of three grain sizes. Sand grains are 2 to 0.05 millimeters; silt is 0.05 to 0.002 millimeters; clay is finer than 0.002 millimeters. The soil texture triangle is a chart that gives a name to each mix. Loam, the mix farmers prize, is roughly 40 percent sand, 40 percent silt, and 20 percent clay. Textbooks give the common figure that an inch of topsoil forms in hundreds of years, but measured rates vary widely with climate and parent material, and crops have grown on fresh volcanic ash within a few years.

The Dust Bowl. In the 1910s and 1920s, high wheat prices led farmers to plow up millions of acres of native grassland on the southern Great Plains: the Oklahoma and Texas panhandles, western Kansas, and nearby parts of Colorado and New Mexico. The roots that had held the soil were gone. When drought arrived in 1931, the exposed topsoil dried to powder and the wind took it. On April 14, 1935, remembered as Black Sunday, a wall of dust turned day to night across the region. In 1935 Congress created the Soil Conservation

Service under Hugh Hammond Bennett, and farmers learned contour plowing, terracing, shelterbelts of trees, and cover crops. The lesson is the oldest command given to man: “And the LORD God took the man, and put him into the garden of Eden, to dress it and to keep it” (Genesis 2:15, KJV). Soil formation and soil loss are a core topic of AP Environmental Science.

PICTURE STUDY



Farmer and sons walking in the face of a dust storm, Cimarron County, Oklahoma, Arthur Rothstein, April 1936,

Look at the drifted soil against the shed and fence: that is A-horizon topsoil, the product of centuries, moved in a single season. Notice that the sky, not the ground, is where the farm has gone.

Look closely

Talk about it

Safety first. Vinegar is the only acid to use; do not substitute any stronger cleaner, and rinse hands after handling steel wool.

HANDS-ON ACTIVITY: WEATHERING JARS

You will need

- Three clear jars or cups
- White vinegar
- Water
- A piece of blackboard chalk or a small chunk of limestone
- Two pads of plain steel wool

- A small plastic water bottle with a cap
- A freezer

Steps

1. Put one chalk piece in vinegar and an identical piece in plain water; watch for bubbles and check both after a day.
2. Wet one steel wool pad and leave the other dry on a plate; check both after two days.
3. Fill the plastic bottle completely with water, cap it tightly, and freeze it overnight.

Check your work

- The chalk in vinegar fizzes and shrinks, which is dissolution; the wet steel wool rusts, which is oxidation; the frozen bottle bulges or splits, which is frost wedging.

PRACTICE

1. What is the difference between weathering and erosion?
2. Name the three kinds of chemical weathering described in the reading and give one example of each.
3. Explain why an old marble gravestone becomes hard to read while a granite one nearby stays sharp.
4. A student does a soil jar test. After the layers settle, the sand layer is 6 centimeters thick, the silt layer 3 centimeters, and the clay layer 1 centimeter, for a total of 10 centimeters. What percentage of each does the soil contain, and is it closer to loam or to a sandy soil?
5. Why did the Dust Bowl happen on the southern Great Plains and not in, say, Ohio, which also had drought years?

Exam connection. AP Environmental Science tests soil horizons, the soil texture triangle, soil erosion, and conservation practices directly, and the Dust Bowl is a standard case. The ACT science section often presents a data table of weathering rates in different climates and asks you to read a trend.

For families. Ask at dinner where the dirt in your yard came from and what it would look like a foot down. The one number scholars argue about is how fast soil forms; the honest answer is that it depends on climate and parent material, and the measured range is wide. For the activity, the frozen bottle can crack sharply, so let it thaw in a sink before handling.

Practice answers

1. Weathering is the breakdown of rock in place; erosion is the removal and transport of the broken material by water, ice, wind, or gravity.
2. Dissolution, as when carbonic acid dissolves limestone to make caves; oxidation, as when iron-bearing minerals rust to make red soil; hydrolysis, as when feldspar in granite turns to

clay.

3. Marble is calcium carbonate and dissolves slowly in slightly acidic rainwater. Granite is mostly quartz and feldspar; quartz barely weathers at all, and feldspar weathers much more slowly than calcite.
4. 60 percent sand, 30 percent silt, 10 percent clay. Loam is about 40 percent sand, 40 percent silt, and 20 percent clay, so this soil is sandier than loam; on the texture triangle it falls in the sandy loam region.
5. The Plains had just been stripped of the deep-rooted native grass that held the soil, had a drier climate with strong winds, and had drought beginning in 1931; Ohio's wetter climate, forests, and different farming kept its soil in place.

3.2 RIVERS AND STREAMS

Video. Videos coming.

KEY VOCABULARY

drainage basin

The whole area of land that drains into a particular river and its tributaries; also called a watershed.

competence

The largest particle a stream can move at a given velocity.

base level

The lowest level to which a stream can erode its channel; ultimately sea level.

CORE IDEAS

“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). That verse is a complete statement of the **hydrologic cycle**. Water evaporates from the ocean and from lakes, soil, and leaves; it rises, cools, condenses into clouds, and falls as rain or snow; some soaks into the ground, and the rest runs downhill in streams back to the sea. Rivers are the return trip.

Drainage basins and divides. Every stream collects water from an area of land called its **drainage basin**, or watershed. The high ground separating one basin from the next is a **divide**. The greatest divide in North America is the Continental Divide along the crest of the Rocky Mountains: rain on one side ends in the Pacific, rain on the other in the Gulf of Mexico or the Atlantic. The Mississippi River basin is the largest in the country. It drains about 1.2 million square miles, roughly 41 percent of the lower forty-eight states, gathering the Missouri, the Ohio, and the Arkansas before reaching the Gulf.

What a river carries. A stream carries its **load** in three ways. The **dissolved load** is invisible: ions of calcium, sodium, and other elements taken from weathered rock. The **suspended load** is the fine silt and clay that cloud the water; the Missouri earned the name Big Muddy from it. The **bed load** is sand and gravel that roll, slide, or bounce along the bottom. How much a stream can carry depends chiefly on its **velocity**. The largest particle a stream can move is its **competence**, and competence rises steeply with speed: doubling the velocity lets a stream move a particle many times heavier. This is why a flood that normally shifts sand can roll boulders the size of cars.

Every stream does three jobs: it **erodes** rock and soil, it **transports** the pieces, and it **deposits** them when it slows. Where the stream speeds up, it picks up; where it slows, it lays down.

Features of a river's course. In its headwaters a stream is steep and fast, cutting downward into bedrock to make a **V-shaped valley** with rapids and waterfalls. Farther

down, where the slope is gentle, the river swings from side to side in great loops called **meanders**. On the outside of each bend the water runs fastest and cuts the bank; on the inside it slows and drops a crescent of sand called a point bar. In time a meander loops so far that the river cuts across the neck and abandons the old bend, leaving a curved **oxbow lake**. The flat land the river builds on either side is its **floodplain**, and when a flood spills over its banks and suddenly slows, it drops its coarsest load right at the edge, building low ridges called **natural levees**.

Where a river meets the sea it slows almost to a stop and dumps its load in a **delta**. The Mississippi delta, seen from the air, looks like a bird's foot, because the river has built long fingers of levee out into the Gulf. In dry country, a mountain stream that rushes out onto a flat valley floor drops its load in a fan-shaped pile called an **alluvial fan**; Death Valley is ringed with them.

Every stream cuts down toward a level below which it cannot erode, its **base level**. For most rivers the ultimate base level is the sea. A lake or a hard rock ledge can act as a local base level for the stream above it.

Waterfalls and the question of rate. Niagara Falls pours over a hard cap of dolomite that rests on soft shale. Spray and frost eat the shale from under the cap, the undermined ledge collapses, and the falls step backward upstream. The retreat has been measured. In the 1800s surveys showed roughly one meter, about three feet, per year. Since the 1950s, when much of the river's flow was diverted to power plants by treaty, the measured rate has fallen to roughly 4 to 12 inches (0.1 to 0.3 meter) per year. The gorge below the falls runs about eleven kilometers north to the escarpment at Lewiston; the box below does the arithmetic.

Floods: hazard and builder. A flood is a river using its whole floodplain. The soil of the Nile valley, of the Mississippi bottomlands, and of every river delta was laid down by floods; some of the richest farmland on earth is flood deposit. But people build on floodplains because the land is flat and fertile, and the river returns. In the spring of 1927, after months of heavy rain across the basin, the Mississippi broke through its levees in about 145 places and spread over some 27,000 square miles. Around 700,000 people were driven from their homes. Estimates of the dead range from about 250 to 500. Congress answered with the Flood Control Act of 1928, which put the Army Corps of Engineers in charge of a system of levees, floodways, and reservoirs that still governs the river. The wisdom of the Lord's parable is also good engineering: "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).



Thinking About Time

What the sign says. Signs at Niagara say the falls have retreated about eleven kilometers from the escarpment at Lewiston over roughly 12,000 years, and museum displays tie this to the end of the last Ice Age.

What we observe. The gorge is about eleven kilometers long. The retreat rate was measured at about one meter per year in the 1800s, and it is slower today because flow has been diverted. Eleven thousand meters divided by one meter per year gives about 11,000 years. That is the whole calculation.

How Christians read it. The figure assumes a steady rate, but the measured rate has already changed within two centuries, and a river carrying far more meltwater would have cut faster. Many Christian families understand the gorge within a young earth, cut rapidly by the great volumes of water draining after the Flood of Genesis 6–9. Other Christians accept the longer figure and read the days of Genesis 1 differently. Both agree on what is observed: the gorge is real, the retreat is measured, and the age is an inference from an assumed rate.

PICTURE STUDY



Niagara, Frederic Edwin Church, 1857,

Church painted the Horseshoe Falls from the Canadian brink so that the viewer seems to stand in the water. Notice the flat hard ledge the river pours over and the mist rising from the plunge pool: the mist is the shale being attacked beneath the cap.

Look closely

Talk about it

Safety first. Do this outdoors or on a towel; sand in a sink drain is a plumber's bill.

HANDS-ON ACTIVITY: STREAM TABLE

You will need

- A paint roller tray or a rimmed cookie sheet
- About two quarts of play sand or sandbox sand
- A watering can or a cup with a small hole
- A few books
- A towel

Steps

1. Fill the tray with damp sand and smooth it, leaving the lower end empty as the “sea.” Prop the upper end on one book.
2. Pour a slow, steady trickle at the top and watch for several minutes.
3. Then raise the slope with a second book and repeat with the same trickle.

Check your work

- At the gentle slope the stream wanders and builds a small delta where it meets the standing water; at the steeper slope it cuts a straighter, deeper channel and the delta grows faster. Add a pebble “boulder” mid-channel and watch the stream bend around it.

PRACTICE

1. Name the three parts of a stream’s load.
2. Explain why a river builds a natural levee along its banks rather than spreading its sediment evenly across the floodplain.
3. The table below gives a simplified version of the velocity a stream needs to pick up particles of different sizes. Using it, which particle is picked up at the lowest velocity, and why does clay need a faster current than sand even though clay is far smaller? | Particle | Size | Approximate velocity needed to erode | |---|---|---| | Clay | 0.001 mm | about 100 cm/s | | Silt | 0.01 mm | about 40 cm/s | | Fine sand | 0.2 mm | about 20 cm/s | | Gravel | 10 mm | about 100 cm/s | | Cobble | 100 mm | about 300 cm/s |
4. The Niagara gorge is about 11 kilometers long. If the falls retreated at a constant 1 meter per year, how long would the gorge have taken to form? If the average rate had instead been 3 meters per year, how long? What assumption is the calculation making?
5. What is base level, and what happens to a river’s erosion as it approaches base level?

Exam connection. AP Environmental Science covers watersheds, the hydrologic cycle, floodplains, and levee trade-offs. ACT science passages frequently present stream velocity against particle size as a graph and ask you to read it, exactly like question 3. SAT math uses rate problems of the Niagara kind.

For families. Find your own drainage basin: where does the water from your street end up? The 1927 flood is a good story for the table, including the choice to dynamite a levee below New Orleans to save the city. Scholars still debate the death toll, so the reading

gives a range. The stream table is messy but harmless; a garage floor or driveway is the right place for it.

Practice answers

1. Dissolved load, suspended load, and bed load.
2. When floodwater leaves the channel it suddenly slows, and a slower stream has less competence, so it drops its coarsest sediment immediately at the channel edge, building a ridge there.
3. Fine sand is picked up at the lowest velocity, about 20 cm/s. Clay needs a faster current because its flat particles stick to one another and to the bed; they are cohesive, so a stream must work harder to lift them, even though once lifted they stay suspended at very low speeds.
4. 11,000 meters divided by 1 meter per year is about 11,000 years; at 3 meters per year it is about 3,700 years. The calculation assumes the rate was constant, and the measured rate has already changed within recorded history.
5. Base level is the lowest point to which a stream can cut; for most rivers it is sea level. As a river nears base level its slope and velocity fall, downcutting nearly stops, and the river shifts to side-to-side meandering and deposition.

3.3 GLACIERS

Video. Videos coming.

KEY VOCABULARY

firn

Granular, compacted snow that has survived at least one summer and is on its way to becoming glacial ice.

striations

Parallel scratches cut into bedrock by rocks dragged along the base of a moving glacier, showing the direction of flow.

till

Unsorted sediment, from clay to boulders, deposited directly by glacial ice.

CORE IDEAS

“Out of whose womb came the ice? and the hoary frost of heaven, who hath gendered it? The waters are hid as with a stone, and the face of the deep is frozen” (Job 38:29-30, KJV). A **glacier** is a thick mass of ice, formed from snow, that moves under its own weight. Much of the northern United States bears their marks.

Two kinds. Alpine glaciers, or valley glaciers, form in mountains and flow down valleys like slow rivers of ice. They exist today in the Alps, the Himalayas, the Rockies, the Cascades, and by the tens of thousands in Alaska. **Continental glaciers**, or ice sheets, are so large that they bury whole landscapes, mountains included, and spread outward in all directions from their thickest point. Only two exist today: Greenland, up to about three kilometers thick, and Antarctica, which holds roughly ninety percent of the world’s ice.

How a glacier forms and moves. Snow that survives the summer is buried by the next winter’s. The flakes are pressed and refrozen into grainy **firn**, and firn under more weight becomes solid glacial ice. A glacier forms wherever snow accumulates faster than it melts, year after year.

Surface ice is brittle and cracks into **crevasses**, but ice more than about fifty meters down flows under pressure like stiff putty. This is **internal creep**. Where the base is wet, the whole glacier also slides over its bed on a film of meltwater, which is **basal sliding**. Most glaciers move a few centimeters to a meter or so a day. Some outlet glaciers in Greenland have been clocked at tens of meters per day. “He casteth forth his ice like morsels: who can stand before his cold?” (Psalm 147:17, KJV).

How a glacier erodes. A glacier works two ways. By **plucking**, meltwater seeps into cracks in the bedrock, freezes to the glacier, and the moving ice rips the block out. By **abrasion**, rocks frozen into the base grind the bedrock like sandpaper, polishing it and scratching long parallel grooves called **striations** that point the direction the ice moved.

The results are unmistakable. A stream cuts a V-shaped valley; a glacier fills it and grinds it out into a broad **U-shaped valley** with a flat floor and steep walls. Yosemite Valley is the classic American example. At the head of an alpine glacier a bowl called a **cirque** is scooped out; where two cirques eat back toward each other they leave a knife-edge ridge, an **arête**; where three or more meet they leave a pyramid, a **horn**, of which the Matterhorn is the famous one. Side valleys whose glaciers were smaller are left hanging high on the main valley wall, and their streams fall off the edge: that is Bridalveil Fall in Yosemite. Where a glacial valley reaches the sea and the sea floods it, the result is a **fjord**, as in Norway, Alaska, and Puget Sound.

How a glacier deposits. Everything a glacier carries is dumped where the ice melts. The unsorted mix of clay, sand, and boulders dropped directly by ice is **till**. Ridges of till are **moraines**: lateral moraines along the sides, a medial moraine where two glaciers join, a terminal moraine marking the farthest advance, and ground moraine spread under the ice. Streamlined egg-shaped hills of till, **drumlins**, lie in swarms around Rochester, New York. Meltwater streams sort the sediment, washing out layered sand and gravel called **outwash**; a winding ridge of outwash left by a stream that ran under the ice is an **esker**, and a mound left in a hole in the ice is a **kame**. Boulders carried far from their source and left stranded are **erratics**.

The American record. The Great Lakes lie in basins the ice scooped out and then dammed with moraine. The eleven Finger Lakes of New York are long, deep troughs gouged along old river valleys; Seneca Lake is more than 600 feet deep. Long Island and Cape Cod are terminal moraines with outwash plains to their south. In Yosemite, John Muir traced the striations and argued the valley was carved by ice, against the state geologist Josiah Whitney, and Muir won.

Glaciers in recorded history. Glaciers advance and retreat, and people have written it down. During the centuries from roughly 1300 to 1850, a period historians call the Little Ice Age, Alpine glaciers grew. Villagers at Chamonix petitioned for relief as the Mer de Glace crushed farms, and Norwegian farms were overrun. Since the mid-1800s most of those glaciers have drawn back. In Alaska, Captain Vancouver in 1794 found the mouth of Glacier Bay plugged by ice; when Muir came in 1879 the ice had retreated some forty miles, and it has retreated further since. Nearby, Hubbard Glacier is advancing, and in 1986 and 2002 it dammed Russell Fiord. Both directions are what glaciers do when snowfall and melt go out of balance.

In 1837 the Swiss naturalist Louis Agassiz told the Swiss Society of Natural Sciences at Neuchâtel that striations, erratics, and moraines far from any living glacier meant that ice had once covered much of Europe. His *Études sur les glaciers* followed in 1840. Agassiz will return in Units 6 and 8. The signs along northern roads that say “Ice Age” and “Pleistocene” descend from his argument.



Thinking About Time

What the sign says. Signs across the northern states speak of the Pleistocene Ice Age, of the Laurentide Ice Sheet reaching its greatest extent about 20,000 years ago, and of the ice melting back over the following ten thousand years.

What we observe. Striations, U-shaped valleys, drumlins, eskers, erratics, and moraines cover the land from Long Island to Puget Sound, exactly matching the deposits of living glaciers in Alaska and the Alps. Ice has visibly advanced and retreated miles within written history.

How Christians read it. Many Christian families understand a single Ice Age following the Flood of Genesis 6–9, when warm oceans and cold continents made heavy snow, lasting a few centuries. Other Christians accept the longer timeline and multiple ice advances, reading the days of Genesis 1 differently. Both readings accept the observations; the number of years and the number of advances are inferences.

PICTURE STUDY



Looking Down Yosemite Valley, California, Albert Bierstadt, 1865,

Bierstadt painted the valley from the east with the sun low. Look for the U-shape: the flat floor, the sheer walls of El Capitan on the right and Cathedral Rocks on the left, and the thin thread of Bridalveil Fall dropping out of a hanging valley.

Look closely

Talk about it

Safety first. The ice block is heavy and cold; wear a glove or use the towel, and keep fingers out from under it.

HANDS-ON ACTIVITY: MAKE YOUR OWN STRIATIONS

You will need

- A plastic container such as a yogurt tub
- Coarse sand and small gravel
- Water
- A freezer
- A bar of soft soap or a slab of modeling clay
- An old towel

Steps

1. Mix sand and gravel into water in the tub and freeze it solid overnight.
2. Pop out the block and, holding it with the towel, drag it slowly and firmly across the soap or clay in one direction.

Tips

- **Alternative.** mix two cups of cornstarch with one cup of water to make “glacier goo,” pile it at the top of a tilted tray, and watch it creep downhill as a glacier does.

Check your work

- The grit frozen into the base scratches long parallel grooves, exactly like the striations on bedrock, and the direction of the grooves records the direction you dragged.

PRACTICE

1. What two conditions must be met for a glacier to form?
2. How does a glacier carve a valley differently from a stream?
3. A glacier is measured moving 30 centimeters per day. About how far does it travel in a year, and how many years would it take an erratic carried in the ice to travel 5 kilometers at that rate?
4. Explain how a geologist can tell till from outwash in a gravel pit.
5. What did Agassiz observe in 1837 that led him to argue that ice had once covered much of Europe?

Exam connection. AP Environmental Science treats glaciers under earth systems and freshwater resources, since glacial ice is the largest store of fresh water. ACT science passages use glacier velocity and length data in tables, as in question 3.

For families. If you live anywhere north of the Ohio and Missouri rivers, there is likely a glacial feature within an hour’s drive: a kettle pond, a drumlin, an erratic in a field. Scholars still debate how many separate ice advances there were and exactly why glaciers grow and shrink; the reading gives the observed record without settling that. The frozen block is heavy, so an adult should handle it for younger children.

Practice answers

1. Snow must accumulate faster than it melts over many years, and the snow must become thick enough to compress into ice and move under its own weight.
2. A stream cuts a narrow V-shaped valley; a glacier, filling the valley from wall to wall, plucks and abrades it into a broad U-shaped trough with a flat floor and steep sides.
3. 30 cm times 365 days is about 110 meters per year. Five kilometers is 5,000 meters, so about 45 years.
4. Till is unsorted, with clay, sand, and boulders jumbled together, because ice drops everything at once. Outwash is sorted into layers of sand and gravel, because flowing meltwater drops coarse grains first and fine ones later.
5. Striations, polished bedrock, erratic boulders, and moraines far from any existing glacier, matching features found next to living glaciers in the Alps.

3.4 DESERTS, WIND, AND COASTS

Video. Videos coming.

KEY VOCABULARY

deflation

The removal of loose fine sediment from a surface by wind.

loess

A deposit of windblown silt, typically yellowish, unlayered, and very fertile.

longshore drift

The movement of sand along a shore, caused by waves that strike the beach at an angle.

CORE IDEAS

A desert is defined by water, not by heat. Geographers call a region a desert when it receives less than about 25 centimeters, ten inches, of precipitation a year. By that rule the largest desert on earth is Antarctica, and the Gobi in Mongolia is bitterly cold in winter. Deserts form where air is sinking and dry, as in the belt of high pressure that holds the Sahara and the deserts of Arabia; in the **rain shadow** behind mountains, as in the Great Basin of Nevada east of the Sierra Nevada; deep in continental interiors; and along coasts washed by cold currents, as in the Atacama of Chile.

Wind at work. Where plants are scarce, the wind moves what water leaves loose. **Deflation** is the removal of fine grains by wind, which can lower a whole surface and scoop out hollows called blowouts. When the sand and silt are gone, a layer of pebbles too heavy to lift is left behind: **desert pavement**. Rocks exposed to blowing sand are polished and faceted into **ventifacts**.

Sand that the wind drops piles into **dunes**. A dune has a gentle windward slope and a steep lee face, the slip face, which stands at the angle of repose, about 34 degrees for dry sand. Grains blow up the gentle side and tumble down the steep side, so the dune as a whole marches downwind. **Barchan** dunes are crescents with their horns pointing downwind, formed where sand is scarce and the wind steady. **Transverse** dunes are long ridges at right angles to the wind, formed where sand is plentiful. **Longitudinal** dunes run parallel to the wind. **Star** dunes, with arms in several directions, form where the wind shifts around the compass. Great Sand Dunes National Park in Colorado holds the tallest dunes in North America, around 750 feet, built where winds crossing the San Luis Valley pile sand against the Sangre de Cristo Mountains. White Sands National Park in New Mexico is a dune field of a different mineral: about 275 square miles of white gypsum sand, the largest gypsum dune field in the world, blown from the dry bed of Lake Lucero.

Wind also carries silt, far finer than sand, for hundreds of miles and lets it fall as **loess**, a yellowish, crumbly, remarkably fertile deposit. The Loess Plateau of northern China is

hundreds of feet thick, and the Yellow River is yellow with it. In America, loess forms the tall bluffs above the Mississippi at Vicksburg and Natchez, the Loess Hills of western Iowa, and the wheat country of the Palouse in Washington.

Waves at work. On the coast the mover is water again, but driven by wind into **waves**. A wave disturbs the water only to about half its wavelength in depth. As a wave comes into shallow water it slows, steepens, and breaks. Because the part of a wave in shallower water slows first, waves bend as they approach shore; this is **refraction**, and it concentrates the energy of the waves on headlands and spreads it out in bays. Headlands are therefore attacked and worn back; bays are filled with sand. The sea works to straighten its coasts.

Waves almost always strike the beach at a slight angle, so each wave pushes sand up the beach at an angle and the backwash carries it straight down. Grain by grain, the sand zigzags along the shore. This is **longshore drift**, and it moves sand by the hundreds of thousands of cubic yards a year along some beaches. Where the shoreline turns, the drift keeps going straight and builds a finger of sand out into open water, a **spit**. Off low, gently sloping coasts, drift and waves build long ridges of sand parallel to the shore with a lagoon behind: **barrier islands**. The Outer Banks of North Carolina are the famous American example. Barrier islands migrate. In 1999 the Cape Hatteras lighthouse, built in 1870 some 1,500 feet from the surf, had the sea at its feet, and it was moved 2,900 feet inland on rails.

On rocky coasts, waves undercut the land to make **sea cliffs** and leave a flat wave-cut platform at their feet. Where a headland is attacked from both sides, the sea bores through to make a **sea arch**; when the arch collapses, a pillar called a **stack** is left standing offshore, as at Haystack Rock on the Oregon coast.

Fighting the drift. Because longshore drift carries sand away, towns build walls out into the sea to stop it. A **groin** is a short wall at right angles to the beach; a **jetty** is a pair of longer walls that keep a harbor inlet open. Both trap sand on the side the drift comes from, and both starve the beach on the far side, which then erodes. The trade-off is unavoidable: a wider beach here means a narrower beach there. Pumping sand back onto a beach, called nourishment, works until the next storm. The Lord Himself names the boundary: “which have placed the sand for the bound of the sea by a perpetual decree, that it cannot pass it: and though the waves thereof toss themselves, yet can they not prevail; though they roar, yet can they not pass over it?” (Jeremiah 5:22, KJV).

PICTURE STUDY



Northeaster, Winslow Homer, 1895,

Homer painted this storm from the rocks at Prouts Neck, Maine. Look at the wave breaking on bare ledge, not sand: this is a rocky coast being cut back, and the spray thrown into the air is the force that undercuts sea cliffs.

Look closely

Talk about it

Safety first. Keep the fan and the water apart; a glass dish should sit flat on a counter, not be carried full.

HANDS-ON ACTIVITY: WAVE TANK

You will need

- A glass or metal baking dish or clear storage bin
- Play sand
- Water
- A stiff piece of cardboard or a small cutting board for a paddle
- A few pebbles

Steps

1. Pile sand at one end of the dish into a sloping “beach” and add water until it reaches partway up the slope.
2. Make gentle waves with the paddle at the far end, first straight at the beach, then at an angle.

3. Set a pebble “headland” out from the beach and watch the waves bend around it.
4. Place a row of pebbles as a groin across the beach and make angled waves.

Tips

- **Alternative.** a shoebox wind box with a small fan, dry sand, and a pencil stub as an obstacle shows deflation and a tiny dune.

Check your work

- Straight waves build a berm; angled waves walk sand along the beach; the groin traps sand on one side and strips it on the other.

PRACTICE

1. How is a desert defined, and why is Antarctica counted as one?
2. Explain why wave refraction wears away headlands and fills in bays.
3. A barchan dune is measured moving 15 meters a year downwind. How far will it move in 20 years, and in what direction do its horns point?
4. A town builds a groin to widen its beach. Explain what happens to the beach on each side and why.
5. Name the four dune types in the reading and the wind condition that produces each.

Exam connection. AP Environmental Science includes coastal erosion, barrier islands, and the trade-offs of groins, jetties, and beach nourishment, as well as desertification and soil loss by wind. ACT science passages use dune migration and longshore transport rates as data, and SAT math uses rate problems like question 3.

For families. Ask where the sand on your nearest beach or lake shore came from and where it is going; the answer is always “from upstream, to downdrift.” The Cape Hatteras lighthouse move is a good story about building on sand. The dollar figures and exact sand-transport rates quoted for particular beaches vary by source. For the wave tank, expect splashing; a bath towel under the dish saves the floor.

Practice answers

1. A desert receives less than about 25 centimeters, ten inches, of precipitation a year. Antarctica’s interior gets far less than that, so despite being ice-covered it is a desert.
2. Waves slow in shallow water, so they bend toward the headlands that stick out into deeper water and converge on them, concentrating energy; in bays the waves spread out, lose energy, and deposit sand.
3. 300 meters. The horns point downwind, the direction the dune is moving.
4. Sand carried by longshore drift piles up on the updrift side, widening that beach; the downdrift side no longer receives sand and erodes, because the drift continues to carry sand away from it without replacement.
5. Barchan: limited sand, steady wind, crescent with horns downwind. Transverse: abundant sand, steady wind, ridges across the wind. Longitudinal: ridges parallel to a strong steady

wind. Star: winds from several directions.

UNIT 3 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) What is the difference between weathering and erosion?
2. (5 pts) Name the three kinds of chemical weathering described in the reading and give one example of each.
3. (5 pts) Explain why an old marble gravestone becomes hard to read while a granite one nearby stays sharp.
4. (5 pts) A student does a soil jar test. After the layers settle, the sand layer is 6 centimeters thick, the silt layer 3 centimeters, and the clay layer 1 centimeter, for a total of 10 centimeters. What percentage of each does the soil contain, and is it closer to loam or to a sandy soil?
5. (5 pts) Why did the Dust Bowl happen on the southern Great Plains and not in, say, Ohio, which also had drought years?
6. (5 pts) Name the three parts of a stream's load.
7. (5 pts) Explain why a river builds a natural levee along its banks rather than spreading its sediment evenly across the floodplain.
8. (5 pts) The table below gives a simplified version of the velocity a stream needs to pick up particles of different sizes. Using it, which particle is picked up at the lowest velocity, and why does clay need a faster current than sand even though clay is far smaller?

Particle	Size	Approximate velocity needed to erode
Clay	0.001 mm	about 100 cm/s
Silt	0.01 mm	about 40 cm/s
Fine sand	0.2 mm	about 20 cm/s
Gravel	10 mm	about 100 cm/s
Cobble	100 mm	about 300 cm/s
9. (5 pts) The Niagara gorge is about 11 kilometers long. If the falls retreated at a constant 1 meter per year, how long would the gorge have taken to form? If the average rate had instead been 3 meters per year, how long? What assumption is the calculation making?
10. (5 pts) What is base level, and what happens to a river's erosion as it approaches base level?
11. (5 pts) What two conditions must be met for a glacier to form?
12. (5 pts) How does a glacier carve a valley differently from a stream?
13. (5 pts) A glacier is measured moving 30 centimeters per day. About how far does it travel in a year, and how many years would it take an erratic carried in the ice to travel 5 kilometers at that rate?
14. (5 pts) Explain how a geologist can tell till from outwash in a gravel pit.
15. (5 pts) What did Agassiz observe in 1837 that led him to argue that ice had once covered much of Europe?
16. (5 pts) How is a desert defined, and why is Antarctica counted as one?
17. (5 pts) Explain why wave refraction wears away headlands and fills in bays.

18. (5 pts) A barchan dune is measured moving 15 meters a year downwind. How far will it move in 20 years, and in what direction do its horns point?
19. (5 pts) A town builds a groin to widen its beach. Explain what happens to the beach on each side and why.
20. (5 pts) Name the four dune types in the reading and the wind condition that produces each.

Answer key

1. Weathering is the breakdown of rock in place; erosion is the removal and transport of the broken material by water, ice, wind, or gravity.
2. Dissolution, as when carbonic acid dissolves limestone to make caves; oxidation, as when iron-bearing minerals rust to make red soil; hydrolysis, as when feldspar in granite turns to clay.
3. Marble is calcium carbonate and dissolves slowly in slightly acidic rainwater. Granite is mostly quartz and feldspar; quartz barely weathers at all, and feldspar weathers much more slowly than calcite.
4. 60 percent sand, 30 percent silt, 10 percent clay. Loam is about 40 percent sand, 40 percent silt, and 20 percent clay, so this soil is sandier than loam; on the texture triangle it falls in the sandy loam region.
5. The Plains had just been stripped of the deep-rooted native grass that held the soil, had a drier climate with strong winds, and had drought beginning in 1931; Ohio's wetter climate, forests, and different farming kept its soil in place.
6. Dissolved load, suspended load, and bed load.
7. When floodwater leaves the channel it suddenly slows, and a slower stream has less competence, so it drops its coarsest sediment immediately at the channel edge, building a ridge there.
8. Fine sand is picked up at the lowest velocity, about 20 cm/s. Clay needs a faster current because its flat particles stick to one another and to the bed; they are cohesive, so a stream must work harder to lift them, even though once lifted they stay suspended at very low speeds.
9. 11,000 meters divided by 1 meter per year is about 11,000 years; at 3 meters per year it is about 3,700 years. The calculation assumes the rate was constant, and the measured rate has already changed within recorded history.
10. Base level is the lowest point to which a stream can cut; for most rivers it is sea level. As a river nears base level its slope and velocity fall, downcutting nearly stops, and the river shifts to side-to-side meandering and deposition.
11. Snow must accumulate faster than it melts over many years, and the snow must become thick enough to compress into ice and move under its own weight.
12. A stream cuts a narrow V-shaped valley; a glacier, filling the valley from wall to wall, plucks and abrades it into a broad U-shaped trough with a flat floor and steep sides.
13. 30 cm times 365 days is about 110 meters per year. Five kilometers is 5,000 meters, so about 45 years.
14. Till is unsorted, with clay, sand, and boulders jumbled together, because ice drops everything at once. Outwash is sorted into layers of sand and gravel, because flowing meltwater drops coarse grains first and fine ones later.

15. Striations, polished bedrock, erratic boulders, and moraines far from any existing glacier, matching features found next to living glaciers in the Alps.
16. A desert receives less than about 25 centimeters, ten inches, of precipitation a year. Antarctica's interior gets far less than that, so despite being ice-covered it is a desert.
17. Waves slow in shallow water, so they bend toward the headlands that stick out into deeper water and converge on them, concentrating energy; in bays the waves spread out, lose energy, and deposit sand.
18. 300 meters. The horns point downwind, the direction the dune is moving.
19. Sand carried by longshore drift piles up on the updrift side, widening that beach; the downdrift side no longer receives sand and erodes, because the drift continues to carry sand away from it without replacement.
20. Barchan: limited sand, steady wind, crescent with horns downwind. Transverse: abundant sand, steady wind, ridges across the wind. Longitudinal: ridges parallel to a strong steady wind. Star: winds from several directions.

GROUNDWATER, CAVES, AND THE WATER BENEATH OUR FEET

Most of the fresh liquid water on Earth is not in rivers or lakes. It is underground, held in the tiny spaces between grains of sand and gravel and in the cracks of solid rock. This unit follows that hidden water: how it soaks in, how it is stored and pumped, how it carves caves out of limestone, how it rises boiling in Yellowstone, and how it can flood a valley or carry a pollutant for miles. Along the way you will learn the vocabulary that AP Environmental Science and state exams expect, and you will see how a careful observer separates what is measured from what is inferred.

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 4.1, Groundwater and Aquifers, and define water table, permeability, cone of depression.
- I can explain the main ideas of Lesson 4.2, Caves and Karst, and define karst, speleothem, stalagmite.
- I can explain the main ideas of Lesson 4.3, Hot Springs, Geysers, and Geothermal Energy, and define geyser, travertine, caldera.
- I can explain the main ideas of Lesson 4.4, Floods, Water Quality, and Stewardship, and define 100-year flood, plume, non-point source.

4.1 GROUNDWATER AND AQUIFERS

Video. Videos coming.

KEY VOCABULARY

water table

The boundary between the zone of aeration above, where pores hold air and water, and the zone of saturation below, where pores are full of water.

permeability

The ease with which water moves through a material, depending on the size and connection of its pores; distinct from porosity, which is the percentage of open space.

cone of depression

The funnel-shaped lowering of the water table around a pumping well.

CORE IDEAS

Where the rain goes. When rain falls on a pasture, some runs off into creeks, some evaporates or is drawn up by roots, and the rest soaks into the soil, a process called **infiltration**. That third portion becomes groundwater.

Just below the surface the soil and rock hold both air and water in their pore spaces. Geologists call this the **zone of aeration**. Dig deeper and you reach a level where every pore is completely filled with water: the **zone of saturation**. The boundary between the two is the **water table**. If you dig a well a few feet below the water table, water seeps in and fills the hole up to that level. The water table is not flat; it rises under hills, sinks under valleys, and rises and falls with the seasons.

Porosity and permeability. Two properties decide whether a rock makes a good water supply. **Porosity** is the percentage of the rock's volume that is open space. **Permeability** is how easily water can move through that space, which depends on whether the pores are large and connected.

Material	Typical porosity	Permeability
Gravel	25 to 40 percent	Very high
Sand	25 to 50 percent	High
Clay	40 to 70 percent	Very low
Solid granite	Less than 1 percent, up to about 10 percent if fractured	Very low

The surprise in the table is clay. It holds a great deal of water, but its pores are so small and poorly connected that the water barely moves; a clay layer can be soaking wet and still act as a wall. Granite has almost no pore space, and water travels through it only along cracks.

Aquifers and confining layers. An **aquifer** is a body of sediment or rock porous and permeable enough to supply useful amounts of water to a well or spring. Sand, gravel, sandstone, and cracked limestone make good aquifers. A layer of clay or shale that blocks water is called an **aquitard** or **confining layer**.

If the water table lies at the top of the aquifer, open to the air above, the aquifer is **unconfined**. If the aquifer is sandwiched between two confining layers, it is **confined**, and the water inside it is under pressure. Drill a well into a confined aquifer whose recharge area lies higher in the hills, and pressure pushes water up the pipe without a pump, sometimes all the way out at the surface. This is an **artesian well**, named for the old French province of Artois.

A **spring** is simply a place where the water table meets the surface of the land, often on a hillside where a permeable layer rests on an impermeable one. The Psalmist saw them: "He sendeth the springs into the valleys, which run among the hills." (Psalm 104:10, KJV)

Wells, drawdown, and recharge. When a pump pulls water from a well, the water table near the well sinks into the shape of a funnel. This funnel is the **cone of depression**, and the distance the water level falls is the **drawdown**. A large irrigation well can lower the water table for a mile around, and a neighbor's shallow well may go dry.

Aquifers refill by **recharge**: rain and snowmelt that infiltrate and work their way down. Recharge is slow, often less than an inch a year in dry country. When pumping exceeds recharge year after year, the water table falls steadily. Hydrologists call this mining the aquifer.

The Ogallala and the Edwards. The largest example in the United States is the **Ogallala Aquifer**, also called the High Plains Aquifer. It lies under about 174,000 square miles in parts of eight states: South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. It is mostly sand and gravel from the Rocky Mountains, and it supplies about thirty percent of all the groundwater used for irrigation in the country.

The USGS has measured water levels in thousands of Ogallala wells since the 1950s, and the results are plain facts, not predictions. In parts of southwestern Kansas and the Texas panhandle the water table has dropped more than 100 feet since large-scale pumping began. In Nebraska, where recharge is greater, levels have held steady or even risen in places. Farmers and local water districts have responded with drip irrigation, soil moisture sensors, and voluntary pumping limits. This is stewardship in the sense of Genesis 2:15, "to dress it and to keep it."

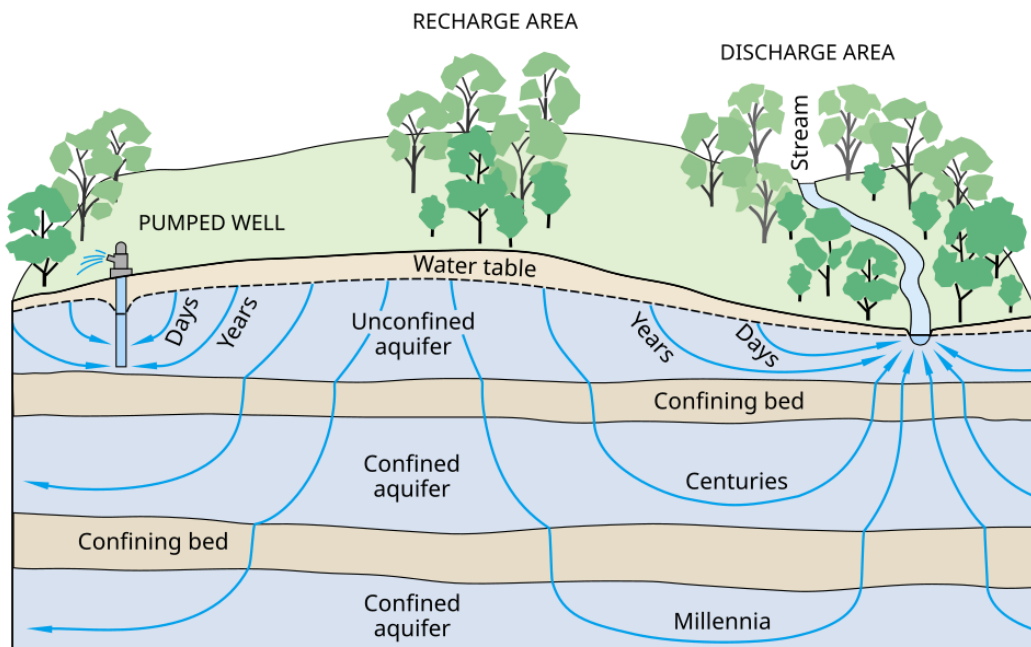
The **Edwards Aquifer** in central Texas is cracked and cavernous limestone, so water moves through it quickly. It supplies the city of San Antonio and feeds Comal Springs and San Marcos Springs, and its level responds to a heavy rain within days.

Salt water and sinking land. Along a coast, fresh groundwater floats on denser salt water. Pump the fresh water too hard and salt water creeps inland into the wells: **saltwater intrusion**, a familiar problem in Florida, on Long Island, and on Cape Cod.

Where an aquifer contains thick clay layers, pumping squeezes water out of the clay, which compacts permanently, and the land above sinks. In California's San Joaquin Valley the ground fell about 28 feet near the town of Mendota between 1925 and 1977. This is **land subsidence**, and it does not reverse when pumping stops.

Everything in this lesson is core content in AP Environmental Science, under water resources.

PICTURE STUDY



Ground-water flow paths, U.S. Geological Survey, from Circular 1139, Ground Water and Surface Water: A Single Resource, 1998,

Find the water table under the hill and follow the arrows. Notice that some water takes a short, shallow path to the nearest stream while some sinks deep and travels far before it surfaces; the deep paths take much longer.

Look closely

Talk about it

HANDS-ON ACTIVITY: AQUIFER IN A CUP

You will need

- A clear plastic cup or jar
- Aquarium gravel
- Clean sand
- A small lump of modeling clay
- A drinking straw
- A pitcher of water

- Food coloring
- And a turkey baster or syringe

Steps

1. Put an inch of gravel in the cup, then an inch of sand.
2. Press a flat pancake of clay over half the sand to make a confining layer.
3. Stand the straw in the gravel on the open side as your well.
4. Slowly pour water down the inside wall until it fills the gravel and part of the sand; mark the water table on the outside of the cup.
5. Add two drops of food coloring on top as a “pollutant” and watch it spread.
6. Now draw water out of the straw with the baster and watch the water table dip around the well.

Check your work

- The water table is visible as the line where the sand changes color; the pumped well forms a small cone of depression; the coloring moves faster through gravel than through sand and is stopped by the clay. Pour the used water on the garden, not down the sink if it is gritty.

PRACTICE

1. What is the difference between the zone of aeration and the zone of saturation, and what do we call the boundary between them?
2. Using the table in the reading, explain why clay can have a higher porosity than sand yet make a poor aquifer.
3. Why does water rise in an artesian well without a pump?
4. A farm well in Kansas showed a water level of 120 feet below the surface in 1960 and 232 feet below the surface in 2020. What was the total decline, and what was the average decline per year?
5. Name the eight states that lie over the Ogallala Aquifer, and state one practical measure farmers have taken in response to measured declines.

Exam connection. Porosity, permeability, aquifers, the Ogallala, saltwater intrusion, and land subsidence appear directly in AP Environmental Science Unit 5 and its free-response questions; ACT science passages often present a table of porosity and permeability values and ask you to pick the best aquifer material.

For families. Ask at dinner where your own tap water comes from: a city reservoir, a river, or a well, and if a well, how deep it is. Scholars agree on the Ogallala measurements but disagree on the best policy mix, which is a fine example of a shared fact and a debated response. For the activity, do it over a tray; food coloring stains.

Practice answers

1. In the zone of aeration the pores hold both air and water; in the zone of saturation every pore is filled with water. The boundary is the water table.
2. Clay's porosity is 40 to 70 percent, higher than sand's 25 to 50 percent, but its pores are tiny and poorly connected, so its permeability is very low. Water is stored but cannot move to a well. Sand has large connected pores and high permeability.
3. The well taps a confined aquifer sealed between confining layers, and the aquifer's recharge area lies higher than the well. The weight of the water in the higher part creates pressure that pushes water up the pipe.
4. The total decline was 112 feet. Over 60 years that averages about 1.9 feet per year.
5. South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. Measures include drip irrigation, soil moisture sensors, and voluntary or district pumping limits.

4.2 CAVES AND KARST

Video. Videos coming.

KEY VOCABULARY

karst

A landscape formed by the dissolving of limestone or similar rock, marked by sinkholes, disappearing streams, large springs, and caves.

speleothem

Any mineral deposit formed in a cave from dripping or flowing water, including stalactites, stalagmites, columns, flowstone, soda straws, and helictites.

stalagmite

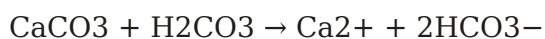
A speleothem that builds upward from the cave floor where drops land; a stalactite hangs from the ceiling.

CORE IDEAS

Water with a little acid in it. Rain is never pure water. As it falls through the air and then seeps through soil, it picks up carbon dioxide, and some of that gas dissolves to make a weak acid. In words: carbon dioxide plus water gives carbonic acid. In symbols:



Carbonic acid is far too weak to burn your skin, but limestone is made of calcite, and calcite is the one common rock mineral that this gentle acid can dissolve. In words: calcium carbonate plus carbonic acid gives dissolved calcium ions and bicarbonate ions. In symbols:



Nothing in that reaction is visible. The limestone simply disappears into the water, atom by atom, and is carried away. Multiply that by every crack in a limestone hillside and you have the whole story of caves.

Karst country. A landscape shaped by dissolving limestone is called **karst**, after the Kras plateau in Slovenia where geologists first studied it. Karst country has a particular look. Streams vanish into the ground and reappear miles away as large springs. Round depressions called **sinkholes** dot the fields where the roof of a hidden hollow has sagged or collapsed. In Florida, which sits on thick limestone, sinkholes open under roads and houses; the Winter Park sinkhole of 1981 swallowed part of a car dealership and a municipal pool. In the Guilin district of southern China, dissolving has gone so far that only steep towers of limestone remain, standing over rice fields like giant teeth. Central Kentucky, southern Indiana, the Ozarks, and the Texas Hill Country are all karst.

How a cave forms. Most limestone caves begin below the water table, in the zone of saturation, where slowly moving groundwater dissolves the rock along bedding planes and joints. The passages widen into a network. Later the water table drops, often because a nearby river cuts its valley deeper, and the passages drain and fill with air. Now a second chapter begins. Water dripping from the ceiling has carried calcium and bicarbonate from the rock above, and as each drop hangs in the open air it loses carbon dioxide. The reaction runs backward and a tiny ring of calcite is left behind.

Speleothems. The decorations that grow in an air-filled cave are called **speleothems**, from Greek words for cave deposit. A **soda straw** is a thin hollow tube growing down from the ceiling, one drip at a time. When the tube clogs, water runs down the outside and it thickens into a **stalactite**, which hangs tight to the ceiling. Drops that fall to the floor build a **stalagmite**, which might reach the ceiling someday. When the two meet they form a **column**. Sheets of water running over a wall leave **flowstone**, which looks like frozen waterfalls and drapery. Strangest of all are **helictites**, twisting fingers of calcite that grow sideways and even upward, apparently fed by water forced through tiny central canals.

The great American caves. **Mammoth Cave** in Kentucky is the longest known cave system in the world. More than 420 miles of passage have been mapped, and the number grows every year as cavers push into new sections. Its upper levels are dry and protected by a cap of sandstone, which is why so much passage survives. **Carlsbad Caverns** in New Mexico is famous for its Big Room, a chamber about 4,000 feet long and up to 255 feet high. Carlsbad is also unusual because it was not carved by carbonic acid. Hydrogen sulfide gas rose from oil-bearing rocks below and mixed with oxygen in the groundwater to make sulfuric acid, which ate out the chambers from below and left thick beds of gypsum as evidence. Nearby **Lechuguilla Cave**, entered in 1986, is more than 150 miles long and over 1,600 feet deep, and is so delicate that only research teams are allowed in. **Luray Caverns** in Virginia, discovered in 1878, is a show cave where a “stalacpipe organ” taps the stalactites to play hymns.

Life in the dark. Caves hold a small but remarkable community of creatures: blind, colorless cave fish and crayfish, cave salamanders, and bats that roost by the thousands and whose droppings feed the whole food chain. Because no sunlight enters, everything in the cave ultimately depends on what washes or flies in from outside.

Caving well. A cave is both dangerous and fragile. Never enter a wild cave without three sources of light, a helmet, warm clothing, an experienced leader, and someone outside who knows your plan and your return time. Floods can fill passages in minutes. And remember the caver’s rule: take nothing but pictures, leave nothing but footprints, kill nothing but time. A stalactite broken off in a moment cannot be put back, and the oil from a single hand can stop calcite from growing on a formation.

Thinking About Time

What the sign says. Signs in show caves commonly tell visitors that a stalactite grows about an inch per century, or one cubic inch per hundred years, and that the formations

before them are tens or hundreds of thousands of years old.

What we observe. Measured growth varies enormously. In dry caves scientists have measured less than a hundredth of a millimeter per year; in wet caves rates of a millimeter or more per year are documented. Under lime mortar and concrete, where a different and faster chemistry is at work, stalactites several inches long have formed in a few decades beneath bridges, in mine tunnels, and in the basement of the Lincoln Memorial in Washington. The honest statement is that a rate measured today in one cave cannot simply be applied to another formation or to another time.

How Christians read it. Many Christian families understand the caves of Kentucky and New Mexico to have been hollowed and decorated quickly in the wet centuries after the Flood of Genesis 6 to 9, when water tables were high and carbon dioxide plentiful, and they point to the measured fast rates as evidence that long ages are not required. Other Christians accept the long ages on the signs and read the days of Genesis 1 as long periods or as a literary frame, holding that God is equally the author of a slow process. Both groups agree on what is observed: the chemistry, the drips, and the measured rates. The ages are inferences from those observations.

PICTURE STUDY



Big Room, Carlsbad Cavern, National Park Service photograph by Anthony Mazzucco, 2021,

Look for the stalagmites rising from the floor and the stalactites above them, and try to find a place where a column has formed. Note the paved trail: the Big Room is large enough that a walk around it is more than a mile.

Look closely

Talk about it

Safety first. Use glass jars with care and keep Epsom salt away from small children; vinegar is the only acid you should use.

HANDS-ON ACTIVITY: GROW A STALACTITE

You will need

- Two glass jars
- A saucer
- A length of wool yarn or cotton string
- Two paper clips
- Epsom salt
- And warm water

Steps

1. Fill both jars with warm water and stir in Epsom salt until no more will dissolve.
2. Tie a paper clip to each end of the yarn, drop one end in each jar, and set the jars a few inches apart with the saucer between them so the yarn sags in the middle.
3. Leave for a week.

Tips

- **Alternative.** weigh a stick of blackboard chalk or a limestone chip, place it in vinegar for a day and another in plain water, then dry and weigh again.

Check your work

- The solution climbs the yarn, drips from the low point, and as the water evaporates it leaves a crust that lengthens into a stalactite, with a stalagmite forming on the saucer. Measure its length each day and compute your own growth rate.

PRACTICE

1. Write, in words, the reaction by which carbonic acid dissolves limestone.
2. Name three features of a karst landscape.
3. Explain why cave passages generally form below the water table but speleothems form only after the cave has drained.
4. A stalactite is 12 inches long. If it grew at the museum-sign rate of one inch per century, how old would it be? If it grew at a measured wet-cave rate of one millimeter per year, how old would it be? (One inch is 25.4 millimeters.)
5. How does the origin of Carlsbad Caverns differ from that of Mammoth Cave?

Exam connection. Karst, sinkholes, and the carbonic acid reaction appear in AP Environmental Science under geologic hazards and water resources; the ACT and SAT

both use growth-rate problems of the form “if a formation grew at rate r , how long did it take,” exactly like question 4.

For families. If a show cave is within reach, go: Mammoth, Carlsbad, Luray, Meramec, Ruby Falls, and many smaller caves give excellent tours. Ask the guide how the age on the sign was determined and listen for the difference between a measurement and an assumption. The chalk experiment needs a kitchen scale that reads tenths of a gram.

Practice answers

1. Calcium carbonate plus carbonic acid gives dissolved calcium ions and bicarbonate ions ($\text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-$).
2. Any three of: sinkholes, disappearing streams, large springs, caves, karst towers.
3. Dissolving requires water filling the passage and moving through it, which happens in the zone of saturation. Speleothems form when a drip hangs in open air, loses carbon dioxide, and leaves calcite behind, which requires an air-filled cave.
4. At one inch per century, 1,200 years. At one millimeter per year, 12 inches is about 305 millimeters, so about 305 years. The point is that the age depends entirely on the rate assumed.
5. Mammoth Cave was dissolved by carbonic acid in groundwater. Carlsbad was dissolved by sulfuric acid formed when hydrogen sulfide rising from oil-bearing rocks met oxygen in the groundwater; thick gypsum deposits are the evidence.

4.3 HOT SPRINGS, GEYSERS, AND GEOTHERMAL ENERGY

Video. Videos coming.

KEY VOCABULARY

geyser

A hot spring that erupts periodically, because superheated water in a constricted channel flashes to steam when the pressure above it drops.

travertine

A banded deposit of calcium carbonate left by spring water, especially hot water, as it loses carbon dioxide at the surface.

caldera

A large basin formed when the ground collapses into an emptied magma chamber after a great eruption; Yellowstone's is about 30 by 45 miles across.

CORE IDEAS

When groundwater meets heat. Everywhere on Earth the rock grows warmer with depth, and in volcanic country a body of hot rock or molten magma may lie only a few miles down. Groundwater that sinks into such rock is heated and rises again, and where it reaches the surface it produces the features we call **hydrothermal**. Job knew that something burned beneath the ground: "As for the earth, out of it cometh bread: and under it is turned up as it were fire." (Job 28:5, KJV)

A **hot spring** is the simplest case: heated water rises through open channels and pools quietly at the surface. A **fumarole** is a vent where only steam and gas escape, because the water boils away before it reaches the top. A **mud pot** forms where acidic gases have rotted the rock into clay and only a little water is available, so the surface is a bubbling gray stew.

How a geyser works. A **geyser** is a hot spring that erupts. It needs three things: plenty of water, a heat source, and a particular kind of plumbing. The plumbing is a narrow, crooked channel with a constriction near the top. Water deep in the channel is under the weight of the water above it, and under pressure water can heat well past its normal boiling point without boiling. This is called **superheating**. Eventually bubbles form near the constriction and lift a little water out the top. That lowers the pressure below, the superheated water flashes into steam all at once, and the whole column is hurled into the air. The channel then refills and the cycle begins again.

Old Faithful in Yellowstone is the best known. It erupts to a height of 100 to 180 feet, and the interval between eruptions ranges from about 60 to 110 minutes, averaging about 90. It is not the largest or the most regular geyser in the park, but it is the most reliably predictable, and park rangers post the next expected time after each eruption. Long

eruptions are followed by long intervals and short by short, which is how the prediction is made.

Yellowstone. Yellowstone sits on an enormous **caldera**, a collapsed volcanic basin about 30 by 45 miles across, with hot rock still close beneath it. The park contains more than 10,000 hydrothermal features and about 500 geysers, roughly half of all the geysers in the world. Iceland, which sits on the Mid-Atlantic Ridge, and the Rotorua district of New Zealand hold most of the rest; the word geyser itself comes from Geysir in Iceland.

The story of the park is worth knowing. Trappers' tales of boiling springs were long dismissed. In 1870 the Washburn expedition explored the region and brought back careful notes, and in 1871 the geologist Ferdinand Hayden led a government survey that included the painter Thomas Moran and the photographer William Henry Jackson. Jackson's photographs and Moran's watercolors were set before Congress, and on March 1, 1872, President Grant signed the act creating Yellowstone National Park, the first national park in the world. Moran's great canvas *The Grand Canyon of the Yellowstone*, painted in 1872, was purchased by Congress and hung in the Capitol.

Terraces that grow before your eyes. At **Mammoth Hot Springs**, in the north of the park, hot water rises through thick limestone, dissolving it on the way just as cave water does. When the water reaches the air it cools and loses carbon dioxide, and calcite drops out as **travertine**, building white and tan terraces in stair-step pools. The growth here is fast and measured: the park reports deposition of as much as several inches a year on active terraces, enough that boardwalks must be moved and trees are buried alive. Travertine is a reminder that mineral deposits from water need not be slow.

Geothermal energy. Hot groundwater is a source of power. Iceland pipes hot water directly into radiators, and about nine of every ten Icelandic homes are heated this way. In California, **The Geysers** north of San Francisco is the largest geothermal power complex in the world, where steam from wells spins turbines. Geothermal plants burn no fuel and run day and night. The trade-offs are real: good sites are rare and far from cities, drilling is expensive, the steam carries some hydrogen sulfide and other gases, and taking out steam faster than water seeps back in lowers output, which is why The Geysers now injects treated wastewater from nearby towns to keep its reservoir charged. Good stewardship means counting both sides honestly.

Veins from hot water. Hot water deep in the crust dissolves minerals that cold water cannot, especially silica and metals. As it rises into cooler cracks the minerals drop out, filling the crack with a **vein** of quartz that may carry gold, silver, copper, or lead. This is why old prospectors followed white quartz veins, and why the great gold and silver districts of Nevada and Colorado lie in old volcanic country. The hot springs of Yellowstone are, in a sense, the top of such a system seen alive.

PICTURE STUDY



Old Faithful in eruption, Yellowstone, William Henry Jackson, 1872, U.S. Geological and Geographical Survey of the Territories; National Archives,

Notice the pale cone of silica, called geyserite, that the geyser has built around its own vent, and the column of water and steam rising above it. Jackson's heavy glass-plate camera needed a long exposure, so the eruption appears soft and cloudlike.

Look closely

Talk about it

Safety first. An adult handles anything hot; do not attempt a sealed-container geyser model.

HANDS-ON ACTIVITY: A TRAVERTINE TERRACE ON PAPER

You will need

- Epsom salt
- Warm water
- A jar
- A sheet of black construction paper
- A shallow tray
- And a spoon

Steps

1. Dissolve as much Epsom salt as the warm water will take.

2. Lay the black paper on the tray and spoon the solution onto it a little at a time, letting it run down a slight slope.
3. Set in a sunny window and add more solution each day for several days.

Check your work

- As the water evaporates, white crystals build up in ridges and rims where the water pooled, imitating the stepped terraces of Mammoth Hot Springs; this is precipitation of a dissolved mineral, the same principle as travertine. Optional, with an adult only: watch a stovetop coffee percolator work, and explain to each other how the rising bubbles lift water up the tube like a geyser.

PRACTICE

1. What three things does a geyser require, and which one distinguishes it from an ordinary hot spring?
2. Explain why water deep in a geyser's channel can be hotter than 100 degrees Celsius without boiling.
3. A ranger records the last five Old Faithful eruptions at 8:04, 9:35, 10:58, 12:31, and 2:02. Compute the four intervals in minutes and their average, and say whether the average fits the range given in the reading.
4. Name the year and the president associated with the founding of Yellowstone National Park, and two members of the 1871 Hayden survey whose work helped persuade Congress.
5. Give one advantage and two real drawbacks of geothermal power.

Exam connection. Geothermal energy, its advantages and trade-offs, is listed directly in AP Environmental Science Unit 6 on energy resources; the interval calculation in question 3 is the kind of data-table task the ACT science section favors.

For families. Yellowstone is the single most instructive geology trip a family can take; if it is not possible, the NPS website streams Old Faithful live. Scholars agree on how geysers work but still debate details of Yellowstone's deep plumbing and the timing of its past great eruptions. The Epsom salt activity is safe for all ages; keep the solution out of the mouth.

Practice answers

1. Water, a heat source, and a constricted channel. The plumbing with a constriction is the difference; it lets water superheat under pressure and then flash to steam.
2. The weight of the water above it raises the pressure, and the boiling point of water rises with pressure. When a little water is lifted out and the pressure drops, the superheated water boils all at once.
3. The intervals are 91, 83, 93, and 91 minutes. The average is 89.5 minutes, which fits the 60 to 110 minute range and is close to the typical average of about 90.

4. 1872, President Ulysses S. Grant; the painter Thomas Moran and the photographer William Henry Jackson.
5. Advantage: it burns no fuel and runs continuously. Drawbacks: any two of rare and remote sites, expensive drilling, gases such as hydrogen sulfide in the steam, and declining output if steam is withdrawn faster than the reservoir recharges.

4.4 FLOODS, WATER QUALITY, AND STEWARDSHIP

Video. Videos coming.

KEY VOCABULARY

100-year flood

A flood with a one percent chance of being equaled or exceeded in any given year; not a flood that occurs once every hundred years.

plume

The elongated body of contaminated groundwater that moves downgradient from a pollution source.

non-point source

Pollution that enters water from many diffuse places across the landscape, such as fertilizer from farm fields, as opposed to a point source such as a single leaking tank.

CORE IDEAS

Two kinds of flood. A **flash flood** comes within hours of a heavy rain, usually in a small, steep basin or a dry canyon, and is over in a day. A **regional flood** builds for days or weeks on a great river as rain and snowmelt from a whole watershed arrive together. Both spread water over the **floodplain**, the flat land beside a river that the river itself built from sediment during past floods. Floodplains are level and fertile, which is why people build there and why they are flooded.

The hundred-year flood. Engineers describe floods by probability. A **100-year flood** is a flood so large that it has a one percent chance of being equaled or exceeded in any given year. It does not mean such a flood comes once a century on schedule. Two can come in consecutive years. This is a classic test question, and the mistake is to read “100-year” as a calendar. Over a 30-year mortgage the chance of at least one such flood is $1 - 0.99^{30}$, which works out to about 26 percent. A 500-year flood has a 0.2 percent annual chance.

The Federal Emergency Management Agency publishes **flood maps** that show the 100-year floodplain, and homes inside it generally need flood insurance. Reading one before buying a house is plain prudence.

Levees and their trade-offs. A **levee** is an earthen wall along a river built to hold floodwater in the channel. Levees protect farms and towns, but they have costs. Water kept out of one floodplain rises higher and runs faster downstream, so a levee on one bank raises the risk on the other. And a levee that is overtopped or fails floods the land behind it suddenly and deeply.

Two American disasters teach the lesson. On May 31, 1889, the South Fork Dam above **Johnstown, Pennsylvania**, an earthen dam that had been poorly repaired, gave way after days of rain. A wall of water swept down the valley and killed about 2,200 people. In 1927

the **Mississippi River** flood overtopped and broke levees from Illinois to Louisiana, covered about 27,000 square miles, drove some 600,000 people from their homes, and led Congress to pass the Flood Control Act of 1928, which gave the Army Corps of Engineers responsibility for the river.

What gets into groundwater. Groundwater moves slowly and unseen, so a pollutant can travel unnoticed for years. The main sources are household **septic systems** that leak bacteria and nitrate, **agricultural nitrate** from fertilizer and manure, **leaking underground tanks** of gasoline at old filling stations, and **road salt** spread in winter.

A dissolved pollutant moves with the groundwater in a long tongue called a **plume**, stretching downgradient from the source and spreading slowly sideways as it goes. If a well lies in the path of a plume, the water from that well will eventually carry the pollutant. A geologist who knows the direction of flow can predict which wells are at risk.

In AP Environmental Science these are divided into **point sources**, which come from a single identifiable place such as a leaking tank or pipe, and **non-point sources**, which come spread across the land, such as fertilizer from thousands of fields.

Protecting a well. The simplest protection is distance. **Wellhead protection** means keeping septic fields, barns, fuel tanks, and chemical storage well away from the well and, better still, downgradient from it. A well should have a sealed casing and a cap so surface water cannot run straight down the hole. Rural families should **test their well water** at least once a year for bacteria and nitrate, and after any flood. The federal limit for nitrate is 10 milligrams per liter as nitrogen, set because higher levels are dangerous to infants.

Public water systems in the United States are regulated under the **Safe Drinking Water Act of 1974**, which requires testing for a list of contaminants and sets maximum levels. Private wells are not covered by it; the owner is responsible.

On dowsing. Some people still hire a dowser, who walks a property with a forked stick or a pair of bent wires and says the stick dips where water lies. The USGS has looked at this carefully and reports that it is not reliable. The reason is simple. In most country, groundwater is present nearly everywhere below the water table, so a well drilled where the stick dipped will usually find water, and so will a well drilled where it did not. The honest way to site a well is to look at the geology and at the records of neighboring wells.

Stewardship. The Scriptures frame the matter. "And the LORD God took the man, and put him into the garden of Eden, to dress it and to keep it." (Genesis 2:15, KJV) The land God gives is good: "a land whose stones are iron, and out of whose hills thou mayest dig brass" (Deuteronomy 8:9, KJV), and the water under it is part of that gift. Stewardship is not alarm and not activism. It is the ordinary work of a household: keep the septic tank pumped, fertilize what the crop needs and no more, store fuel properly, test the well, and read the flood map. Do these things and your children will drink clean water from the same ground you did.

PICTURE STUDY



Johnstown Flood, 1889: Masonic Headquarters, photographer unknown, 1889; Library of Congress Prints and Photographs Division,

Look at how the wreckage of houses and timbers is piled against the surviving stone building, and at the mud line on the walls that marks how high the water stood.

Look closely

Talk about it

Safety first. An adult cuts the bottle; the cut edge is sharp.

HANDS-ON ACTIVITY: BUILD A FILTER AND TEST IT

You will need

- A two-liter plastic bottle
- Scissors
- A coffee filter or piece of cloth
- Clean gravel
- Clean sand
- A jar
- And a cup of muddy water

Steps

1. Have an adult cut the bottom off the bottle and invert it over the jar like a funnel.
2. Put the coffee filter in the neck, then two inches of sand, then two inches of gravel.
3. Pour the muddy water in slowly and watch what comes out.

Tips

- **Alternative or in addition.** compute $1 - 0.99^{30}$ on a calculator and then try $1 - 0.99^{50}$ and $1 - 0.99^{100}$ to see how the chance grows.

Check your work

- The water clears noticeably because particles are trapped in the sand, which is how an aquifer cleans water of mud and some bacteria. Write this on the jar: the filtered water is NOT safe to drink, because dissolved chemicals and most germs pass straight through.

PRACTICE

1. What does “100-year flood” actually mean, and what is the common mistake?
2. Compute the probability of at least one 100-year flood during a 30-year period. Show the setup.
3. Explain why a levee on one side of a river can increase flood risk on the other side.
4. Give two point sources and two non-point sources of groundwater contamination.
5. A farm’s well lies 300 feet east of its septic field, and groundwater flows from west to east. Is the well at risk, and what would you change?

Exam connection. Point versus non-point sources, groundwater contamination, and the Safe Drinking Water Act are AP Environmental Science Unit 8 content; the 100-year flood probability is a favorite of both AP Environmental Science and SAT math as a compound-probability problem.

For families. Look up your own address on the FEMA flood map and talk about what you find. If you have a well, find the last test result or schedule one; if you are on city water, read the annual water quality report the utility mails or posts. Scholars agree on the probability math but debate how much levee building is wise on the lower Mississippi, which is a good table conversation about trade-offs.

Practice answers

1. It means a flood with a one percent chance of being equaled or exceeded in any single year. The mistake is to think it happens once every hundred years on schedule.
2. The chance of no such flood in one year is 0.99. Over 30 independent years the chance of none is 0.99^{30} , about 0.74. So the chance of at least one is $1 - 0.74$, about 0.26 or 26 percent.
3. The levee keeps water from spreading onto its own floodplain, so the same volume of water rises higher in the channel and presses against the opposite bank, which may be overtopped.
4. Point: a leaking underground fuel tank, a leaking septic tank, a landfill. Non-point: nitrate fertilizer from many fields, road salt, manure runoff across a region.

5. Yes. The well is downgradient from the septic field, so any plume will move toward it. Either move the well upgradient, to the west of the septic field, or relocate the septic field downgradient of the well.

UNIT 4 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) What is the difference between the zone of aeration and the zone of saturation, and what do we call the boundary between them?
2. (5 pts) Using the table in the reading, explain why clay can have a higher porosity than sand yet make a poor aquifer.
3. (5 pts) Why does water rise in an artesian well without a pump?
4. (5 pts) A farm well in Kansas showed a water level of 120 feet below the surface in 1960 and 232 feet below the surface in 2020. What was the total decline, and what was the average decline per year?
5. (5 pts) Name the eight states that lie over the Ogallala Aquifer, and state one practical measure farmers have taken in response to measured declines.
6. (5 pts) Write, in words, the reaction by which carbonic acid dissolves limestone.
7. (5 pts) Name three features of a karst landscape.
8. (5 pts) Explain why cave passages generally form below the water table but speleothems form only after the cave has drained.
9. (5 pts) A stalactite is 12 inches long. If it grew at the museum-sign rate of one inch per century, how old would it be? If it grew at a measured wet-cave rate of one millimeter per year, how old would it be? (One inch is 25.4 millimeters.)
10. (5 pts) How does the origin of Carlsbad Caverns differ from that of Mammoth Cave?
11. (5 pts) What three things does a geyser require, and which one distinguishes it from an ordinary hot spring?
12. (5 pts) Explain why water deep in a geyser's channel can be hotter than 100 degrees Celsius without boiling.
13. (5 pts) A ranger records the last five Old Faithful eruptions at 8:04, 9:35, 10:58, 12:31, and 2:02. Compute the four intervals in minutes and their average, and say whether the average fits the range given in the reading.
14. (5 pts) Name the year and the president associated with the founding of Yellowstone National Park, and two members of the 1871 Hayden survey whose work helped persuade Congress.
15. (5 pts) Give one advantage and two real drawbacks of geothermal power.
16. (5 pts) What does "100-year flood" actually mean, and what is the common mistake?
17. (5 pts) Compute the probability of at least one 100-year flood during a 30-year period. Show the setup.
18. (5 pts) Explain why a levee on one side of a river can increase flood risk on the other side.
19. (5 pts) Give two point sources and two non-point sources of groundwater contamination.
20. (5 pts) A farm's well lies 300 feet east of its septic field, and groundwater flows from west to east. Is the well at risk, and what would you change?

Answer key

1. In the zone of aeration the pores hold both air and water; in the zone of saturation every pore is filled with water. The boundary is the water table.
2. Clay's porosity is 40 to 70 percent, higher than sand's 25 to 50 percent, but its pores are tiny and poorly connected, so its permeability is very low. Water is stored but cannot move to a well. Sand has large connected pores and high permeability.
3. The well taps a confined aquifer sealed between confining layers, and the aquifer's recharge area lies higher than the well. The weight of the water in the higher part creates pressure that pushes water up the pipe.
4. The total decline was 112 feet. Over 60 years that averages about 1.9 feet per year.
5. South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. Measures include drip irrigation, soil moisture sensors, and voluntary or district pumping limits.
6. Calcium carbonate plus carbonic acid gives dissolved calcium ions and bicarbonate ions ($\text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-$).
7. Any three of: sinkholes, disappearing streams, large springs, caves, karst towers.
8. Dissolving requires water filling the passage and moving through it, which happens in the zone of saturation. Speleothems form when a drip hangs in open air, loses carbon dioxide, and leaves calcite behind, which requires an air-filled cave.
9. At one inch per century, 1,200 years. At one millimeter per year, 12 inches is about 305 millimeters, so about 305 years. The point is that the age depends entirely on the rate assumed.
10. Mammoth Cave was dissolved by carbonic acid in groundwater. Carlsbad was dissolved by sulfuric acid formed when hydrogen sulfide rising from oil-bearing rocks met oxygen in the groundwater; thick gypsum deposits are the evidence.
11. Water, a heat source, and a constricted channel. The plumbing with a constriction is the difference; it lets water superheat under pressure and then flash to steam.
12. The weight of the water above it raises the pressure, and the boiling point of water rises with pressure. When a little water is lifted out and the pressure drops, the superheated water boils all at once.
13. The intervals are 91, 83, 93, and 91 minutes. The average is 89.5 minutes, which fits the 60 to 110 minute range and is close to the typical average of about 90.
14. 1872, President Ulysses S. Grant; the painter Thomas Moran and the photographer William Henry Jackson.
15. Advantage: it burns no fuel and runs continuously. Drawbacks: any two of rare and remote sites, expensive drilling, gases such as hydrogen sulfide in the steam, and declining output if steam is withdrawn faster than the reservoir recharges.
16. It means a flood with a one percent chance of being equaled or exceeded in any single year. The mistake is to think it happens once every hundred years on schedule.
17. The chance of no such flood in one year is 0.99. Over 30 independent years the chance of none is 0.99^{30} , about 0.74. So the chance of at least one is $1 - 0.74$, about 0.26 or 26 percent.
18. The levee keeps water from spreading onto its own floodplain, so the same volume of water rises higher in the channel and presses against the opposite bank, which may be overtopped.
19. Point: a leaking underground fuel tank, a leaking septic tank, a landfill. Non-point: nitrate fertilizer from many fields, road salt, manure runoff across a region.

20. Yes. The well is downgradient from the septic field, so any plume will move toward it. Either move the well upgradient, to the west of the septic field, or relocate the septic field downgradient of the well.

FOSSILS AND READING ROCK LAYERS

Fossils are the most argued-over objects in geology, and also the most beautiful. In this unit you will learn how a dead creature becomes stone, how to read a stack of rock layers in the order they formed, what the names on museum signs mean, and how the numbers beside those names are obtained. At every step we will keep two questions apart: what is actually observed, and what is inferred from it. That habit is the heart of this course's approach to time, and it will serve you well in any science and on any exam.

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 5.1, How Fossils Form, and define permineralization, trace fossil, glossopetrae.
- I can explain the main ideas of Lesson 5.2, Steno's Principles and Reading Rock Layers, and define superposition, unconformity, cross-cutting relationships.
- I can explain the main ideas of Lesson 5.3, The Geologic Column and Index Fossils, and define index fossil, faunal succession, lagerstätte.
- I can explain the main ideas of Lesson 5.4, Dating Methods, Relative and Radiometric, and define half-life, isotope, closed system.

5.1 HOW FOSSILS FORM

Video. Videos coming.

KEY VOCABULARY

permineralization

Preservation in which mineral-bearing water fills the pores of bone, shell, or wood and deposits minerals there, turning the original into stone while keeping its structure.

trace fossil

A preserved record of an animal's activity rather than its body: a track, trail, burrow, or coprolite.

glossopetrae

"tongue stones," the triangular fossils found in Mediterranean rock that Steno identified in 1667 as the teeth of sharks.

CORE IDEAS

What counts as a fossil. A fossil is any evidence of past life preserved in rock or sediment: a bone, a shell, a leaf impression, a footprint, a burrow, even a piece of dung. The word comes from the Latin *fossilis*, "dug up." For centuries it covered anything dug from the ground, crystals included; today it means the remains or traces of once-living things.

The first requirement: rapid burial. Here is the observation that governs everything else in this lesson. When an animal dies today, whether a fish on the sea floor, a deer in the forest, or a whale on a beach, it does not lie quietly waiting to become a fossil. Scavengers, bacteria, waves, and weather take it apart. Marine biologists who have sunk whale carcasses to the deep sea floor and watched them with cameras report that hagfish, sleeper sharks, and crabs strip the soft tissue within weeks to months, and that worms bore into the scattered bones. On land a carcass is reduced to gnawed, scattered bones within weeks, and in most climates those bones crumble within a few years. Dead fish float, bloat, and are eaten; they almost never settle intact onto the mud.

So for a fossil to form, a dead organism must be buried quickly, and deeply enough to be kept from scavengers and oxygen. Hard parts such as shells, bones, teeth, and wood survive far more often than soft parts. This is why the great majority of fossils are marine animals with shells, buried in water-laid sediment.

Modes of preservation. Permineralization. Mineral-rich water soaks into the pores of bone or wood and deposits silica, calcite, or pyrite in the spaces, so the original structure is locked in stone. The petrified logs of Petrified Forest National Park in Arizona are the familiar example; under a microscope the cell walls are still visible. Petrification need not be slow. At the Tateyama hot springs in Japan, researchers reported in 2004 that fallen wood

had become partly silicified in about 36 years, and laboratory workers have produced silica-filled wood in days.

Molds and casts. A shell buried in sediment dissolves away, leaving a hollow mold. If the mold later fills with mineral, the filling is a cast, a replica of the original's outer shape.

Carbonization. The organism is pressed flat and its volatile parts driven off, leaving a thin black film of carbon. Fern fronds in the shales above Pennsylvania coal beds are preserved this way, and so are many of the fine plant and animal fossils inside the ironstone nodules of Mazon Creek, Illinois.

Unaltered remains. Insects sealed in amber, which is hardened tree resin. Mammoths frozen in Siberian ground, such as the Berezovka mammoth recovered in 1901 with food still between its teeth. The bones of dire wolves, saber-toothed cats, and mammoths soaked in asphalt at the La Brea tar pits in Los Angeles, where more than a million bones have been recovered.

Trace fossils. Tracks, trails, burrows, and coprolites, a word for fossil dung coined by William Buckland in 1829. A trace fossil records behavior rather than a body.

Fossils that record a moment. Some fossils freeze an instant. In the Green River Formation at Fossil Butte National Monument, Wyoming, collectors have found a fish fossilized with another fish halfway down its throat, and slabs covered with hundreds of fish of one species lying together, called mass-mortality layers. At Holzmaden in Germany an ichthyosaur, a dolphin-shaped marine reptile, was fossilized in the act of giving birth, the young one partway out. Whatever the age on the museum sign, these specimens record burial in hours or less, not a slow drizzle of sediment over a carcass. That is an observation, and Christians who hold a young earth and geologists who hold an old one agree on it. They differ on how often and how widely such rapid burials happened.

Steno and the shark's head. In October 1666 fishermen near Livorno, Italy, landed a great white shark, and the Grand Duke of Tuscany had its head sent to a young Danish anatomist, Niels Stensen, known to us as Nicolaus Steno. Steno noticed that the shark's teeth matched the "tongue stones," *glossopetrae*, found embedded in rock on Malta and elsewhere. Many people believed tongue stones had fallen from the sky or had grown inside the rock. Steno concluded that they were the teeth of sharks, and therefore that the rock holding them had once been loose sediment that settled around them. He published this in 1667. From this small puzzle he went on to the principles of rock layers you will study in the next lesson.

Collecting fossils honestly. Fossil hunting is a fine hobby, but there are rules. In United States national parks and monuments, collecting anything is forbidden. On most Bureau of Land Management and National Forest land, a person may casually collect small amounts of common invertebrate and plant fossils for personal use, but vertebrate fossils such as bones and teeth require a permit. On private land the fossils belong to the landowner; always ask. Good collectors write down where each specimen came from, because a fossil without a location has lost most of its scientific value. "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter" (Proverbs 25:2, KJV).

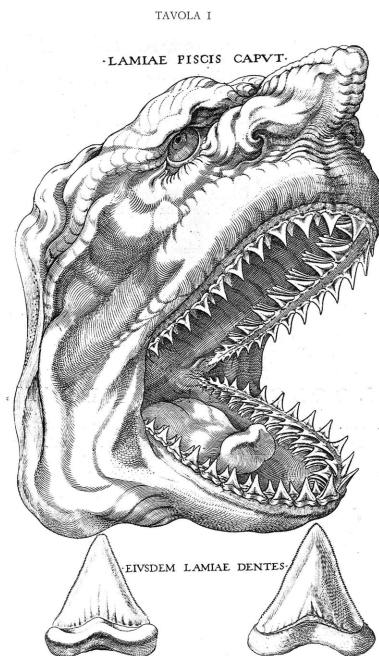
Thinking About Time

What the sign says. A label on a Green River fish reads “Eocene, about 50 million years old,” and a petrified log in Arizona is labelled “Late Triassic, about 220 million years old.” These are museum figures. They come from radiometric dating of volcanic layers and from the fossil’s position in the geologic column, which you will study in Lessons 5.3 and 5.4.

What we observe. The fossil itself: its shape, the rock enclosing it, the fineness of its detail, and the plain fact that it was buried before scavengers and decay could take it apart. No fossil carries a date. The age is an inference attached afterward.

How Christians read it. Many Christian families understand most fossil beds as the work of the Flood of Genesis 6–9 and its aftermath, which supplied exactly the rapid, deep, watery burial that fossils require, and they regard the museum ages as resting on assumptions they do not share. Other Christians accept the long ages and read fossils as the record of life over a long history under God’s providence, with each rapid-burial fossil recording a local storm, flood, or ash fall. Both read Genesis as true history, and the exceptional fossils are a fact for both.

PICTURE STUDY



*Head of a shark, with its teeth, Nicolaus Steno, 1667, from *Elementorum myologiae specimen*,*

Compare the two large teeth drawn below the head with the teeth in the open jaw. Notice how the engraver has shown the teeth standing in rows, and ask yourself what Steno must have thought when he set a “tongue stone” from Malta beside one of them.

Look closely

Talk about it

Safety first. Plaster warms as it sets, so never pour plaster around any part of your body or let a child put hands into it; wash tools before the plaster hardens, and put leftovers in the trash, never down the drain.

HANDS-ON ACTIVITY: MOLDS AND CASTS IN PLASTER

Materials. Plaster of Paris, a disposable cup and spoon, petroleum jelly, modeling clay or play dough, and a few sturdy shells, leaves, or a large pine cone scale.

Steps. (1) Flatten a pad of clay about an inch thick and press a shell firmly into it, then lift it out; the hollow is your mold. (2) Rub a thin film of petroleum jelly inside the mold. (3) Mix plaster with water in the cup to the thickness of pancake batter and pour it into the mold; let it set for an hour. (4) Peel away the clay; the plaster is your cast. (5) Compare the cast, the mold, and the original shell, and note which fine details survived.

What to notice. The cast is a copy of the outside of the shell only; nothing of the shell's inside or material is present, yet an expert could still identify the species.

You will need

Steps

PRACTICE

1. What single condition must be met before almost any fossil can form, and why?
2. Name three modes of fossil preservation and give one real example of each.
3. Explain why a fish fossilized with another fish in its throat, or an ichthyosaur fossilized while giving birth, is important evidence about the speed of burial.
4. What were glossopetrae, what did people believe about them, and what did Steno conclude in 1667?
5. A slab from the Green River Formation measures 60 centimeters by 40 centimeters and holds 180 fish of one species. How many fish is that per square meter, and what does such a layer suggest about how they died?

Exam connection. AP Environmental Science asks how coal, oil, and natural gas form from buried organic matter, which is the same burial-and-preservation story told here. ACT science passages often present a table of specimens with their preservation type and the sediment they were found in, and ask you to spot the pattern.

For families. Ask at the table: what would it take for your family pet, or the deer that crosses the road, to become a fossil? The answer, almost always, is a flood of mud. Scholars still debate how often mass-mortality fish layers formed, whether from poison algae, volcanic ash, or sudden sediment, but no one debates that each layer was buried

fast. Before the activity, read the plaster package; it must not be mixed in the kitchen sink, and the warming while it sets is normal.

Practice answers

1. Rapid burial. A dead organism left exposed is scavenged, scattered, and decayed within weeks; only quick burial in sediment protects it from scavengers and oxygen long enough to be preserved.
2. Any three of: permineralization (petrified wood, Arizona); molds and casts (dissolved shells in limestone); carbonization (fern films above Pennsylvania coal, Mazon Creek nodules); unaltered remains (amber insects, frozen mammoths, La Brea bones); trace fossils (tracks, burrows, coprolites).
3. A fish that died while swallowing prey would have been eaten or rotted within days if left on the bottom; the same is true of a mother ichthyosaur mid-birth. For the scene to be frozen in stone, sediment must have covered the animals within hours or less. This is an observation that every geologist accepts, whatever age he puts on the layer.
4. "Tongue stones" were triangular objects found in rock on Malta and elsewhere, believed to have fallen from the sky or grown in the rock. After dissecting a shark's head in 1666, Steno concluded they were shark teeth, so the rock enclosing them must once have been loose sediment.
5. The slab is $0.6 \times 0.4 = 0.24$ square meters; $180 \div 0.24 = 750$ fish per square meter. A layer so crowded with one species suggests a mass death and burial in a single event, not fish dying one at a time over a long period.

5.2 STENO'S PRINCIPLES AND READING ROCK LAYERS

Video. Videos coming.

KEY VOCABULARY

superposition

Steno's rule that in an undisturbed stack of sedimentary layers, each layer is younger than the one below and older than the one above.

unconformity

A surface within a rock sequence representing a break in deposition, usually with erosion, before deposition resumed; angular unconformities, disconformities, and nonconformities are the three kinds.

cross-cutting relationships

The rule that any feature which cuts across a rock, such as a dike, fault, or erosion surface, is younger than the rock it cuts.

CORE IDEAS

A book that was only a preface. In 1669 Steno published *De solido intra solidum naturaliter contento dissertationis prodromus*, which means "a forerunner to a dissertation on a solid naturally contained within a solid." He meant it as the preface to a larger book he never wrote; he became a Catholic bishop instead. The *Prodromus* nevertheless laid down three rules that every geologist still uses to read layered rock.

Superposition. In a stack of undisturbed sedimentary layers, each layer is younger than the one beneath it and older than the one above. A layer cannot be laid down on nothing.

Original horizontality. Sediment settles out of water in flat-lying sheets. Layers that are now tilted or folded were moved after they formed.

Lateral continuity. A layer extends sideways until it thins out or reaches the edge of its basin. Matching layers on the two walls of a canyon were once joined; the canyon was cut afterward.

Later geologists added two more.

Cross-cutting relationships. Anything that cuts across a rock is younger than the rock it cuts: a fault, a dike of once-molten rock, or an erosion surface.

Inclusions. A fragment enclosed in a rock is older than the rock that holds it. The pebbles in a conglomerate came from a rock that existed before the conglomerate did.

These rules give order, not age. Superposition says the sandstone is older than the shale above it; it does not say by how much. Everyone who reads rock this way, whatever he believes about the age of the earth, arrives at the same order.

Unconformities: the gaps. An unconformity is a surface in the rock where the record is broken. Layers were deposited, then something happened, whether erosion, a pause in deposition, or tilting, and then deposition resumed. There are three kinds.

An **angular unconformity** has tilted or folded layers below, eroded flat, with horizontal layers above. A **disconformity** has parallel layers above and below, separated by an erosion surface that may show channels or a bed of pebbles. A **nonconformity** has sedimentary layers resting on eroded igneous or metamorphic rock, as the Tapeats Sandstone rests on the Vishnu Schist deep in the Grand Canyon.

The most famous angular unconformity is at Siccar Point on the east coast of Scotland. In 1788 James Hutton took a boat there with his friends John Playfair and Sir James Hall and showed them near-vertical gray beds of greywacke capped by gently sloping red sandstone. Hutton reasoned that the lower beds had been laid down flat, hardened, stood on end, worn away, and buried under new sand, and that each step took time. Playfair wrote years later that, listening to Hutton, his mind seemed to grow dizzy looking so far into the depths of time (paraphrase; from Playfair's biographical account of Hutton, published 1805). In 1787 Hutton had found a similar unconformity at Jedburgh, drawn by his friend John Clerk of Eldin; that drawing is this lesson's picture.

Keep observation and inference apart here too. The observation: tilted beds, an erosion surface, flat beds on top, in that order. The inference: how long each step took. Hutton inferred an immense span. A Christian geologist who reads the record through Genesis 6–9 sees the same sequence but assigns far shorter intervals, pointing to the sharp, little-weathered contact and the lack of a deep ancient soil at the boundary. Others answer that an advancing sea strips soil easily, so a clean contact proves little. The order is settled; the duration is argued.

Reading a cross-section. A cross-section is a drawing of a vertical slice through the ground. Picture this one.

Five sedimentary layers lie one above another: A at the bottom, then B, C, D, and E at the top. Layers A through D all dip gently toward the east. A dark dike of basalt cuts straight up through A, B, C, and D, but its top is worn flat at the same surface as the top of D, and it does not enter E. A fault offsets A, B, C, D, and the dike, and it too stops at that surface. Layer E lies flat across the eroded tops of everything beneath it.

Now read it. First, A, B, C, and D were deposited in that order, bottom to top, by superposition, and flat, by original horizontality. Second, the dike intruded, because it cuts all four layers. Third, the fault moved, because it offsets the dike as well as the layers; had the dike cut across the fault, the order of those two would be reversed. Fourth, the whole stack was tilted and then eroded flat, truncating the layers, the dike, and the fault alike. Fifth, E was deposited across that erosion surface. Six steps, and any trained reader will arrive at the same order. What the drawing cannot tell you is the number of years between any two steps.

Relative and absolute. Geologists call this reading **relative dating**: it ranks events but gives no numbers. **Absolute dating** puts a number of years on a rock, and depends on the methods and assumptions of Lesson 5.4. The relative order is observed and agreed by everyone; the absolute age is inferred, and the inference is where readings part ways. “Of old hast thou laid the foundation of the earth: and the heavens are the work of thy hands” (Psalm 102:25, KJV).

Thinking About Time

What the sign says. At Siccar Point the sign says the gray beds are Silurian, about 435 million years old, and the red sandstone above is Devonian, about 370 million years old, so the gap at the unconformity represents some 65 million years. These are museum figures.

What we observe. Two sets of beds meeting at a sharp surface: the lower set nearly vertical and eroded flat, the upper set lying across it. The order of events is beyond dispute.

How Christians read it. Many Christian families read Siccar Point as a record of events during and after the Flood of Genesis 6–9: rapid deposition, tilting while the sediment was still soft or newly hardened, scouring by moving water, and rapid reburial, all within a short time; they note that the contact shows little sign of long exposure. Other Christians accept Hutton’s long intervals and see them as the ordinary working of the world God upholds. Both agree on the sequence; the two readings differ on duration, and a thoughtful student should be able to state each one.

PICTURE STUDY



*The Jedburgh unconformity, John Clerk of Eldin, 1787, engraved for Hutton’s *Theory of the Earth*, 1795,*

Find the near-vertical beds at the bottom, the flat-lying beds above them, and the surface where they meet. Then notice the carriage on the road at the top, which Clerk drew to show the scale, and read the picture from the bottom up as a sequence of events.

Look closely

Talk about it

Safety first. Use a plastic knife only, and keep clay away from small children and pets.

HANDS-ON ACTIVITY: LAYER-CAKE STRATIGRAPHY

Materials. Four or five colors of modeling clay or play dough, a plastic knife, a drinking straw, a shallow pan, and a sheet of paper.

Steps. (1) Press the clay into the pan in flat layers of different colors, one on top of another; these are layers A through D. (2) Push the straw straight down through all the layers and leave it; this is your dike. (3) With the knife, slice through the whole stack at an angle and slide one side up a quarter inch; this is your fault. Notice it offsets the straw too. (4) Tilt the pan, then use the knife to shave the top flat, cutting off the raised side, the top of the straw, and the top of the fault. (5) Lay a final layer of a new color across the shaved surface; this is layer E. (6) Cut the whole cake in half to expose a cross-section, draw it, and write the sequence of events in order, giving the rule that justifies each step.

What to notice. Whoever reads your drawing should reach the same order you built, and the drawing cannot tell them how many minutes each step took you.

You will need

Steps

PRACTICE

1. State Steno's three principles in your own words.
2. What is the difference between relative dating and absolute dating, and which one does everyone agree on?
3. Explain why a dike that cuts through layers A through D but not layer E must be younger than D and older than E.
4. A cross-section shows three flat layers, 1 at the bottom, 2, and 3 on top. A fault offsets layers 1 and 2 but not layer 3, and the top of the fault is eroded at the base of 3. A dike cuts through all three layers and also cuts the fault. List the events in order.
5. Name the three kinds of unconformity and say which one is found where the Tapeats Sandstone rests on the Vishnu Schist in the Grand Canyon.

Exam connection. The ACT science test regularly shows a labelled cross-section or a diagram of layers with a dike and fault and asks which feature is oldest or youngest; CLT reading passages have included excerpts from Hutton and Playfair. Knowing the five rules could let you answer such questions in seconds.

For families. A good table conversation: everyone agrees on the order of events at Siccar Point, so why do people disagree about the time? Try to state the young-earth reading

and the old-earth reading each in two sentences, and ask whether the rock itself settles the question. Scholars still debate how much time a clean unconformity surface requires, with the Mount St. Helens eruption of 1980 showing that erosion surfaces can be cut in hours. For the activity, clay layers cut more cleanly if they are firm, so chill the cake for ten minutes before slicing.

Practice answers

1. Superposition: lower layers are older than upper layers in an undisturbed stack. Original horizontality: sediment is laid down in flat sheets, so tilted layers were moved later. Lateral continuity: layers extend sideways until they thin out, so matching layers across a valley were once connected.
2. Relative dating gives the order of events without numbers; absolute dating assigns a number of years. The relative order is read directly from the rock and is agreed on by everyone; the absolute age is an inference that depends on assumptions.
3. By cross-cutting relationships, the dike is younger than everything it cuts, so it is younger than A through D. Since it does not enter E and its top is eroded at the surface E rests on, the dike was already in place and worn down before E was deposited; therefore it is older than E.
4. (1) Layer 1 deposited; (2) layer 2 deposited; (3) the fault moved, offsetting 1 and 2; (4) erosion cut the fault and layers flat; (5) layer 3 deposited across the erosion surface; (6) the dike intruded, cutting all three layers and the fault, so it is the youngest event.
5. Angular unconformity, disconformity, and nonconformity. Sedimentary Tapeats Sandstone on metamorphic Vishnu Schist is a nonconformity, part of the Great Unconformity.

5.3 THE GEOLOGIC COLUMN AND INDEX FOSSILS

Video. Videos coming.

KEY VOCABULARY

index fossil

A fossil that is widespread, abundant, easily recognized, and confined to a narrow band of layers, so that it identifies the layer wherever it is found.

faunal succession

William Smith’s principle that fossil kinds occur in a definite, recognizable order from the bottom of a sequence to the top, and that the same order recurs from place to place.

lagerstätte

A deposit of exceptional fossil preservation, often including soft parts, such as the Burgess Shale or the Green River Formation.

CORE IDEAS

The names on the signs. Walk through any natural history museum and you will see the same words on sign after sign: Cambrian, Jurassic, Cretaceous, Pleistocene. These names belong to the **geologic column**, the standard ordering of rock layers and their fossils agreed on by geologists around the world. The column is divided into eons, eras, periods, and epochs. The largest division is between the **Precambrian** (an informal name covering the Hadean, Archean, and Proterozoic eons) and the Phanerozoic eon, “visible life,” which holds nearly all the fossils. The Phanerozoic is divided into three eras: the **Paleozoic** (“old life”), the **Mesozoic** (“middle life”), and the **Cenozoic** (“recent life”). Each era is divided into periods, listed below with the ages that appear on museum signs. These ages are museum figures, rounded from the International Chronostratigraphic Chart; the observed facts are the names, the order, and the fossils, and the ages are inferences from the methods of Lesson 5.4.

Era	Period	Museum age of the start, millions of years (rounded)	Fossils commonly on the sign
Paleozoic	Cambrian	539	trilobites, brachiopods, Burgess Shale animals
Paleozoic	Ordovician	485	graptolites, nautiloids, early corals
Paleozoic	Silurian	444	eurypterids, early land plants
Paleozoic	Devonian	419	armored fish, first ammonites

Era	Period	Museum age of the start, millions of years (rounded)	Fossils commonly on the sign
Paleozoic	Carboniferous (Mississippian and Pennsylvanian in the United States)	359	coal-swamp ferns, giant insects, crinoids
	Permian	299	last trilobites, Dimetrodon
Mesozoic	Triassic	252	first dinosaurs, petrified forests
Mesozoic	Jurassic	201	Stegosaurus, Archaeopteryx, ammonites
Mesozoic	Cretaceous	145	Tyrannosaurus, chalk, last ammonites
Cenozoic	Paleogene	66	Green River fish, early mammals
Cenozoic	Neogene	23	grasslands, horses, apes
Cenozoic	Quaternary	2.6	mammoths, La Brea animals, ice ages

A sentence to remember the periods in order: Camels Often Sit Down Carefully, Perhaps Their Joints Creak; Painfully, Nervously, Quietly.

William Smith and faunal succession. The man who taught the world to read fossils in order was an English canal surveyor, William Smith. Walking the cuttings of canals in the 1790s, he noticed that each rock layer held its own characteristic fossils, and that the same layers with the same fossils appeared in the same order wherever he dug. In 1815 he published the first geological map of a whole country, *A Delineation of the Strata of England and Wales, with part of Scotland*, and beginning in 1816 he issued *Strata Identified by Organized Fossils*, plates of the fossils that identified each layer. His rule is now called the **principle of faunal succession**: fossil kinds occur in a definite, recognizable order from bottom to top, and the same order is found from place to place.

Smith's rule made **index fossils** possible. A good index fossil is widespread, abundant, easy to recognize, and confined to a narrow band of layers. Trilobites mark the Paleozoic; graptolites, tiny colonial animals preserved like pencil marks on shale, mark the Ordovician and Silurian especially; ammonites, coiled relatives of the squid, mark the Devonian through the Cretaceous, with species that change from layer to layer. Find a known ammonite and you can match your layer to layers in another country.

How the column was assembled. No single place on earth shows the whole column. It was pieced together by correlation: Smith's layers in England, Murchison's Silurian in Wales, the Permian named from Perm in Russia, the Jurassic from the Jura Mountains, the Cretaceous

from the Latin for chalk. A few places do show a long run of it in order. The walls of the Grand Canyon rise from the Cambrian Tapeats Sandstone through the Mississippian Redwall Limestone to the Permian Kaibab Limestone at the rim, with the Ordovician and Silurian missing. Drill cores from the Williston Basin of North Dakota and nearby pass through rock assigned to every period from the Cambrian to the Quaternary, one above another. The order is real and consistent; that much is observation.

The Cambrian explosion. On a sign the words **Cambrian explosion** describe a rapid evolutionary radiation in the early Cambrian. Here is what is observed. Below the Cambrian, fossils are mostly microbes, with a layer of soft-bodied Ediacaran forms. In the lowest fossil-rich Cambrian layers, nearly every major animal body plan appears already distinct: trilobites with compound eyes, brachiopods, mollusks, echinoderms, worms, and even early chordates. The Burgess Shale in British Columbia, found by Charles Walcott in 1909, and the Chengjiang beds of China show this abruptly and in superb detail. Mainstream geologists infer a burst of evolution over a stretch of tens of millions of years; many Christians read it as the first layers in which the created kinds of the sea floor were buried. Both agree the appearance is abrupt.

Living fossils and lagerstätten. In 1938 a museum curator in South Africa, Marjorie Courtenay-Latimer, found a strange blue fish in a trawler's catch: a coelacanth, a kind known until then only from fossils and thought extinct since the Cretaceous. In 1994 a park officer in Australia, David Noble, walked into a grove of Wollemi pines, a tree known only from fossils. Horseshoe crabs on Atlantic beaches match fossils in Jurassic limestone almost line for line. These **living fossils** teach caution: a creature absent from the upper layers is not necessarily extinct, and tens of millions of museum years can pass with no visible change. A **lagerstätte** (German for "storage place," plural *lagerstätten*) is a deposit of extraordinary preservation: the Burgess Shale, Solnhofen in Germany where *Archaeopteryx* was found in 1861, Holzmaden, Mazon Creek, and the Green River Formation. Each shows soft parts, which means each was buried fast.

Why you must know the names. The names and their order are the shared language of geology, and every exam uses them. Learn them as you would learn the Latin names of the bones: as true descriptions of what is found, whatever you conclude about when. "The works of the LORD are great, sought out of all them that have pleasure therein" (Psalm 111:2, KJV).

Thinking About Time

What the sign says. The geologic column represents hundreds of millions of years of slow deposition, during which life evolved from single cells to the animals of today, each period's fossils recording the life of its time.

What we observe. A real and consistent worldwide order of fossils in the layers, so reliable that oil companies hire paleontologists to use it. Abrupt appearances of complex animals, most strikingly at the base of the Cambrian. Vast flat layers spanning continents, such as the Tapeats Sandstone and its equivalents across North America. Sharp, flat contacts between layers with few traces of the soils, burrows, root beds, and worn

landscapes that long gaps of ordinary time would be expected to leave. Living fossils unchanged across many museum ages.

How Christians read it. Many Christians read the column mainly as the order of burial during and after the Flood of Genesis 7–8. On this reading the lowest layers hold sea-floor dwellers because they lived lowest and could not flee; swimming creatures, then amphibians and reptiles, then the mammals and birds of the highlands were overwhelmed later, so the order reflects ecological zones and mobility rather than ages; the continent-wide layers, sharp contacts, and lagerstätten are what fast watery burial would leave; and “the waters prevailed exceedingly upon the earth; and all the high hills, that were under the whole heaven, were covered” (Genesis 7:19, KJV). Other Christians accept the long ages and read the order as the true history of life unfolding under God’s providence, with the evidence for them resting on radiometric dates, the thickness and variety of deposits, and the fit between fossil order and the sequence of life. They read the days of Genesis 1 as long or as a literary frame, and still hold the Flood as a real event. Both groups honor Genesis as true history. A student should be able to explain each reading and name the evidence each uses, and should know that mainstream geologists, including many Christians among them, hold the second view as careful people drawing inferences from evidence.

PICTURE STUDY



A Delineation of the Strata of England and Wales, with part of Scotland, William Smith, 1815,

Follow the colored bands as they sweep from the southwest coast up toward the northeast; each band is a layer that reaches the surface, and Smith colored each one to match the fossils he found in it. Notice that the bands lie in order, so that walking across England from east to west is like walking down through the column.

Look closely

Talk about it

Safety first. None needed beyond cleaning up the water.

HANDS-ON ACTIVITY: BACKYARD BURIAL ORDER

Materials. A tall clear jar or two-liter bottle with the top cut off, water, and a collection of small objects from your yard or kitchen that stand for creatures: a pebble or clam shell (bottom-dwelling shellfish), a marble (a snail), a bit of sponge (coral), a plastic fish, a feather (a bird), an acorn (a land plant), a small plastic animal (a mammal), and a few handfuls of sand and soil.

Steps. (1) Decide where each “creature” lived in a pond: on the bottom, swimming, in the shallows, on land nearby, or flying above. (2) Imagine a sudden flood of muddy water sweeping the pond. Drop the objects in, in the order the flood would bury them, pouring sand and soil in between to make layers. (3) Let it settle and draw the jar from the side, labelling each layer and its “fossil.” (4) Then make a second drawing of the same jar, labelled with the geologic column names a museum would give those layers from bottom to top, and compare the two.

What to notice. Both drawings show the same order; they differ only in what the order is taken to mean. For a quieter version, write the twelve period names on cards and sort them from oldest to youngest against the clock.

You will need

Steps

PRACTICE

1. Name the three eras of the Phanerozoic in order, oldest first, and give the meaning of each name.
2. Using the table, how long does the Mesozoic era last in museum years, and which period in the table is the longest?
3. A layer contains both trilobites and ammonites. Using the ranges given in the reading, which periods could the layer belong to?
4. Explain why the discovery of the living coelacanth in 1938 matters for how we read the fossil record.
5. State what is observed at the base of the Cambrian, and then state the mainstream inference and the inference many Christians draw.

Exam connection. The SAT, ACT, CLT, and AP Environmental Science all expect you to use the standard names and their order as given facts: an ACT passage may give a table of index fossils with their periods and ask which layer is oldest, and AP Environmental Science asks about the Carboniferous coal swamps and the Quaternary ice ages by name.

Answer with the standard sequence on every test; knowing a name does not commit you to a belief about its age.

For families. Have the student teach the table to the family: three eras, twelve periods, in order. Then ask for both readings of the Cambrian explosion in the student's own words. Scholars still debate how sharp the base of the Cambrian really is and what the Ediacaran creatures were, and that is a fine thing to mention. Many Christian geologists work in oil and mining using the column every day; respect for them, and for the Christian families who read the column as a Flood record, is the tone to aim for.

Practice answers

1. Paleozoic ("old life"), Mesozoic ("middle life"), Cenozoic ("recent life").
2. The Mesozoic begins at 252 million and ends at 66 million, so $252 - 66 = 186$ million museum years. The longest period in the table is the Cretaceous, $145 - 66 = 79$ million; the shortest is the Quaternary.
3. Trilobites run from the Cambrian to the Permian; ammonites from the Devonian to the Cretaceous. The overlap is Devonian, Carboniferous, or Permian.
4. The coelacanth was known only from fossils and believed extinct since the Cretaceous, yet it was alive. So the absence of a creature from upper layers does not prove it died out, and a creature can remain essentially unchanged through many museum ages. Gaps in the record are gaps in burial, not necessarily gaps in life.
5. Observed: nearly all the major animal body plans appear abruptly in the lowest fossil-rich layers, fully formed, with little beneath them but microbes and soft-bodied Ediacaran forms. Mainstream inference: a rapid evolutionary radiation over tens of millions of years. Many Christians' inference: the first layers of a great burial, in which the sea-floor creatures of the created world were buried first.

5.4 DATING METHODS, RELATIVE AND RADIOMETRIC

Video. Videos coming.

KEY VOCABULARY

half-life

The time required for half of the atoms of a radioactive parent isotope in a sample to decay into the daughter isotope.

isotope

A form of an element whose atoms have the usual number of protons but a different number of neutrons, as carbon-14 differs from carbon-12.

closed system

A rock or sample that has neither gained nor lost parent or daughter atoms since it formed; one of the three assumptions behind every radiometric date.

CORE IDEAS

Two kinds of answer. Relative dating puts events in order without numbers. But a museum sign says “150 million years,” and that number comes from **radiometric dating**, a clock built on radioactive decay.

How the clock works. Some atoms are unstable. A **parent isotope** gives off radiation and becomes a **daughter isotope** at a rate that, in every laboratory test, has been steady and unaffected by heat, pressure, or chemistry. The time for half of a sample of parent atoms to decay is the **half-life**. After one half-life, one half of the parent remains; after two, one quarter; after three, one eighth; after n half-lives, the fraction left is $(\frac{1}{2})^n$. On a graph the parent falls along a smooth decay curve as the daughter rises.

Carbon-14 is the best known. Cosmic rays striking nitrogen in the upper air make carbon-14, which enters plants and animals, so every living thing carries a small, steady amount. At death the intake stops and the carbon-14 decays with a half-life of 5,730 years; measure what is left against the living amount and you have an age. A piece of charcoal holds one eighth of the carbon-14 of living wood. One eighth is $(\frac{1}{2})^3$, so three half-lives have passed: $3 \times 5,730 = 17,190$ years. SAT problems write it as an equation: $N = N_0(\frac{1}{2})^{(t/5730)}$. After nine half-lives only $1/512$ remains, too little to measure reliably; so carbon-14 has a museum limit of about 50,000 years and works only on once-living material: wood, bone, shell, charcoal.

Potassium-argon (potassium-40 to argon-40, half-life 1.25 billion years, a museum figure) is used on volcanic rock; **uranium-lead** (uranium-238 to lead-206, 4.5 billion years, a museum figure) on zircon crystals in igneous rock; **rubidium-strontium** (rubidium-87 to strontium-87, about 49 billion years) on igneous and metamorphic rock. None dates a sedimentary layer directly, because its grains came from older rocks; instead geologists date igneous

layers above and below it, such as lava flows or ash beds, and bracket the sediment between them.

The three assumptions. Every radiometric date rests on three assumptions. First, the **starting amount**: how much daughter the rock held when it formed. Second, the **constant rate**: that the half-life has never changed. Third, the **closed system**: that no parent or daughter has leaked in or out since. Argon is a gas and can escape or be trapped; uranium dissolves in groundwater. Geologists test the first and third with isochron plots and by matching several clocks on one rock. The assumptions are reasonable, and they are assumptions: a measured ratio is an observation, and an age is an inference.

When the clock disagrees with the calendar. Rocks of known age make the best test. In 1996 Steven Austin published potassium-argon results on dacite from the lava dome that grew in the crater of Mount St. Helens in 1986: whole rock, 0.35 million years; separated mineral fractions, up to 2.8 million. In 1998 Andrew Snelling published potassium-argon ages of up to 3.5 million years for lava flows of 1949, 1954, and 1975 from Mount Ngauruhoe in New Zealand. The mainstream explanation is **excess argon**: argon dissolved in the magma, or carried in older crystals, was trapped as the lava cooled, so the starting amount was not zero. Laboratories warn that potassium-argon is unreliable on very young rocks for this reason, and call these tests a known limit, not a general failure. Christians who hold a young earth reply that if excess argon is present here, no one can be sure it is absent from rocks nobody saw erupt.

A second case is carbon-14 in coal and diamonds. In 2003 a team of Christian scientists reported measurable carbon-14, roughly a tenth to a half of one percent of the living amount, in coal labelled hundreds of millions of museum years old, and in 2005 the same team reported smaller traces in diamonds; any carbon-14 at all should be gone after a million years. The mainstream reply is that the amounts lie near the instruments' detection floor and are best explained by contamination in handling or by new carbon-14 made underground by uranium radiation in the surrounding rock. The team answered that the amounts were consistent and above the blank.

Other clocks, other assumptions. Tree rings: living bristlecone pines in California are more than 4,800 years old by ring count; the assumption is one ring per year, though stressed trees can add or skip a ring. Varves: thin paired lake layers, light in summer and dark in winter, assumed one pair per year; but at Mount St. Helens a single pyroclastic flow on June 12, 1980 laid down a deposit about 25 feet thick made of many fine layers in a few hours. Ice cores: Greenland cores are counted at over 100,000 layers; yet six P-38 fighters and two B-17 bombers forced down on the Greenland ice cap in 1942, the "Lost Squadron," were found in 1988 under about 250 feet of ice, and one P-38 was dug out in 1992 from about 268 feet, where snowfall is many times heavier than at the ice sheet's center. Each clock is a real measurement, and each ticks only as fast as its assumption allows.

The believer's posture. Careful measurement honors God. But every clock rests on assumptions about a past no one measured. Hold the measured ratios with confidence and the ages with humility. "Through faith we understand that the worlds were framed by the

word of God, so that things which are seen were not made of things which do appear” (Hebrews 11:3, KJV).

Thinking About Time

What the sign says. “Uranium-lead dating of zircons gives an age of 4.5 billion years for the earth,” and “the Green River fish are 50 million years old by argon dating of ash beds.”

What we observe. Ratios of parent and daughter atoms measured in a laboratory with great precision; decay rates measured over decades and found steady; and in rocks of known age, some dates that match history and some that do not.

How Christians read it. Many Christian families hold that the starting amounts and rates assumed for these clocks were not what they are today, pointing to the known-age lava tests and to carbon-14 in coal, and read the earth as young. Other Christians hold that the agreement of many different clocks on many rocks is strong evidence for an old earth, and that the known-age failures are understood limitations. Both honor Scripture; both ask that measurement be separated from assumption, and both can learn the methods well enough to pass any exam.

PICTURE STUDY



Knightia eocaena from the Green River Formation, Fossil Butte National Monument, National Park Service photograph, 2024,

Look at the fine rays of the fins and the row of ribs, preserved in pale limestone that split along the layer. The museum age of this fish, about 50 million years, is not written on the

rock; it comes from argon dating of volcanic ash beds in the same lake deposits.

Look closely

Talk about it

Safety first. None, but keep candies away from small children if used as counters.

HANDS-ON ACTIVITY: HALF-LIFE WITH A HUNDRED PENNIES

Materials. 100 pennies (or candies with a mark on one side), a box with a lid, graph paper, and a pencil.

Steps. (1) Put all 100 pennies heads up in the box; this is the fresh sample. (2) Close the lid, shake, open, and remove every penny that landed tails; those have “decayed.” Count the heads that remain and write it down as the result of one half-life. (3) Repeat with the remaining pennies, recording the count after each shake, until none remain. (4) Plot shakes on the horizontal axis and pennies remaining on the vertical axis, and draw a smooth curve through the points; compare it with the ideal 100, 50, 25, 12.5, 6, 3. (5) Now play detective: a friend shakes a fresh box an unknown number of times and hands you the survivors. From the count, estimate how many shakes passed, then ask what you had to assume to do it (that the box began with 100, that every shake removed about half, that no pennies were added or lost).

What to notice. Your curve wobbles from the ideal because chance is at work with small numbers, which is one reason real laboratories count enormous numbers of atoms.

You will need

Steps

PRACTICE

1. A bone contains one sixteenth of the carbon-14 of living bone. How many half-lives have passed, and what is the carbon-14 age?
2. An SAT-style problem: a sample begins with 800 carbon-14 atoms. Using $N = 800 \times (\frac{1}{2})^{(t/5730)}$, how many remain after 11,460 years, and after 17,190 years?
3. Which method would a geologist choose to date each of the following, and why: a charred log in a cave; a lava flow; a zircon crystal in granite; a layer of shale?
4. Name the three assumptions behind every radiometric date and explain why the Mount St. Helens result of 1996 bears on one of them.
5. Explain why a sedimentary layer is usually not dated directly by radiometric methods, and how its museum age is obtained instead.

Exam connection. The SAT math section includes exponential decay problems in exactly the form $N = N_0(\frac{1}{2})^{(t/h)}$, and the ACT science test presents decay curves and half-life

tables to read. AP Environmental Science covers radioactive half-life in its unit on energy resources and nuclear waste, and expects the carbon-14 figure of 5,730 years.

For families. This is the lesson where a family's convictions touch the science most directly, so talk through it together. Ask: what is measured, and what is assumed? Scholars still debate the source of the carbon-14 found in coal and whether accelerated decay in the past is physically possible, a proposal some Christian physicists have made while acknowledging the heat it would release. Whatever your family's reading, your student should be able to do the half-life arithmetic flawlessly and state both views fairly. The penny activity needs ten minutes and a steady table.

Practice answers

1. One sixteenth is $(\frac{1}{2})^4$, so four half-lives; $4 \times 5,730 = 22,920$ years.
2. $11,460 \div 5,730 = 2$ half-lives, so $800 \times \frac{1}{4} = 200$ atoms remain. $17,190 \div 5,730 = 3$ half-lives, so $800 \times \frac{1}{8} = 100$ atoms remain.
3. Charred log: carbon-14, because it was once alive and is likely under 50,000 years. Lava flow: potassium-argon, for volcanic rock. Zircon in granite: uranium-lead, for igneous crystals. Shale: no direct method; date igneous layers such as ash beds above and below it and bracket the age.
4. Known starting amount, constant decay rate, and closed system. The 1986 dome gave potassium-argon ages of hundreds of thousands to millions of years because argon was already present when the rock formed, so the starting amount was not zero; this challenges the first assumption, and the mainstream reply is that the excess is a known limitation of the method on very young rock.
5. The grains in a sedimentary rock came from older rocks, so dating them gives the age of the source, not the layer. Geologists date igneous layers above and below, such as lava flows or ash beds, and place the sedimentary layer between those two ages.

UNIT 5 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) What single condition must be met before almost any fossil can form, and why?
2. (5 pts) Name three modes of fossil preservation and give one real example of each.
3. (5 pts) Explain why a fish fossilized with another fish in its throat, or an ichthyosaur fossilized while giving birth, is important evidence about the speed of burial.
4. (5 pts) What were glossopetrae, what did people believe about them, and what did Steno conclude in 1667?
5. (5 pts) A slab from the Green River Formation measures 60 centimeters by 40 centimeters and holds 180 fish of one species. How many fish is that per square meter, and what does such a layer suggest about how they died?
6. (5 pts) State Steno's three principles in your own words.
7. (5 pts) What is the difference between relative dating and absolute dating, and which one does everyone agree on?
8. (5 pts) Explain why a dike that cuts through layers A through D but not layer E must be younger than D and older than E.
9. (5 pts) A cross-section shows three flat layers, 1 at the bottom, 2, and 3 on top. A fault offsets layers 1 and 2 but not layer 3, and the top of the fault is eroded at the base of 3. A dike cuts through all three layers and also cuts the fault. List the events in order.
10. (5 pts) Name the three kinds of unconformity and say which one is found where the Tapeats Sandstone rests on the Vishnu Schist in the Grand Canyon.
11. (5 pts) Name the three eras of the Phanerozoic in order, oldest first, and give the meaning of each name.
12. (5 pts) Using the table, how long does the Mesozoic era last in museum years, and which period in the table is the longest?
13. (5 pts) A layer contains both trilobites and ammonites. Using the ranges given in the reading, which periods could the layer belong to?
14. (5 pts) Explain why the discovery of the living coelacanth in 1938 matters for how we read the fossil record.
15. (5 pts) State what is observed at the base of the Cambrian, and then state the mainstream inference and the inference many Christians draw.
16. (5 pts) A bone contains one sixteenth of the carbon-14 of living bone. How many half-lives have passed, and what is the carbon-14 age?
17. (5 pts) An SAT-style problem: a sample begins with 800 carbon-14 atoms. Using $N = 800 \times (\frac{1}{2})^{(t/5730)}$, how many remain after 11,460 years, and after 17,190 years?
18. (5 pts) Which method would a geologist choose to date each of the following, and why: a charred log in a cave; a lava flow; a zircon crystal in granite; a layer of shale?
19. (5 pts) Name the three assumptions behind every radiometric date and explain why the Mount St. Helens result of 1996 bears on one of them.

20. (5 pts) Explain why a sedimentary layer is usually not dated directly by radiometric methods, and how its museum age is obtained instead.

Answer key

1. Rapid burial. A dead organism left exposed is scavenged, scattered, and decayed within weeks; only quick burial in sediment protects it from scavengers and oxygen long enough to be preserved.
2. Any three of: permineralization (petrified wood, Arizona); molds and casts (dissolved shells in limestone); carbonization (fern films above Pennsylvania coal, Mazon Creek nodules); unaltered remains (amber insects, frozen mammoths, La Brea bones); trace fossils (tracks, burrows, coprolites).
3. A fish that died while swallowing prey would have been eaten or rotted within days if left on the bottom; the same is true of a mother ichthyosaur mid-birth. For the scene to be frozen in stone, sediment must have covered the animals within hours or less. This is an observation that every geologist accepts, whatever age he puts on the layer.
4. "Tongue stones" were triangular objects found in rock on Malta and elsewhere, believed to have fallen from the sky or grown in the rock. After dissecting a shark's head in 1666, Steno concluded they were shark teeth, so the rock enclosing them must once have been loose sediment.
5. The slab is $0.6 \times 0.4 = 0.24$ square meters; $180 \div 0.24 = 750$ fish per square meter. A layer so crowded with one species suggests a mass death and burial in a single event, not fish dying one at a time over a long period.
6. Superposition: lower layers are older than upper layers in an undisturbed stack. Original horizontality: sediment is laid down in flat sheets, so tilted layers were moved later. Lateral continuity: layers extend sideways until they thin out, so matching layers across a valley were once connected.
7. Relative dating gives the order of events without numbers; absolute dating assigns a number of years. The relative order is read directly from the rock and is agreed on by everyone; the absolute age is an inference that depends on assumptions.
8. By cross-cutting relationships, the dike is younger than everything it cuts, so it is younger than A through D. Since it does not enter E and its top is eroded at the surface E rests on, the dike was already in place and worn down before E was deposited; therefore it is older than E.
9. (1) Layer 1 deposited; (2) layer 2 deposited; (3) the fault moved, offsetting 1 and 2; (4) erosion cut the fault and layers flat; (5) layer 3 deposited across the erosion surface; (6) the dike intruded, cutting all three layers and the fault, so it is the youngest event.
10. Angular unconformity, disconformity, and nonconformity. Sedimentary Tapeats Sandstone on metamorphic Vishnu Schist is a nonconformity, part of the Great Unconformity.
11. Paleozoic ("old life"), Mesozoic ("middle life"), Cenozoic ("recent life").
12. The Mesozoic begins at 252 million and ends at 66 million, so $252 - 66 = 186$ million museum years. The longest period in the table is the Cretaceous, $145 - 66 = 79$ million; the shortest is the Quaternary.
13. Trilobites run from the Cambrian to the Permian; ammonites from the Devonian to the Cretaceous. The overlap is Devonian, Carboniferous, or Permian.
14. The coelacanth was known only from fossils and believed extinct since the Cretaceous, yet it was alive. So the absence of a creature from upper layers does not prove it died out, and a creature can remain essentially unchanged through many museum ages. Gaps in the record are gaps in burial, not necessarily gaps in life.

15. Observed: nearly all the major animal body plans appear abruptly in the lowest fossil-rich layers, fully formed, with little beneath them but microbes and soft-bodied Ediacaran forms. Mainstream inference: a rapid evolutionary radiation over tens of millions of years. Many Christians' inference: the first layers of a great burial, in which the sea-floor creatures of the created world were buried first.
16. One sixteenth is $(\frac{1}{2})^4$, so four half-lives; $4 \times 5,730 = 22,920$ years.
17. $11,460 \div 5,730 = 2$ half-lives, so $800 \times \frac{1}{4} = 200$ atoms remain. $17,190 \div 5,730 = 3$ half-lives, so $800 \times \frac{1}{8} = 100$ atoms remain.
18. Charred log: carbon-14, because it was once alive and is likely under 50,000 years. Lava flow: potassium-argon, for volcanic rock. Zircon in granite: uranium-lead, for igneous crystals. Shale: no direct method; date igneous layers such as ash beds above and below it and bracket the age.
19. Known starting amount, constant decay rate, and closed system. The 1986 dome gave potassium-argon ages of hundreds of thousands to millions of years because argon was already present when the rock formed, so the starting amount was not zero; this challenges the first assumption, and the mainstream reply is that the excess is a known limitation of the method on very young rock.
20. The grains in a sedimentary rock came from older rocks, so dating them gives the age of the source, not the layer. Geologists date igneous layers above and below, such as lava flows or ash beds, and place the sedimentary layer between those two ages.

THE FLOOD, CATASTROPHE, AND THE ICE AGE

This unit asks the biggest question in geology: did the past work like the present, or did rare and violent events do most of the work? You will meet the men who argued each side, from Cuvier and Hutton to Bretz and Ager, and you will see how catastrophe returned to mainstream geology in the twentieth century. You will read the Flood account in Genesis closely, learn what flood geologists point to and how mainstream geologists answer, and then test both ways of thinking on the Grand Canyon and the Ice Age. The goal throughout is a habit, not a slogan: say what is observed, say what is inferred, and keep the two apart.

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 6.1, Uniformitarianism and Catastrophism, and define uniformitarianism, catastrophism, turbidity current.
- I can explain the main ideas of Lesson 6.2, The Flood of Genesis and Flood Geology, and define flood geology, polystrate fossil, hiatus.
- I can explain the main ideas of Lesson 6.3, The Grand Canyon as a Case Study, and define Great Unconformity, monocline, antecedent river.
- I can explain the main ideas of Lesson 6.4, The Ice Age, and define erratic, moraine, pluvial lake.

6.1 UNIFORMITARIANISM AND CATASTROPHISM

Video. Videos coming.

KEY VOCABULARY

uniformitarianism

The principle that present-day processes, acting at present-day rates, explain the geologic past.

catastrophism

The view that rare, sudden, high-energy events have shaped much of the rock record.

turbidity current

A fast, dense flow of sediment-laden water down an underwater slope that deposits a graded bed called a turbidite.

CORE IDEAS

Two ways to read the rocks. Two long words frame this unit. Uniformitarianism is the idea that the processes we watch today, rivers carrying silt, waves grinding sand, lava cooling into rock, have always worked the same way at about the same rates, so that enough time explains everything we see in the layers. Catastrophism is the idea that much of the rock record was made by rare, violent events: floods, eruptions, collapses, impacts, each doing in hours or days what ordinary processes could not do in centuries.

Both describe how a geologist reasons from what he sees to what he cannot see. Neither is itself an observation.

Cuvier and the bones of Paris. Georges Cuvier, 1769 to 1832, was the greatest anatomist in France. Working with Alexandre Brongniart on the rocks around Paris, he mapped the Paris Basin and found alternating beds of marine and freshwater deposits, with whole populations of animals vanishing from one layer to the next. He concluded that the earth's surface had been swept by sudden revolutions, and he read the fossils as a record of catastrophe.

Hutton and Lyell. James Hutton, a Scottish farmer and physician, read the rocks differently. He watched hills decay and sediment settle and inferred a cycle of destruction and renewal with no visible limit. His *Theory of the Earth* of 1788 closes with a sentence every geologist knows: "The result, therefore, of our present enquiry is, that we find no vestige of a beginning,—no prospect of an end."

Charles Lyell made Hutton's idea a system; his book's full title is his method: *Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation*, published in three volumes from 1830 to 1833. Only present causes, acting at present rates, were allowed to explain the past. A young Charles

Darwin carried the first volume aboard the Beagle in 1831 and received the second during the voyage, and Lyell's slow earth became the stage for Darwin's slow biology.

The slogan "the present is the key to the past" is often attached to Hutton, but it is not his sentence. It is a later summary of his idea, popularized by the Scottish geologist Archibald Geikie.

Catastrophe comes back. For a century after Lyell, a geologist who proposed a sudden, enormous event risked his reputation. Then the evidence pushed back.

In 1923 J Harlen Bretz published a paper in the *Journal of Geology* arguing that the Channeled Scablands of eastern Washington had been carved by a flood of almost unimaginable size. He was ridiculed, most famously at a 1927 meeting in Washington, D.C. His weakness was that he had no source for the water. Joseph Pardee supplied it in 1940, in a talk published in full in 1942, with evidence that Glacial Lake Missoula in Montana had drained suddenly when its ice dam failed. Aerial and satellite photographs of the 1960s and 1970s showed the whole flood landscape, and in 1979, at age 96, Bretz received the Penrose Medal, the Geological Society of America's highest award.

In 1929 an earthquake off the Grand Banks of Newfoundland snapped a dozen transatlantic telegraph cables in sequence down the continental slope. In 1952 Bruce Heezen and Maurice Ewing showed that a turbidity current, a dense underwater avalanche of mud and sand, had raced downhill at tens of miles per hour and spread a graded bed across the deep sea floor in a single day. Geologists now recognize such beds, called turbidites, all through the rock record.

On May 18, 1980, Mount St. Helens showed a watching nation how fast geology can happen. A landslide, a lateral blast, and mudflows laid down hundreds of feet of layered deposits in hours, and streams later cut canyons through them in days.

In 1980 Luis and Walter Alvarez and their colleagues reported a thin, worldwide clay layer rich in iridium at the boundary museum signs call the Cretaceous-Paleogene and proposed that an asteroid impact had made it. A buried crater at Chicxulub, Mexico, was identified in 1991. Whatever one makes of the sign's ages, the claim that a single day's event left a layer around the globe is now mainstream science.

Derek Ager, a British stratigrapher, gathered these threads in *The Nature of the Stratigraphical Record* in 1973. His point, in paraphrase, was that the record of any one place is mostly long quiet gaps broken by short violent episodes that do most of the depositing; he called this neo-catastrophism. Ager held to an old earth, and that is worth noticing: catastrophe came back into geology not as a religious movement but as a response to the rocks.

What a Christian brings to this. The question of whether the past was like the present is older than geology. The apostle Peter wrote of people who assume that all things continue as they were, and he answered them: "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). A Christian student can use uniformitarian reasoning as a tool for measuring rates and testing ideas, while refusing to make it a creed that rules out in advance what Scripture reports and the rocks now permit.

Thinking About Time

What the sign says. The iridium layer marks the Cretaceous-Paleogene boundary, dated at about 66 million years, when an asteroid impact ended the age of dinosaurs.

What we observe. A thin clay layer unusually rich in iridium, shocked quartz grains, and tiny glass spheres is found at the same position in rock sequences on several continents, and a buried circular structure about 110 miles across lies under the Yucatán Peninsula.

How Christians read it. Many Christian families understand the rock record within a young earth and the Flood of Genesis 6-9, and see the iridium layer as one violent event within a year of upheaval. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the museum date for the impact. Both agree that the layer is real and that it was made quickly.

PICTURE STUDY



Mount St. Helens eruption, May 18, 1980, Austin Post, U.S. Geological Survey, 1980,

Look at the scale of the ash column against the mountain and notice the dark, ground-hugging cloud at its base; this is the morning David Johnston radioed "Vancouver! Vancouver! This is it!" and the day modern geologists watched catastrophe at work.

Look closely

Talk about it

HANDS-ON ACTIVITY: SLOW DRIP VERSUS SINGLE POUR

You will need

- Two clear jars or drinking glasses
- A mix of coarse sand
- Fine sand
- And a spoonful of potting soil or flour
- Water
- A dropper or a cup with a pinhole
- A ruler
- A timer

Steps

1. Fill both jars half full of water.
2. Into the first, drip the sediment mix a pinch at a time over about an hour, letting each pinch settle before the next.
3. Into the second, stir the same amount of mix into a cup of water and pour it in all at once.
4. Let both stand overnight.
5. Measure the total thickness of sediment in each jar and look at the layering from the side.

Check your work

- The single pour usually produces one graded bed, coarse grains at the bottom fining upward, like a turbidite. The slow drip produces many thin laminae or an unsorted pile. The same amount of sediment, laid down in two ways, leaves two different records. Ask which jar looks more like the layers in a road cut near you.

PRACTICE

1. In one sentence each, define uniformitarianism and catastrophism.
2. Give the full title of Lyell's *Principles of Geology* and explain what the subtitle promises.
3. Who popularized the slogan "the present is the key to the past," and why should a careful student not attribute it to Hutton?
4. Explain why the 1929 Grand Banks cable breaks mattered to the debate between slow and fast geology.
5. Bretz published his flood explanation in 1923 and received the Penrose Medal in 1979. How many years passed between the paper and the medal, and what two kinds of evidence helped change geologists' minds?

Exam connection. ACT Science passages often present two conflicting viewpoints on the same data and ask you to identify what each side would predict; the uniformitarian-catastrophist debate is a classic example of that reasoning. AP Environmental Science covers geologic hazards, including volcanic eruptions and the 1980 Mount St. Helens event.

For families. At the table, ask whether a process has to be slow just because it is ordinary; a river that floods once a decade may move more sediment in that week than in the other nine years combined. Scholars still argue about how much of the record is “quiet time” and how much is “event,” and Ager’s neo-catastrophism remains influential. The activity is messy but safe; do it over a tray or outdoors.

Practice answers

1. Uniformitarianism holds that present processes at present rates explain the past; catastrophism holds that rare, sudden, violent events did much of the work recorded in the rocks.
2. *Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth’s Surface, by Reference to Causes Now in Operation.* The subtitle promises to explain the past only by causes that can be seen working today.
3. Archibald Geikie popularized it. Hutton never wrote the sentence; it is a later summary of his idea, so attributing it to him puts words in his mouth.
4. The cables broke in sequence down the slope, timed to the hour, which let Heezen and Ewing show that a single turbidity current had traveled hundreds of miles and laid a graded bed across a vast area in one day. It proved that a thick, widespread sedimentary layer can form in hours, not only over long ages.
5. 56 years. Pardee’s 1940 evidence for Glacial Lake Missoula supplied the source of the water, and aerial and satellite photographs in the 1960s and 1970s showed the whole flood landscape at once.

6.2 THE FLOOD OF GENESIS AND FLOOD GEOLOGY

Video. Videos coming.

KEY VOCABULARY

flood geology

The reading, held by many Christian geologists, that most fossil-bearing rock was deposited during and soon after the Flood of Genesis.

polystrate fossil

A fossil, usually a tree trunk, that stands upright through more than one sedimentary layer.

hiatus

A gap in the rock record where time passed but little or no sediment was preserved.

CORE IDEAS

What the text says. Begin with the text itself. “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). Two sources of water are named, and the first is from below. “And the waters prevailed exceedingly upon the earth; and all the high hills, that were under the whole heaven, were covered. Fifteen cubits upward did the waters prevail; and the mountains were covered.” (Genesis 7:19–20, KJV). “And God remembered Noah, and every living thing, and all the cattle that was with him in the ark: and God made a wind to pass over the earth, and the waters asswaged; The fountains also of the deep and the windows of heaven were stopped, and the rain from heaven was restrained; And the waters returned from off the earth continually: and after the end of the hundred and fifty days the waters were abated.” (Genesis 8:1–3, KJV).

Genesis gives dates. Rain fell forty days. The waters prevailed one hundred fifty days. The ark grounded on the mountains of Ararat in the seventh month, mountaintops appeared in the tenth, and Noah walked out on dry ground in the second month of the following year. From first rain to dry land, the Flood lasted about a year.

Christians have always done Flood geology. Thomas Burnet’s *Sacred Theory of the Earth* of 1681 pictured a smooth original earth whose crust collapsed into the waters beneath. John Woodward’s *An Essay toward a Natural History of the Earth* of 1695 argued that the Flood dissolved the earth’s surface and resettled it in layers by weight, fossils included. In 1823 William Buckland, Oxford’s first Reader in Geology, published *Reliquiae Diluvianae; or, Observations on the Organic Remains contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, attesting the Action of an Universal Deluge*, reading cave bones and gravels as Flood relics. By 1840, after Louis Agassiz visited Britain, Buckland

concluded that those gravels were the work of glaciers and withdrew his global reading. The Flood did not leave the church, but it left the geology departments.

George McCready Price, a self-taught writer, argued in the 1920s that the fossil order was not fixed. In 1961 John Whitcomb, a theologian, and Henry Morris, a hydraulic engineer, published *The Genesis Flood*, a detailed model of a global Flood as the source of most fossil-bearing rock. That book is the root of modern flood geology, a reading many Christian geologists hold.

What flood geologists point to. First, flat layers that cross continents. The Tapeats Sandstone at the base of the Grand Canyon has equivalents from Arizona to Wisconsin and beyond; the Coconino Sandstone covers tens of thousands of square miles; the chalk of the English Downs runs under the Channel into France and east across Europe to Kazakhstan. Water that covers continents, they argue, lays continent-sized sheets.

Second, flat contacts. Many layer boundaries are knife-sharp and nearly planar, with little sign of the valleys, soils, and roots a long-exposed surface should show.

Third, polystrate fossils: upright tree trunks passing through several layers at Joggins, Nova Scotia, and the stacked buried forests of Specimen Ridge in Yellowstone. After 1980, waterlogged logs on Spirit Lake at Mount St. Helens sank root-end first and stood upright in fresh sediment, an analogy reported in the journal *Geology* in 1983.

Fourth, soft-sediment folding. In the Kaibab monocline the Tapeats Sandstone bends through tight folds without the shattering expected of brittle rock.

Fifth, fossil graveyards: beds packed with jumbled, well-preserved creatures, such as the nautiloids of the Redwall Limestone.

Sixth, marine fossils on mountaintops: the summit of Everest is limestone holding sea creatures.

The mainstream replies, fairly stated. Shallow seas have repeatedly flooded continental interiors, and a slowly sinking shelf can receive sheet after sheet. Flat contacts are read as hiatuses: time passed, but little was deposited or eroded, and burrows and soils are often found on close inspection. Upright trees at Joggins are read as local rapid burial by river floods, and Specimen Ridge as repeated volcanic mudflows; no one disputes fast burial, only how many events and how far apart. Sandstone buried deep, warm, and under pressure can bend by ductile flow or by countless tiny fractures. Fossil beds are read as local events: storms, red tides, river floods. Everest's limestone was lifted by the collision of India with Asia, so marine rock on a mountain argues for uplift, not a water level.

Both sides agree on the observations; they disagree about how much time and how many events lie behind them.

Other Christian readings. Many Christians who hold an old earth read the Flood as a real judgment but regional, covering the world known to Noah; others hold a global Flood that was tranquil enough to leave little geologic signature. They point out that the text does not

say the Flood made the rock layers. Young-earth readers answer that fountains of the great deep and water above the mountains describe something no regional flood can be.

This course does not hand you a verdict. It trains you to say what is observed and what is inferred, and to give both the geologist and the text their due.

Thinking About Time

What the sign says. The Coconino Sandstone was deposited as desert dunes about 280 million years ago, and the chalk of England formed on a quiet sea floor over millions of years in the Cretaceous.

What we observe. Vast, flat-lying sheets of sandstone and chalk with sharp contacts; cross-beds in the Coconino whose angles have been measured and debated; tiny shells in the chalk; and no witness to the rate of deposition.

How Christians read it. Many Christian families understand these sheets as deposits of the Flood of Genesis 6-9 laid down within months, and read the sharp contacts as evidence against long gaps. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the museum ages while affirming the Flood as history. Both readings rest on the same rocks.

PICTURE STUDY



Noah's Ark, Edward Hicks, 1846,

Hicks, a Pennsylvania Quaker and sign painter, shows the animals walking two by two toward the ark under a darkening sky; notice how calm the scene is, and ask what the painting leaves out that Genesis 7:11 puts first.

Look closely

Talk about it

Safety first. An adult handles the knife, and cut away from your body.

HANDS-ON ACTIVITY: THE FLAT GAP

You will need

- Two shallow trays or baking pans
- Play sand
- A bag of potting soil or dark sand for contrast
- A spray bottle
- A kitchen knife

Steps

1. In both trays lay down a one-inch layer of light sand and press it flat.
2. In tray A, immediately add a one-inch layer of dark sand on top.
3. Put tray B outdoors, or spray it with water every day, for one week; let it dry, crack, get rained on, and collect leaves or dust.
4. Then add the dark layer to tray B.
5. Let both dry and slice straight down through each with the knife to see the contact in cross section.

Check your work

- The contact in tray A is a clean straight line; the contact in tray B shows cracks, pits, grains worked in from above, and perhaps roots or debris. Then ask: what would a contact look like after a thousand years of exposure? Flood geologists and mainstream geologists both use this reasoning; they differ on what the real contacts show.

PRACTICE

1. According to Genesis 7:11, what were the two sources of the Flood's water, and which is named first?
2. Using the text's own numbers, how many days did the rain fall, how many days did the waters prevail, and roughly how long was the whole Flood from first rain to dry ground?
3. Give the exact title of Buckland's 1823 book and explain what changed his mind by 1840.
4. Choose one piece of evidence flood geologists point to and state, in one sentence each, the flood-geology reading and the mainstream reading. Then say what both sides agree on.
5. Explain why the old-earth Christian readings described in this lesson are not the same as denying the Flood.

Exam connection. The CLT and SAT reading sections reward exactly the skill this lesson practices: separating a claim from the evidence offered for it and restating an opposing view fairly. ACT Science “conflicting viewpoints” passages are built the same way.

For families. This is the lesson most likely to raise questions at the table, so read the Genesis passages aloud together first. Christians who love Scripture hold different views on the Flood’s extent and its geologic effects, and this course states the main readings without choosing for you; your family’s church and conscience do that. Before the activity, decide where tray B will sit for a week so it is not kicked over.

Practice answers

1. The fountains of the great deep and the windows of heaven; the fountains of the deep are named first.
2. Forty days of rain, one hundred fifty days prevailing, and about one year in all.
3. *Reliquiae Diluvianae; or, Observations on the Organic Remains contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, attesting the Action of an Universal Deluge.* After Agassiz’s visit to Britain he concluded that the gravels and scratched rocks he had called Flood deposits were the work of glaciers.
4. Example: upright trees at Joggins. Flood geologists read them as rapid burial by Flood-borne sediment; mainstream geologists read them as rapid burial by local river floods in a swamp. Both agree the trees were buried quickly before they could rot.
5. Those readers affirm that the Flood happened as a real judgment in history; they differ on its extent or on whether it left a large geologic signature, not on whether Genesis is true.

6.3 THE GRAND CANYON AS A CASE STUDY

Video. Videos coming.

KEY VOCABULARY

Great Unconformity

The surface in the Grand Canyon separating tilted Precambrian rocks below from flat-lying Tapeats Sandstone above.

monocline

A step-like fold in otherwise flat layers, such as the Kaibab monocline on the canyon's east side.

antecedent river

A river that kept its course by cutting down through land that rose beneath it.

CORE IDEAS

The place. The Grand Canyon of the Colorado River in Arizona runs about 277 river miles from Lees Ferry to the Grand Wash Cliffs, is up to 18 miles wide from rim to rim, and is about a mile deep. Nowhere else is so much of the rock record laid open in one view.

The layers. At the bottom of the inner gorge lie the Vishnu Schist and the granites that cut it, dark, twisted, metamorphic rock. On them, in places, rests the Grand Canyon Supergroup, a thick, tilted stack of sedimentary layers and lava flows. Then comes a flat surface that geologists call the Great Unconformity, and above it the horizontal layers everyone photographs.

Layer	Rock type	Museum age (years)
Kaibab Limestone	cherty limestone	270 million (Permian)
Toroweap Formation	limestone, sandstone, gypsum	275 million (Permian)
Coconino Sandstone	cross-bedded sandstone	280 million (Permian)
Hermit Formation	red shale and siltstone	285 million (Permian)
Supai Group	red sandstone, shale, limestone	290 to 320 million (Pennsylvanian-Permian)
Redwall Limestone	gray limestone stained red	340 million (Mississippian)
Muav Limestone	limestone	504 million (Cambrian)
Bright Angel Shale	green shale	506 million (Cambrian)
Tapeats Sandstone	coarse brown sandstone	508 million (Cambrian)
Grand Canyon Supergroup	tilted sandstone, shale, limestone, basalt	729 to 1,250 million (Precambrian)
Vishnu Schist and granites	metamorphic and igneous	1,680 to 1,840 million (Precambrian)

The Redwall Limestone, the great cliff halfway down, holds a bed of fossil nautiloids, straight-shelled relatives of the squid, estimated in the millions over a wide area. The Coconino shows sweeping cross-beds; the Kaibab at the rim is full of marine shells.

Two questions, not one. Visitors ask how the canyon formed, but that is two questions: how were the layers laid down, and how was the canyon cut through them? The evidence for each is different.

Powell. In 1869 Major John Wesley Powell, a one-armed Civil War veteran, led nine men in four wooden boats down the Green and Colorado rivers. On August 13 he wrote in his journal, "We are now ready to start on our way down the Great Unknown." He named the Great Unconformity, saw that the tilted Supergroup had been planed off before the flat layers were laid, and argued that the river had cut the canyon while the land rose beneath it.

The carving puzzle. The Kaibab Plateau is an upwarp, a broad arch in the rock. Water runs downhill, yet the Colorado runs through the arch, not around it, cutting a mile deep through its crest. Four answers have been proposed.

Antecedence: the river was there first and sawed down as the land rose beneath it. This was Powell's view.

Superposition: the river set its course on younger layers that once covered the arch, then cut down through them into the structure below.

Headward erosion and stream capture: a steep stream working back from the west eroded upstream through the plateau, captured an older drainage, and pulled its water through the gap. Most mainstream geologists have held this view since the 1960s, with the river reaching the Gulf of California about five to six million years ago on the museum timeline.

Spillover: ancient lakes in the Bidahochi and Hopi basins east of the Kaibab filled until they overtopped the arch, and the escaping water cut the canyon rapidly. Mainstream geologists proposed versions of this idea as early as 1934 and revived it in the early 2000s; many Christian geologists also hold it, arguing that a post-Flood lake breach could have cut the canyon in weeks rather than ages.

Mainstream geologists still disagree about the canyon's age. One 2012 study argued that parts of the western canyon were cut as early as seventy million years ago on the museum timeline; a 2014 paper answered that the canyon is a set of segments of different ages, joined into one river only about five to six million years ago. The puzzle is open.

What Mount St. Helens showed. On March 19, 1982, a small eruption at Mount St. Helens melted snow in the crater and sent a mudflow across the pumice plain laid down in 1980. In one day it cut a canyon system through the loose deposits, in places up to about a hundred feet (30 meters) deep, with a winding course and side canyons, a landscape that would look, in a photograph with nothing for scale, like a desert canyon carved by a river over ages. This was loose material, and the Grand Canyon is cut in hard rock; but the example sets a rule: canyon shape alone does not tell you how long the cutting took.

Observation and inference. Observed: eleven major layers, mostly flat, with sharp contacts; tilted rocks beneath; a river running through an arch; a nautiloid bed; cross-beds; the shape of the gorge. Inferred: the ages in the table, the number of seas that came and went, which of the four carving ideas is right, and how long the cutting took. The honest student holds the first list tightly and the second list loosely.

Thinking About Time

What the sign says. The layers from Tapeats to Kaibab record nearly 240 million years of deposition, from about 508 to 270 million years ago, and the Colorado River carved the canyon over the last five to six million years.

What we observe. A measurable stack of flat layers with sharp contacts, the Great Unconformity between tilted and flat rock, fossils sorted into particular beds, and a river that today carries sediment and cuts bedrock at measurable rates.

How Christians read it. Many Christian families understand the flat layers as deposits of the Flood of Genesis 6–9 and the canyon as cut by a later lake breach or by Flood waters draining off the continent, within a few thousand years. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the museum ages for both the layers and the carving. Both can read Powell’s journal with profit.

PICTURE STUDY



The Chasm of the Colorado, Thomas Moran, 1873–74,

Moran traveled with Powell in 1873 and painted this for Congress; find the horizontal bands of the layers in the far walls, the storm over the gorge, and the tiny river at the bottom, and

ask whether the painter shows erosion as slow or violent.

Look closely

Talk about it

HANDS-ON ACTIVITY: CUTTING A CANYON TWO WAYS

You will need

- A clear plastic storage box or two clear shoebox-sized containers
- Flour
- Cornmeal
- Cocoa powder
- Colored craft sand or sand mixed with a little food coloring
- A pitcher of water
- A cup
- A piece of stiff cardboard
- A towel

Steps

1. Build four or five flat, contrasting layers an inch thick each in each box, pressing each down.
2. Tilt each box slightly by placing a book under one end.
3. In box A, pour water very slowly from a cup at the high end for twenty minutes, keeping the stream thin.
4. In box B, stand the cardboard as a dam near the high end, pour water behind it to form a “lake,” then pull the dam out suddenly.

Check your work

- The slow trickle tends to cut a narrow, V-shaped channel; the breach tends to cut a wide, flat-bottomed channel fast, often with side channels and a fan of debris at the low end. Compare the shapes with photographs of the Grand Canyon and of the Channeled Scablands coulees. Flour and cocoa stain; work on a towel.

PRACTICE

1. State the three standard dimensions of the Grand Canyon.
2. Using the table, which layer lies directly above the Redwall Limestone, and what is the museum-age gap between the Redwall and the Muav beneath it? What does a geologist call that gap?
3. Explain why the Colorado River’s route through the Kaibab upwarp is a puzzle, and name the four kinds of proposed answers.
4. Quote Powell’s August 13, 1869 journal line and give one geologic observation he made.

5. What does the 1982 Mount St. Helens canyon prove, and what does it not prove?

Exam connection. The layer table is exactly the kind of data display ACT Science asks you to read and compare; practice finding the largest gap and ordering the layers. AP Environmental Science treats plate tectonics and uplift as earth-system processes and uses the Colorado River as a water-resources case study.

For families. Ask the family which of the two questions, laying the layers or cutting the canyon, each piece of evidence actually bears on. Scholars still debate the canyon's age even on the museum timeline, with published estimates ranging from six million to seventy million years, which is a good reminder that an open question is not a weakness in science but its daily work. The activity is messy; do it outdoors or on a towel, and have a second adult hold the box when the dam is pulled.

Practice answers

1. About 277 river miles long, up to 18 miles wide, and about a mile deep.
2. The Supai Group lies above the Redwall. The museum ages are about 340 and about 505 million years, a gap of about 165 million years. The gap is called an unconformity or hiatus.
3. Water runs downhill, yet the river crosses the crest of an arch instead of flowing around it. The proposals are antecedence, superposition, headward erosion with stream capture, and lake spillover.
4. "We are now ready to start on our way down the Great Unknown." He recognized the Great Unconformity, the planed-off surface between the tilted Supergroup and the flat Tapeats above.
5. It proves that a canyon with a winding course and side canyons can be cut in a day when the material is loose and the flow is large, so shape alone does not reveal time. It does not prove that the Grand Canyon, cut in hard rock, formed the same way.

6.4 THE ICE AGE

Video. Videos coming.

KEY VOCABULARY

erratic

A boulder carried by ice and left resting on bedrock of a different kind.

moraine

A ridge or blanket of unsorted rock debris deposited at the edge or beneath a glacier.

pluvial lake

A large lake, such as Lake Bonneville, that filled a dry basin during a wetter, cooler period.

CORE IDEAS

The evidence under your feet. Across the northern United States and most of Canada, and across northern Europe, the land carries marks of ice. Boulders the size of houses, called erratics, sit on bedrock of an entirely different kind, carried from hundreds of miles away. Bedrock surfaces are polished and scored with parallel scratches called striations, all pointing the same way. Long ridges of mixed gravel and clay, called moraines, mark where an ice front stood: Long Island is built on two of them, and Cape Cod is another. Smooth, elongated hills called drumlins lie in swarms, their long axes pointing the direction the ice moved. The Great Lakes fill basins the ice gouged and dammed. Downwind of the old ice margins lie thick blankets of wind-blown silt called loess, which make the farmland of Iowa and the bluffs of the Mississippi.

In the dry West the Ice Age left water. Lake Bonneville filled much of western Utah to a depth of about a thousand feet, and its shoreline benches are cut into the mountainsides above Salt Lake City like the rings in a bathtub; the highest, the Bonneville level, stands near 5,100 feet, the Provo level near 4,750 to 4,800 feet, and the Great Salt Lake today sits near 4,200 feet. Lake Lahontan did the same in Nevada. And in eastern Washington, the Channeled Scablands record the Missoula floods: an ice dam in Idaho held back a lake of about 500 cubic miles, roughly half of Lake Michigan, nearly 2,000 feet deep at the dam, which burst and drained in a matter of days, stripping the soil off thousands of square miles and cutting Dry Falls, a horseshoe cliff three and a half miles wide and 400 feet high over which no water now falls.

Agassiz. In 1837 Louis Agassiz, president of the Swiss Society of Natural Sciences, stood before the society at Neuchâtel and argued that ice had once covered not only the Alpine valleys but much of Europe. In 1840 he published *Études sur les glaciers*, with measurements and plates, and traveled to Britain, where he showed William Buckland the same striations and moraines in Scotland. Buckland, who had once read such deposits as relics of the Flood, became a convert and defended glacial theory before the Geological

Society of London that November. Agassiz, a creationist and later a famous opponent of Darwin, had given geology the Ice Age.

The animals. The Ice Age had its own animals, and they were large. Woolly mammoths, with curved tusks and shaggy coats, ranged across the northern continents; some are found frozen in Siberian ground with skin and hair. Mastodons, shorter and heavier, browsed the forests of the eastern United States. Giant ground sloths stood taller than a man, and saber-toothed cats hunted them. At La Brea in Los Angeles, natural asphalt seeps trapped thousands of these animals, and their bones are still being dug out of the tar. With so much water locked in ice, the sea stood lower by a museum figure of about 120 meters, nearly 400 feet, and a land bridge joined Siberia to Alaska across what is now the Bering Strait.

Causes: two readings. Why would ice cover a third of the land? The mainstream answer, worked out by the Serbian engineer Milutin Milanković in the 1920s and 1930s, is that slow wobbles in the earth's orbit and tilt change how much summer sunlight reaches the far north, and that when northern summers are cool enough, winter snow fails to melt and ice sheets grow. On the museum timeline there were many glaciations within the Pleistocene, which began about 2.6 million years ago, and the last glacial maximum came about 20,000 years ago.

Many Christian geologists hold a different reading: a single Ice Age that followed the Flood and lasted a few centuries. Its physical logic is worth understanding whatever you conclude. Snow needs two things, moisture and cold. If the Flood left the oceans warm, because the fountains of the great deep and volcanic activity had heated them, evaporation would have been enormous and snowfall in the north heavy. If volcanic dust and gases from the same upheaval dimmed the sun for years, summers would have been cool and the snow would not have melted. Warm oceans give the snow; cold summers keep it. As the oceans cooled, snowfall dropped, and the ice retreated.

Both readings agree on the observations: erratics, striations, moraines, drumlins, shoreline benches, loess, and the scablands. They differ on the number of ice ages and the time they took.

The Ice Age in Job. God asked Job, "Hast thou entered into the treasures of the snow? or hast thou seen the treasures of the hail," (Job 38:22, KJV), and again, "Out of whose womb came the ice? and the hoary frost of heaven, who hath gendered it? The waters are hid as with a stone, and the face of the deep is frozen." (Job 38:29–30, KJV). Some Christians read these lines as a memory of the Ice Age itself, since Job is often placed early in history and the book speaks of ice more than any other. Label this as a reading, not a proof: the verses are certainly about God's power over frost and sea; whether they describe a particular age is an inference.



Thinking About Time

What the sign says. The Pleistocene epoch began about 2.6 million years ago and saw more than a dozen glacial advances driven by Milankovitch cycles; the last glacial

maximum was about 20,000 years ago.

What we observe. Glacial landforms and deposits on two continents, stacked sequences of till in some places, shoreline benches on dry mountainsides, frozen mammoths, and present-day glaciers whose rates of movement and melting can be measured.

How Christians read it. Many Christian families understand the evidence as one Ice Age following the Flood of Genesis 6-9, driven by warm post-Flood oceans and volcanic dust, and lasting a few hundred years. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the museum timeline of repeated glaciations. Both can walk a moraine and agree on what it is.

PICTURE STUDY



Dry Falls, Washington, photograph by Marvin D. Boland, about 1918,

This is the silent cataract of the Channeled Scablands, a cliff about 400 feet high and more than three miles wide with no river at its lip. Look at the plunge pools at its foot and the bare basalt, and picture the whole brink under water when Lake Missoula's ice dam broke.

Look closely

Talk about it

HANDS-ON ACTIVITY: MAP YOUR REGION'S ICE, OR BREAK THE ICE DAM

Option A, materials. A USGS topographic map or your state geological survey's surficial geology map, which most states publish free online, a pencil, and a notebook.

Steps. Find your home on the map and look for named moraines, drumlin fields, kettle lakes, outwash plains, or glacial lake shorelines; if you live south of the ice limit, find the limit itself or the loess bluffs along the big rivers, or the pluvial lake shorelines of the Great Basin. Sketch what you find and, if you can, drive to one feature and photograph it.

Option B, materials. A large tray or baking pan, sand, a strip of stiff plastic or a plastic lid as a dam, a pitcher of water, a towel.

Steps. Tilt the tray, build a sand “valley” across the high end, set the plastic dam across it, fill a lake behind the dam, then pull the dam out at once.

What to notice. The water strips a channel through the sand far wider than the dam opening, leaves gravel bars and a fan, and does it in seconds. Then do the same with the dam left in place and a slow leak through a small hole. Compare.

You will need

Steps

PRACTICE

1. Name four landforms or deposits that record the presence of ice, and say what each one shows.
2. Glacial Lake Missoula held about 500 cubic miles of water, and the peak outflow through the Eddy Narrows has been estimated at roughly 10 cubic miles per hour. If the lake drained at that rate throughout, about how long did it take to empty? Why is the real time somewhat longer?
3. The Bonneville shoreline stands near 5,100 feet and the Great Salt Lake today near 4,200 feet. About how much higher did the Ice Age lake stand than the lake today?
4. Explain, step by step, the physical reasoning behind the post-Flood Ice Age reading held by many Christian geologists.
5. What did Buckland change his mind about in 1840, and who persuaded him?

Exam connection. AP Environmental Science covers earth-system cycles, including the Milankovitch cycles and the sea-level changes of glacial periods. The SAT and ACT both use unit-rate and ratio problems like the Lake Missoula drainage question.

For families. At the table, ask what your own county looked like with a mile of ice above it, or with the ice front a few hundred miles north and mammoths grazing the plains. The number of ice ages and their length are exactly where the two Christian readings diverge; the landforms themselves are not in dispute. If you choose Option A, state geological surveys and the USGS both offer free map viewers, and a parent should help find the right map series.

Practice answers

1. Erratics show that ice carried boulders far from their source; striations show the direction ice scraped bedrock; moraines show where an ice front stood; drumlins show the direction of ice flow. Loess and the Great Lakes basins also count.
2. 500 divided by 10 is 50 hours, a little over two days. The real draining took longer because the outflow fell as the lake dropped; estimates range from about two days to a week.
3. About 900 feet higher.
4. Warm oceans after the Flood evaporate quickly and feed heavy snowfall in the north; volcanic dust in the air cools summers so the snow does not melt; ice sheets grow while both conditions hold; as the oceans cool and the air clears, snowfall falls off and the ice retreats.
5. He gave up reading the gravels and scratched rocks of Britain as Flood relics and accepted that glaciers had made them; Louis Agassiz persuaded him on a tour of Scotland.

UNIT 6 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) In one sentence each, define uniformitarianism and catastrophism.
2. (5 pts) Give the full title of Lyell's *Principles of Geology* and explain what the subtitle promises.
3. (5 pts) Who popularized the slogan "the present is the key to the past," and why should a careful student not attribute it to Hutton?
4. (5 pts) Explain why the 1929 Grand Banks cable breaks mattered to the debate between slow and fast geology.
5. (5 pts) Bretz published his flood explanation in 1923 and received the Penrose Medal in 1979. How many years passed between the paper and the medal, and what two kinds of evidence helped change geologists' minds?
6. (5 pts) According to Genesis 7:11, what were the two sources of the Flood's water, and which is named first?
7. (5 pts) Using the text's own numbers, how many days did the rain fall, how many days did the waters prevail, and roughly how long was the whole Flood from first rain to dry ground?
8. (5 pts) Give the exact title of Buckland's 1823 book and explain what changed his mind by 1840.
9. (5 pts) Choose one piece of evidence flood geologists point to and state, in one sentence each, the flood-geology reading and the mainstream reading. Then say what both sides agree on.
10. (5 pts) Explain why the old-earth Christian readings described in this lesson are not the same as denying the Flood.
11. (5 pts) State the three standard dimensions of the Grand Canyon.
12. (5 pts) Using the table, which layer lies directly above the Redwall Limestone, and what is the museum-age gap between the Redwall and the Muav beneath it? What does a geologist call that gap?
13. (5 pts) Explain why the Colorado River's route through the Kaibab upwarp is a puzzle, and name the four kinds of proposed answers.
14. (5 pts) Quote Powell's August 13, 1869 journal line and give one geologic observation he made.
15. (5 pts) What does the 1982 Mount St. Helens canyon prove, and what does it not prove?
16. (5 pts) Name four landforms or deposits that record the presence of ice, and say what each one shows.
17. (5 pts) Glacial Lake Missoula held about 500 cubic miles of water, and the peak outflow through the Eddy Narrows has been estimated at roughly 10 cubic miles per hour. If the lake drained at that rate throughout, about how long did it take to empty? Why is the real time somewhat longer?

18. (5 pts) The Bonneville shoreline stands near 5,100 feet and the Great Salt Lake today near 4,200 feet. About how much higher did the Ice Age lake stand than the lake today?
19. (5 pts) Explain, step by step, the physical reasoning behind the post-Flood Ice Age reading held by many Christian geologists.
20. (5 pts) What did Buckland change his mind about in 1840, and who persuaded him?

Answer key

1. Uniformitarianism holds that present processes at present rates explain the past; catastrophism holds that rare, sudden, violent events did much of the work recorded in the rocks.
2. *Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation*. The subtitle promises to explain the past only by causes that can be seen working today.
3. Archibald Geikie popularized it. Hutton never wrote the sentence; it is a later summary of his idea, so attributing it to him puts words in his mouth.
4. The cables broke in sequence down the slope, timed to the hour, which let Heezen and Ewing show that a single turbidity current had traveled hundreds of miles and laid a graded bed across a vast area in one day. It proved that a thick, widespread sedimentary layer can form in hours, not only over long ages.
5. 56 years. Pardee's 1940 evidence for Glacial Lake Missoula supplied the source of the water, and aerial and satellite photographs in the 1960s and 1970s showed the whole flood landscape at once.
6. The fountains of the great deep and the windows of heaven; the fountains of the deep are named first.
7. Forty days of rain, one hundred fifty days prevailing, and about one year in all.
8. *Reliquiae Diluvianae; or, Observations on the Organic Remains contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, attesting the Action of an Universal Deluge*. After Agassiz's visit to Britain he concluded that the gravels and scratched rocks he had called Flood deposits were the work of glaciers.
9. Example: upright trees at Joggins. Flood geologists read them as rapid burial by Flood-borne sediment; mainstream geologists read them as rapid burial by local river floods in a swamp. Both agree the trees were buried quickly before they could rot.
10. Those readers affirm that the Flood happened as a real judgment in history; they differ on its extent or on whether it left a large geologic signature, not on whether Genesis is true.
11. About 277 river miles long, up to 18 miles wide, and about a mile deep.
12. The Supai Group lies above the Redwall. The museum ages are about 340 and about 505 million years, a gap of about 165 million years. The gap is called an unconformity or hiatus.
13. Water runs downhill, yet the river crosses the crest of an arch instead of flowing around it. The proposals are antedecence, superposition, headward erosion with stream capture, and lake spillover.
14. "We are now ready to start on our way down the Great Unknown." He recognized the Great Unconformity, the planed-off surface between the tilted Supergroup and the flat Tapeats above.
15. It proves that a canyon with a winding course and side canyons can be cut in a day when the material is loose and the flow is large, so shape alone does not reveal time. It does not prove

that the Grand Canyon, cut in hard rock, formed the same way.

16. Erratics show that ice carried boulders far from their source; striations show the direction ice scraped bedrock; moraines show where an ice front stood; drumlins show the direction of ice flow. Loess and the Great Lakes basins also count.
17. 500 divided by 10 is 50 hours, a little over two days. The real draining took longer because the outflow fell as the lake dropped; estimates range from about two days to a week.
18. About 900 feet higher.
19. Warm oceans after the Flood evaporate quickly and feed heavy snowfall in the north; volcanic dust in the air cools summers so the snow does not melt; ice sheets grow while both conditions hold; as the oceans cool and the air clears, snowfall falls off and the ice retreats.
20. He gave up reading the gravels and scratched rocks of Britain as Flood relics and accepted that glaciers had made them; Louis Agassiz persuaded him on a tour of Scotland.

EARTH'S RICHES: MINING, GEMS, AND ENERGY

Every metal spoon, every brick, every gallon of gasoline, and every pinch of salt on the table came out of the ground. This unit follows those things back to their source: the ore bodies, gem deposits, coal seams, oil traps, quarries, and salt beds that God placed in the earth, and the men and women who have learned to find them and bring them up. We will learn how ore forms and how it is mined, what makes a stone precious, where coal and oil come from and what the evidence really shows, and how the plainest materials of all, stone, sand, and gravel, hold up our cities. Along the way we will practice the kind of honest accounting that good stewardship requires: real costs, real benefits, and real reclamation.

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 7.1, Ores and Mining, and define ore, grade, placer.
- I can explain the main ideas of Lesson 7.2, Gems and Precious Stones, and define corundum, carat, lapidary.
- I can explain the main ideas of Lesson 7.3, Coal, Oil, and Natural Gas, and define kerogen, cap rock, hydraulic fracturing.
- I can explain the main ideas of Lesson 7.4, Building Stones, Salt, and Stewardship, and define aggregate, Portland cement, salt dome.

7.1 ORES AND MINING

Video. Videos coming.

KEY VOCABULARY

ore

Rock from which a metal or mineral can be extracted at a profit.

grade

The percentage of useful metal in an ore; it determines how much rock must be mined per ton of metal.

placer

A deposit of heavy minerals such as gold or tin sorted and concentrated by running water.

CORE IDEAS

The oldest mining text in the world. Long before the Romans dug silver in Spain, the book of Job described a mine. “Surely there is a vein for the silver, and a place for gold where they fine it. Iron is taken out of the earth, and brass is molten out of the stone” (Job 28:1–2, KJV). A few verses later the miner himself appears: “He putteth forth his hand upon the rock; he overturneth the mountains by the roots. He cutteth out rivers among the rocks; and his eye seeth every precious thing. He bindeth the floods from overflowing; and the thing that is hid bringeth he forth to light” (Job 28:9–11, KJV). Veins, refining, smelting, tunnelling, and mine drainage are all here. In the King James Bible “brass” means copper or bronze. Job 28 is the oldest description of mining in literature, and nearly every idea in this lesson is already in it.

Ore, gangue, and grade. Rock is called **ore** only when a useful metal can be taken from it at a profit. The worthless minerals mixed in with it, usually quartz, calcite, or pyrite, are called **gangue**. The percentage of metal in the ore is its **grade**, and grade decides everything. Copper today is mined at grades well under 1 percent, often about 0.5 percent. That means a mine must dig, crush, and process about 200 tons of rock to win a single ton of copper, and the other 199 tons become waste rock and tailings. Gold is mined at a few grams per ton: parts per million. This is why a geologist drills, samples, and measures the grade before a shovel ever moves.

How ore bodies form. An ore body exists where some process gathered metals that are otherwise scattered thinly through rock. Geologists recognize several.

Hydrothermal veins. Hot water moving through cracks in the crust dissolves metals, then cools and drops them along with quartz. The Comstock Lode in Nevada was a system of such veins, rich in silver and gold.

Magmatic segregation. As a large body of magma cools, heavy minerals such as chromite settle toward the bottom in layers. Platinum and palladium are mined this way at the

Stillwater Complex in Montana and in the Bushveld of South Africa.

Placers. Running water sorts grains by weight. Gold, tin, and other heavy minerals settle in the slow spots of a stream: the inside of bends, behind boulders, in the black sand at the bottom of gravel.

Banded iron formations. Alternating bands of iron oxide and chert make up the Mesabi Range in northern Minnesota, which since the 1890s has supplied most of America's iron ore.

Evaporites. When seawater or a salt lake evaporates, it leaves beds of halite and potash. The potash mines near Carlsbad, New Mexico, work such beds.

Laterites. In hot, wet climates rain leaches almost everything out of the soil except iron and aluminum oxides. The aluminum ore bauxite is a laterite, mined in Jamaica and Australia.

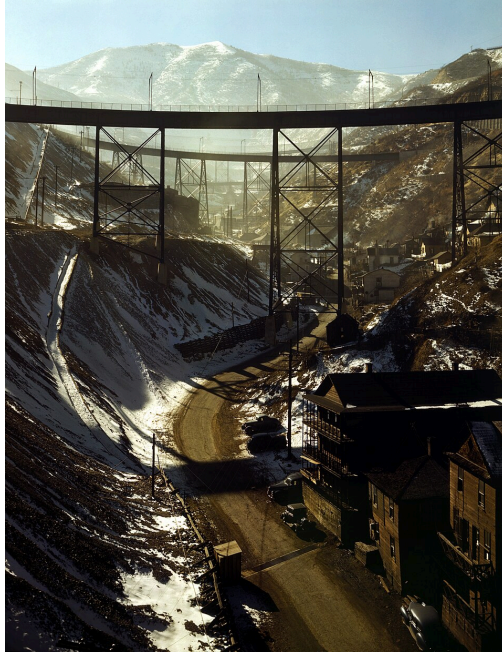
Getting it out. Placer gold is won with a pan, a sluice box, or a dredge. A hard-rock mine follows a vein underground: a **shaft** goes down, a **drift** runs along the vein, and a **stope** is the room from which ore is actually broken out. Where an ore body is large and near the surface, it is cheaper to dig it all at once as an **open pit**. Bingham Canyon, Utah, is about three-quarters of a mile deep and over two and a half miles across, and has produced copper for more than a century. Strip mining peels off the overburden to reach a flat coal seam. Solution mining pumps water down a well to dissolve salt and brings up brine.

Ore is then crushed and concentrated. **Smelting** melts the concentrate with fuel and a flux so the metal separates from the slag; refining, often by electrolysis, purifies it further. Georgius Agricola's *De re metallica* of 1556, with hundreds of woodcuts, remained the standard mining text for two hundred years; Herbert Hoover, a mining engineer before he was president, translated it into English in 1912.

The gold rushes. America's first rush was in Georgia in 1829, around Dahlonega. On January 24, 1848, James Marshall found gold flakes in the tailrace of Sutter's Mill at Coloma, California, and the forty-niners followed in 1849. The Comstock Lode, found in 1859, made Virginia City, Nevada, a silver capital. Gold found on Bonanza Creek in the Yukon in 1896 set off the Klondike rush, whose miners hauled a year's supplies up the Chilkoot Pass in the snow.

Safety and reclamation. Mining has always been dangerous. In 1815 Sir Humphry Davy enclosed a lamp flame in fine wire gauze so that it could not ignite the explosive "firedamp" in coal mines; the Davy lamp saved thousands of lives. In 1977 Congress passed the Surface Mining Control and Reclamation Act, which requires surface coal mines to post a bond and restore the land to its approximate original contour when mining ends. The trade-off is plain: every metal thing you own came from a hole in the ground, and the hole must be dug with care and then healed. Moses promised Israel "a land whose stones are iron, and out of whose hills thou mayest dig brass" (Deuteronomy 8:9, KJV). Digging is not the problem; digging carelessly is.

PICTURE STUDY



Carr Fork Canyon, Bingham Copper Mine, Utah, Andreas Feininger, November 1942,

Look at the scale: the trestle bridge carries ore trains across the canyon above a mining town, and the benched hillsides are the terraces of the open pit. Notice how low-grade ore is handled by sheer volume, with whole trains devoted to waste rock.

Look closely

Talk about it

HANDS-ON ACTIVITY: COOKIE MINING

You will need

- Two or three chocolate chip cookies of different brands
- Toothpicks
- A paper clip
- Graph paper
- A pencil
- A timer

Steps

1. Trace each cookie on the graph paper and count the squares it covers; this is your “land.” Give yourself a budget: each cookie costs 5 units, each toothpick 2 units, the paper clip 4 units, and each minute of mining costs 1 unit.
2. Mine the chips out with your tools only, no fingers, for a fixed time.
3. Each whole chip is worth 3 units; each half chip 1 unit.

4. Then “reclaim”: push the crumbs back inside the traced outline and pay 1 unit for every square the crumbs now cover outside the line.

Tips

- **Alternative.** fill a pie tin with sand and a few painted BBs or bits of pyrite, add water, and learn to swirl and tilt until the heavy grains collect at the bottom edge, exactly as a forty-niner did.

Check your work

- Which cookie had the best grade (chips per square)? Which tools paid for themselves? Did a faster, rougher dig earn more before reclamation and less after? That tension is the real economics of mining.

PRACTICE

1. What is the difference between ore and gangue?
2. Name three ways an ore body can form and give one example of each.
3. A copper mine’s ore averages 0.5 percent copper. How many tons of ore must be dug and processed to produce 1 ton of copper? How many for 50,000 tons of copper, roughly a year’s output for a mid-sized mine?
4. Explain why an open pit is chosen for some ore bodies and underground mining for others.
5. What did the Davy lamp do, and what does the Surface Mining Control and Reclamation Act of 1977 require?

Exam connection. AP Environmental Science tests mining directly in its Land and Water Use unit: ore grade, overburden, tailings, open-pit versus subsurface mining, and reclamation under the 1977 act. ACT science passages often present ore-grade or yield tables and ask you to compute tons of waste per ton of product.

For families. Ask at the table where the copper in the house wiring probably came from, and what 200 tons of rock per ton of copper means for the size of the pit. Scholars still debate how some banded iron formations formed, so treat textbook explanations of them as inference rather than observation. The cookie activity is safe for all ages; the pie-tin panning gets water everywhere, so do it outdoors or in the sink.

Practice answers

1. Ore is rock from which a metal can be extracted at a profit; gangue is the worthless mineral matter, such as quartz or calcite, that comes out mixed with it and must be separated and discarded.
2. Any three: hydrothermal veins (Comstock Lode silver), magmatic segregation (Stillwater platinum and chromite), placers (California gold), banded iron formations (Mesabi Range iron), evaporites (Carlsbad potash), laterites (Jamaican bauxite).

3. $1 \div 0.005 = 200$ tons of ore per ton of copper. For 50,000 tons of copper, $50,000 \times 200 = 10,000,000$ tons of ore.
4. An open pit is cheaper per ton and is used when the ore body is large, low-grade, and near the surface, so that removing the overburden pays. Underground mining follows a narrow, rich vein deep in the rock, where stripping everything above it would cost far more than the ore is worth.
5. The Davy lamp of 1815 enclosed the flame in wire gauze so it would not ignite explosive mine gas. The 1977 act requires surface coal mines to post a bond and reclaim the land, restoring it to approximately its original contour after mining.

7.2 GEMS AND PRECIOUS STONES

Video. Videos coming.

KEY VOCABULARY

corundum

Aluminum oxide, hardness 9; red corundum is ruby, all other colors are sapphire.

carat

The unit of gem weight, exactly 0.2 gram; five carats equal one gram.

lapidary

A craftsman who cuts and polishes gemstones, or the craft itself.

CORE IDEAS

What makes a gem. A gem is a mineral, or occasionally an organic material, that is beautiful, durable, and rare. All three are needed. Fluorite comes in gorgeous purples and greens but, at hardness 4, will not survive on a ring. Quartz is hard enough but too common to be worth much. Diamond has all three: brilliance, hardness 10, and scarcity. Nearly every gem is a crystal, and crystals grow in one of six basic systems according to the symmetry of their atoms: diamond and garnet are cubic, beryl hexagonal, corundum and quartz trigonal, topaz orthorhombic. The system governs the shape of the rough stone and how a cutter can work it.

The chief gems and their minerals. *Diamond* is pure carbon, the hardest natural substance. It forms deep in the mantle and is carried up in narrow volcanic pipes of a rock called **kimberlite**. At Kimberley, South Africa, miners dug the “Big Hole” into a kimberlite pipe by hand between 1871 and 1914, taking out about 14.5 million carats. On January 26, 1905, at the Premier Mine near Pretoria, a mine manager spotted a crystal in the pit wall: the Cullinan, 3,106 carats, the largest gem diamond ever found, cut in Amsterdam in 1908 for the British crown jewels. At Crater of Diamonds State Park in Arkansas visitors dig a weathered pipe and keep what they find; the 40.23-carat Uncle Sam turned up there in 1924.

Ruby and sapphire are both **corundum**, aluminum oxide, hardness 9. A trace of chromium makes it red and we call it ruby; iron and titanium make it blue, and every other color of corundum is called sapphire. Montana produces fine sapphires from Yogo Gulch and from Missouri River and Rock Creek gravels.

Emerald and aquamarine are both **beryl**, hardness 7.5 to 8, green from chromium or blue from iron. *Topaz*, hardness 8, is the standard for that number on the Mohs scale. *Amethyst* and *citrine* are quartz, hardness 7, purple or yellow from traces of iron. *Garnet*, usually deep red, is about 7. *Tourmaline* comes in more colors than any other gem. *Opal* is hardened silica gel whose tiny spheres break light into flashes of color; at hardness about 6 it needs gentle handling. *Jade* is either nephrite or jadeite, tough rather than hard, carved for thousands of

years. *Turquoise* is a blue copper phosphate of the American Southwest. *Pearl* and *amber* are organic: a pearl is layered calcium carbonate built by an oyster around an irritant; amber is fossilized tree resin, hardness only 2 to 2.5.

The four Cs. Jewelers grade a diamond by cut, color, clarity, and carat weight. A **carat** is exactly 0.2 gram, so five carats make a gram; the Cullinan weighed 621.2 grams, about 1.4 pounds. Cut alone depends on human skill; color and clarity are judged against standard scales. Price rises much faster than weight: a 2-carat stone of a given quality costs far more than two 1-carat stones, because large clean crystals are rare.

Cutting and polishing. A **lapidary** shapes gems. Diamond is cut with diamond, using saws and wheels charged with diamond dust, and its many flat faces, or facets, are placed at angles calculated to bounce light back out the top. Softer stones are ground with silicon carbide and polished with finer and finer grit, which is what a rock tumbler does slowly in a barrel.

Honest labelling. Laboratories can now grow diamond, ruby, sapphire, and emerald that are chemically identical to mined stones; these are called **synthetic**. Natural stones are also often heated, irradiated, oiled, or dyed to improve their color. None of this is wrong; hiding it is. Federal trade rules require that synthetic and treated stones be disclosed, because a gem's price rests on rarity, and a buyer who pays for rarity deserves to know whether he is getting it.

Gems in Scripture. The high priest of Israel wore a breastplate set with twelve stones, one for each tribe. "And thou shalt set in it settings of stones, even four rows of stones: the first row shall be a sardius, a topaz, and a carbuncle: this shall be the first row. And the second row shall be an emerald, a sapphire, and a diamond. And the third row a ligure, an agate, and an amethyst. And the fourth row a beryl, and an onyx, and a jasper: they shall be set in gold in their inclosings" (Exodus 28:17-20, KJV). The New Jerusalem is founded on twelve as well: "And the foundations of the wall of the city were garnished with all manner of precious stones. The first foundation was jasper; the second, sapphire; the third, a chalcedony; the fourth, an emerald; The fifth, sardonyx; the sixth, sardius; the seventh, chrysolyte; the eighth, beryl; the ninth, a topaz; the tenth, a chrysoprasus; the eleventh, a jacinth; the twelfth, an amethyst" (Revelation 21:19-20, KJV).

Be careful: ancient stone names do not map neatly onto modern minerals. The word translated "sapphire" very likely meant lapis lazuli, the opaque blue stone of Egypt and Persia, rather than blue corundum, though scholars cannot be certain. Read the lists for what they show: that God counts these stones precious and names them one by one. "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter" (Proverbs 25:2, KJV).

PICTURE STUDY



*The Cullinan diamond in the rough, photographer unknown, circa 1905; from Julius Wodiska, *A Book of Precious Stones*, 1909,*

This is a fist-sized stone, about 4 inches tall. Notice the flat, glassy cleavage surface on one side: the Cullinan is believed to be only part of a larger crystal, and the rest has never been found.

Look closely

Talk about it

Safety first. Alum is a food-grade pickling spice but keep it and the solution away from small children and pets, use a towel with hot water, and do not eat the crystal.

HANDS-ON ACTIVITY: GROW ALUM CRYSTALS

You will need

- Alum from the spice or pickling aisle
- A glass jar
- Hot tap water
- A saucer
- Thread
- A pencil

Steps

1. Stir alum into about half a cup of very hot water a spoonful at a time until no more dissolves, roughly 3 to 4 tablespoons.

2. Pour a little into a saucer and let it sit overnight to make small seed crystals.
3. Tie the best seed to a thread, hang it from a pencil laid across the jar of remaining solution, cover loosely, and leave it undisturbed for a week.

Tips

- **Alternative.** identify a handful of tumbled stones with a hand lens, a steel nail, and a glass plate, using the Mohs numbers in this lesson.

Check your work

- The crystal grows with flat faces at fixed angles, the same angles every time, because its atoms stack in a cubic pattern; that is what a crystal system means.

PRACTICE

1. What three qualities make a mineral a gem, and why does fluorite fail the test?
2. Ruby and sapphire are the same mineral. What is it, and what makes the difference in color?
3. The Cullinan weighed 3,106 carats. Convert that to grams, then to pounds (1 pound is about 454 grams). The largest stone cut from it, Cullinan I, weighs 530.2 carats; what fraction of the original rough is that?
4. Explain why a single 2-carat diamond costs much more than two 1-carat diamonds of the same quality.
5. Why do scholars hesitate to say that the “sapphire” of Exodus 28 is the blue corundum we call sapphire today?

Exam connection. The SAT and ACT math sections regularly use unit conversions and percent problems of exactly the carat-to-gram kind above. AP Environmental Science asks about diamond and gold mining as examples of high-value, low-grade extraction and its land footprint.

For families. Talk about why the twelve stones of the breastplate were named one by one, and what it means that the honor of kings is to search out a matter. Parents should know that the identification of ancient gem names is genuinely uncertain and that reference works disagree. The alum solution is hot when first mixed; a parent should pour.

Practice answers

1. Beauty, durability, and rarity. Fluorite is beautiful but too soft, hardness 4, to survive wear in jewelry.
2. Corundum, aluminum oxide. Traces of chromium make it red (ruby); iron and titanium make it blue, and every non-red color is called sapphire.
3. $3,106 \times 0.2 \text{ g} = 621.2 \text{ g}$, which is $621.2 \div 454 \approx 1.37$ pounds. Cullinan I is $530.2 \div 3,106 \approx 0.17$, about 17 percent of the rough; most of the rest was lost as cuttings and smaller stones.

4. Price depends on rarity, and large flawless crystals are far rarer than small ones; so value rises faster than weight.
5. Ancient stone names were applied by color and appearance, not chemistry. The word most likely referred to lapis lazuli, the opaque blue stone widely used in the ancient Near East, though this remains uncertain.

7.3 COAL, OIL, AND NATURAL GAS

Video. Videos coming.

KEY VOCABULARY

kerogen

The waxy organic matter in source rock that breaks down into oil and gas when heated.

cap rock

An impermeable layer, such as shale or salt, that seals oil and gas in a reservoir.

hydraulic fracturing

Cracking shale with water and sand pumped at high pressure so that oil and gas can flow to a horizontal well.

CORE IDEAS

What they are. Coal, oil, and natural gas are **hydrocarbons**, compounds of hydrogen and carbon that release stored energy as heat when burned. Coal is a solid, mostly carbon, often with plant structure still visible. Crude oil is a liquid mixture of many hydrocarbons. Natural gas is mostly methane, one carbon and four hydrogens.

How coal forms. Coal is made from plants; the fossil bark, leaves, and trunks in the seams settle that. The question is how the plants were buried. The textbook model says a vast peat swamp accumulated plant matter for a very long time; burial under sediment then squeezed and heated the peat into **lignite**, then **bituminous** coal, then **anthracite**, each step raising the carbon content. Roughly ten feet of peat make one foot of coal.

A second model, held by a number of Christian geologists, starts from an observation. When Mount St. Helens erupted in 1980, its blast swept about a million trees into Spirit Lake as a floating log mat. Over the following years the logs sank, many upright, and a layer of bark and wood fragments collected on the lake bottom as a peat-like deposit. On this model many coal seams are log mats torn up and dumped by the Flood of Genesis 6 to 9, not swamps that grew in place. Its supporters note that many seams lie on rock with no soil beneath them, that some are flat and continuous for hundreds of miles, and that upright trunks sometimes cross several layers. Mainstream geologists reply that some seams do have root-penetrated underclays, which the swamp model explains well. Observe the seam; the history is inference.

Where American coal is. The Appalachian basin, Pennsylvania to Alabama, includes the anthracite of northeastern Pennsylvania. The Illinois basin holds bituminous coal. The Powder River Basin of Wyoming and Montana, with seams up to 100 feet thick, is now the largest producer, strip-mined and reclaimed as grazing land behind the pit.

How oil and gas form. Oil begins as plankton and algae buried in fine mud. The mud becomes a **source rock** such as black shale, and its organic matter becomes a waxy

substance called **kerogen**. With heat, kerogen breaks down into oil, and with more heat into gas. Lighter than water, the oil migrates upward through porous rock until something stops it. A good **reservoir rock** such as sandstone or porous limestone holds it in its pores; an impermeable **cap rock** such as shale or salt seals it in; and the shape that holds the oil in place is the **trap**. The commonest traps are an arched fold called an anticline, a fault that slides sealing rock against the reservoir, and a salt dome that pushes up through the layers and bends them.

The American oil story. Edwin Drake struck oil at 69.5 feet at Titusville, Pennsylvania, on August 27, 1859, the first commercial oil well. On January 10, 1901, the Lucas well at Spindletop, near Beaumont, Texas, blew in over a salt dome and spouted an estimated 100,000 barrels a day for nine days before it was capped, and made Texas an oil state. A century later two shale plays rewrote the map: the Bakken of North Dakota for oil and the Marcellus of Pennsylvania for gas.

Finding oil today begins with **seismic surveys**: trucks thump the ground, geophones record the echoes, and computers map the layers and traps a mile down. A rig then drills a hole lined with steel casing and cement. Shale holds oil and gas but does not let them flow, so engineers drill horizontally along the layer and pump water, sand, and a little chemical at high pressure to crack it; the sand props the cracks open. This is **hydraulic fracturing**. It has made the United States the world's largest producer of oil and gas, lowered fuel costs, and brought work to rural counties. Its costs are also real: several million gallons of water per well, salty wastewater that must be handled, small earthquakes linked to deep wastewater injection, and truck traffic and noise. States regulate casing and water handling to manage these. State both columns of the ledger.

Can oil and coal form quickly?. Yes, in the laboratory. In 1913 the German chemist Friedrich Bergius, later a Nobel laureate, heated cellulose under pressure and produced a coal-like material in hours. In 2013 the Pacific Northwest National Laboratory reported turning algae slurry into crude-like oil in under an hour at about 350 degrees Celsius and high pressure. Time, then, is not the essential ingredient; heat and pressure are. Mainstream geologists accept the chemistry and infer that natural burial supplied lower temperatures over longer times; Christian geologists who hold a young earth point to the same experiments as evidence that rapid burial in the Flood could have done the job. The experiments are observation; the history is inference.

Energy density. Fuels differ in heat per pound. Dry wood gives about 16 megajoules per kilogram; lignite 10 to 15; bituminous coal 24 to 30; anthracite about 30 to 33; crude oil 42 to 45; natural gas 50 to 55. That is why oil displaced coal in ships. "The earth is the LORD's, and the fulness thereof; the world, and they that dwell therein" (Psalm 24:1, KJV). These fuels are His provision; using them well, neither wasting nor fearing them, is part of keeping the garden.



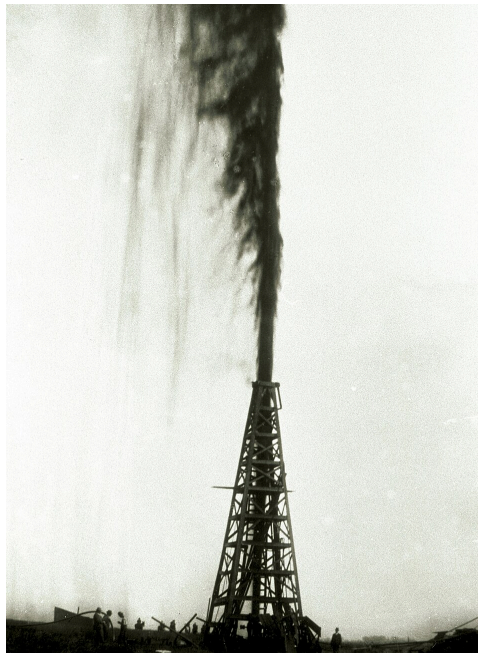
Thinking About Time

What the sign says. Museum labels call Pennsylvania’s anthracite “Carboniferous, about 300 million years old,” and the Bakken oil “Devonian to Mississippian, about 360 million years old.” Textbooks say coal “requires millions of years” to form.

What we observe. Coal seams with plant fossils, upright trunks, and in some places no soil beneath; kerogen in shale; oil in traps; laboratory experiments that make coal-like and oil-like substances in hours to days with heat and pressure; the Spirit Lake log mat forming a peaty layer within a few years of 1980. The ages come from the standard geologic column and from radiometric dates on nearby volcanic layers, which are measured; the ages assigned to the coal itself are inferences.

How Christians read it. Many Christian families understand the coal and oil of the earth as the buried forests and seas of the pre-Flood world, laid down rapidly in the Flood of Genesis 6 to 9 a few thousand years ago. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the museum ages while still confessing that the fuels are God’s provision. Both honor Scripture; neither should sneer at the other or at the geologists who built the column.

PICTURE STUDY



The Lucas Gusher at Spindletop, Texas, John Trost, January 10, 1901,

The plume of oil towers more than 100 feet above the wooden derrick while men stand at its base. This is what an uncontrolled reservoir looks like; the first “blowout preventers” were invented to keep it from happening again.

Look closely

Talk about it

Safety first. Do it on a tray; oil and gravel do not go down the sink.

HANDS-ON ACTIVITY: THE OIL TRAP IN A CUP

You will need

- A clear plastic cup
- Aquarium gravel or coarse sand
- A lump of modelling clay
- Vegetable oil tinted with a drop of food coloring
- A syringe without a needle or a turkey baster
- A drinking straw
- A tray

Steps

1. Fill the cup two-thirds with gravel and add water until it is just covered; this is your reservoir rock.
2. Press a tight layer of clay over the top as cap rock, doming it slightly in the middle.
3. Push the syringe tip through the clay at the edge and inject oil slowly into the gravel; watch it rise and collect under the dome, where the cap stops it.
4. Now “drill”: push the straw through the clay at the crest of the dome and gently draw up.

Check your work

- Oil floats on water and gathers at the highest point under the cap; a straw placed off the crest draws water instead, which is why seismic mapping matters.

PRACTICE

1. List the four stages of coal from least to most mature, and name the coal region that produces the most tonnage in the United States today.
2. What four things are needed for an oil field to exist?
3. Use these approximate figures to compute BTU per dollar and rank the fuels: natural gas at \$4.00 per thousand cubic feet, 1,037 BTU per cubic foot; gasoline at \$3.50 per gallon, 120,000 BTU per gallon; coal at \$60 per ton, 19,500,000 BTU per ton; electricity at \$0.15 per kilowatt-hour, 3,412 BTU per kilowatt-hour.
4. Explain why the “floating forest” model and the “swamp” model can look at the same coal seam and draw different conclusions.
5. State one real benefit and one real cost of hydraulic fracturing.

Exam connection. AP Environmental Science’s Energy Resources and Consumption unit covers coal rank, oil and gas formation, hydraulic fracturing with its trade-offs, and

energy conversion problems exactly like the BTU-per-dollar question above. ACT science passages frequently present energy density tables for ranking fuels.

For families. Ask where the house's heat and electricity come from and what it costs per BTU. The origin of coal seams is a live debate between the swamp and transported-mat models, and even mainstream geologists allow that some seams formed from drifted material; teach it as an open question. The oil-trap activity is messy but safe; younger siblings enjoy the drilling part.

Practice answers

1. Peat, lignite, bituminous, anthracite. The Powder River Basin of Wyoming and Montana.
2. A source rock rich in kerogen, a porous reservoir rock, an impermeable cap rock, and a trap such as an anticline, fault, or salt dome.
3. Natural gas: $1,037,000 \div 4 \approx 259,000$ BTU per dollar. Gasoline: $120,000 \div 3.50 \approx 34,300$. Coal: $19,500,000 \div 60 = 325,000$. Electricity: $3,412 \div 0.15 \approx 22,700$. Ranking from cheapest heat to dearest: coal, natural gas, gasoline, electricity. Note that gasoline and electricity buy convenience, not just heat.
4. Both models accept the observations, plant fossils, flat seams, and the presence or absence of soil beneath. The disagreement is over the unobserved history: whether plants grew in place in a swamp over a long time or were transported and dumped rapidly as a log mat. The seam is observation; the story of how it got there is inference.
5. Benefit: it made the United States the world's largest oil and gas producer and lowered fuel costs. Cost: any of water use of several million gallons per well, salty wastewater that must be handled, small earthquakes linked to deep wastewater injection, truck traffic and noise.

7.4 BUILDING STONES, SALT, AND STEWARDSHIP

Video. Videos coming.

KEY VOCABULARY

aggregate

Crushed stone, sand, and gravel used in concrete and road building; the largest-tonnage mined material in the United States.

Portland cement

The binder in modern concrete, made by burning limestone and clay in a kiln and grinding the clinker with gypsum.

salt dome

A plug of halite that has flowed upward through overlying rock because salt is lighter than the rock above it; a common oil trap along the Gulf Coast.

CORE IDEAS

Stone in architecture. A nation builds with what lies under it. **Granite**, hard and slow to weather, makes monuments. Mount Rushmore was carved from 1927 to 1941 into Black Hills granite, and Quincy, Massachusetts, granite, hauled on America's first railway in 1826, built the Bunker Hill Monument. **Marble**, limestone recrystallized by heat and pressure, takes a polish and glows in sunlight. Vermont and Georgia quarries supplied much of Washington; Carrara in Italy supplied Michelangelo. The Lincoln Memorial is a geology lesson in itself: Colorado Yule marble outside, Indiana limestone for the inner walls and columns, Georgia white marble for the statue, and pink Tennessee marble for the floor. **Limestone** cuts easily and weathers to a soft gray. Indiana limestone from around Bedford faces the Empire State Building, the Pentagon, the National Cathedral, and many state capitols. **Sandstone** is softer still: the brownstones of New York and Boston were cut from Connecticut River quarries. **Slate**, which splits into thin sheets, roofed houses and made blackboards from quarries in Vermont, New York, and eastern Pennsylvania.

You can read these stones in your own town's courthouse, bank, and oldest church. Granite shows speckled crystals of quartz, feldspar, and mica. Limestone is uniform and often holds fossil shells and crinoid stems. Marble has a sugary sparkle and may show swirled bands. Sandstone shows sand grains and sometimes old bedding lines. A hand lens and ten minutes will tell you which you are leaning on.

Concrete and cement. Most building today is concrete: gravel and sand bound by cement. Cement begins with limestone and clay burned in a kiln at about 1,450 degrees Celsius to make clinker, which is ground with a little gypsum into **Portland cement**, patented by Joseph Aspdin of Leeds in 1824. Add water and it forms crystals that lock the aggregate together. Older is lime mortar: limestone burned to quicklime, slaked with water, mixed with sand, and left to harden as it draws carbon dioxide from the air and turns back into calcite.

The Romans found that lime mixed with volcanic ash from near Pozzuoli, by Vesuvius, set hard even under seawater; the Pantheon's dome, poured in the second century, still stands as the largest unreinforced concrete dome in the world.

Salt. Halite, sodium chloride, is the one mineral everyone eats. It occurs as evaporite beds where ancient seas dried, and as **salt domes** where a buried bed, lighter than the rock above, flowed upward in a plug thousands of feet tall. Beneath Detroit, about 1,100 feet down, a mine opened in 1910 works rooms so wide that trucks drive through them. Under Cleveland a mine runs out beneath Lake Erie at about 1,800 feet. Louisiana's salt domes are mined for salt and hollowed for the Strategic Petroleum Reserve. Utah's Great Salt Lake is the remnant of a far larger lake whose old shorelines ring the mountains; its water is several times saltier than the sea. West of it the Bonneville Salt Flats, about 30,000 acres of hard halite, are so flat that land speed records have been set there since the 1930s. In the ancient world salt stood for permanence and worth. "Ye are the salt of the earth: but if the salt have lost his savour, wherewith shall it be salted? it is thenceforth good for nothing, but to be cast out, and to be trodden under foot of men" (Matthew 5:13, KJV).

The humble aggregates. The greatest tonnage mined in America is not coal or iron but crushed stone, sand, and gravel: **aggregate**. The USGS reports roughly 1.5 billion tons of crushed stone and about 1 billion tons of sand and gravel a year, nearly all going into roads, foundations, and concrete. Cheap and heavy, aggregate is quarried near where it is used, so almost every county has a gravel pit or quarry. These are the mines you drive past without noticing.

Reclamation that worked. A quarry does not have to end as a hole. At Tod Inlet on Vancouver Island, Robert Butchart's cement works exhausted its limestone quarry in the early 1900s. His wife Jennie carted in topsoil by horse and wagon, planted the pit floor, and hung ivy down the walls; by 1921 the Sunken Garden was complete, and it now draws a million visitors a year. Since the 1977 reclamation law, mined coal lands in Appalachia and the West have been regraded and returned to pasture, forest, wildlife habitat, even airports; the Abandoned Mine Land fund, paid for by a fee on coal, has reclaimed thousands of older sites abandoned before the law existed.

Your own stewardship. "And the LORD God took the man, and put him into the garden of Eden, to dress it and to keep it" (Genesis 2:15, KJV). Dressing and keeping are both commands: to use and to care for. Responsible use is not refusing to dig; it is digging what is needed, wasting little, recycling, restoring what was disturbed, and being honest about costs. For a student that looks like ordinary things: turning off lights, repairing rather than replacing, and knowing where things come from so that gratitude is possible. "The earth is the LORD's, and the fulness thereof; the world, and they that dwell therein. For he hath founded it upon the seas, and established it upon the floods" (Psalm 24:1-2, KJV). What is His, we keep for Him.

PICTURE STUDY



Lincoln Memorial under construction, Harris & Ewing, 1914,

Notice the marble columns rising in drums on a concrete and granite base, with stacked blocks and a crane in the foreground. Everything in the photograph, from the marble to the steel of the crane, was mined or quarried somewhere.

Look closely

Talk about it

Safety first. Hydrated lime is caustic; wear gloves and safety glasses and keep it off skin and out of eyes. Never scratch a monument or a church wall hard enough to mark it; test on a loose chip or the rough back of a block.

HANDS-ON ACTIVITY: STONE SCAVENGER HUNT

You will need

- A hand lens
- A notebook
- A camera or phone
- A copy of the identification notes from this lesson
- A steel nail

Steps

1. Walk the oldest blocks of your town and record every building faced with natural stone: the courthouse, churches, the post office, banks, cemetery monuments.

2. For each one, note the color, whether you can see crystals or grains or fossils, whether it sparkles, and whether a nail scratches it; then name the rock.
3. Photograph each and mark it on a hand-drawn map.
4. If the building has a cornerstone or a plaque, record the date.

Tips

- **Alternative.** make two small “bricks” in muffin cups, one of sand and water alone and one of sand mixed with hydrated mason’s lime from a hardware store, let both cure for a week, and compare their strength.

Check your work

- Older buildings usually use local stone; newer ones use stone shipped from far away or none at all.

PRACTICE

1. Name four building stones and one famous structure made of each.
2. What is the difference between cement, concrete, and mortar?
3. The USGS reports about 1.5 billion tons of crushed stone and about 1 billion tons of sand and gravel mined in the United States each year. With a population of about 335 million, how many tons of aggregate is that per person per year? About how many pounds?
4. Explain why a salt dome often makes a good oil trap.
5. What did Jennie Butchart do with an exhausted limestone quarry, and what does the 1977 law require of a coal mine today?

Exam connection. AP Environmental Science covers mining impacts and reclamation and expects students to compute per-capita resource use as in question 3. ACT science reasoning passages often include tables of material properties, such as hardness and weathering rates of building stones, to be compared and ranked.

For families. Talk about what the house is made of and where each material came from: the concrete footings, the brick, the shingles, the gravel in the driveway. The salt-dome and evaporite story is well established, but the age of the Great Salt Lake’s old shorelines is a museum figure and depends on dating assumptions, so treat it as inference. The scavenger hunt is a fine family walk; lime bricks need adult supervision.

Practice answers

1. Granite (Mount Rushmore, Bunker Hill Monument), marble (the Lincoln Memorial exterior), limestone (the Empire State Building, the National Cathedral), sandstone (New York brownstones), slate (roofs and blackboards).
2. Cement is the gray powder made by burning limestone and clay; concrete is cement mixed with sand, gravel, and water; mortar is cement or lime mixed with sand and water to bond

bricks or stones.

3. $2.5 \text{ billion} \div 335 \text{ million} \approx 7.5 \text{ tons per person per year}$, or roughly 15,000 pounds.
4. As the salt plug rises it bends the surrounding layers upward and seals against them, and salt itself is impermeable; oil migrating upward through the tilted reservoir rock is caught against the dome and held there.
5. She filled it with topsoil and planted it as the Sunken Garden, now Butchart Gardens. The 1977 act requires that mined land be regraded to approximately its original contour and reclaimed, backed by a bond posted before mining begins.

UNIT 7 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) What is the difference between ore and gangue?
2. (5 pts) Name three ways an ore body can form and give one example of each.
3. (5 pts) A copper mine's ore averages 0.5 percent copper. How many tons of ore must be dug and processed to produce 1 ton of copper? How many for 50,000 tons of copper, roughly a year's output for a mid-sized mine?
4. (5 pts) Explain why an open pit is chosen for some ore bodies and underground mining for others.
5. (5 pts) What did the Davy lamp do, and what does the Surface Mining Control and Reclamation Act of 1977 require?
6. (5 pts) What three qualities make a mineral a gem, and why does fluorite fail the test?
7. (5 pts) Ruby and sapphire are the same mineral. What is it, and what makes the difference in color?
8. (5 pts) The Cullinan weighed 3,106 carats. Convert that to grams, then to pounds (1 pound is about 454 grams). The largest stone cut from it, Cullinan I, weighs 530.2 carats; what fraction of the original rough is that?
9. (5 pts) Explain why a single 2-carat diamond costs much more than two 1-carat diamonds of the same quality.
10. (5 pts) Why do scholars hesitate to say that the "sapphire" of Exodus 28 is the blue corundum we call sapphire today?
11. (5 pts) List the four stages of coal from least to most mature, and name the coal region that produces the most tonnage in the United States today.
12. (5 pts) What four things are needed for an oil field to exist?
13. (5 pts) Use these approximate figures to compute BTU per dollar and rank the fuels: natural gas at \$4.00 per thousand cubic feet, 1,037 BTU per cubic foot; gasoline at \$3.50 per gallon, 120,000 BTU per gallon; coal at \$60 per ton, 19,500,000 BTU per ton; electricity at \$0.15 per kilowatt-hour, 3,412 BTU per kilowatt-hour.
14. (5 pts) Explain why the "floating forest" model and the "swamp" model can look at the same coal seam and draw different conclusions.
15. (5 pts) State one real benefit and one real cost of hydraulic fracturing.
16. (5 pts) Name four building stones and one famous structure made of each.
17. (5 pts) What is the difference between cement, concrete, and mortar?
18. (5 pts) The USGS reports about 1.5 billion tons of crushed stone and about 1 billion tons of sand and gravel mined in the United States each year. With a population of about 335 million, how many tons of aggregate is that per person per year? About how many pounds?
19. (5 pts) Explain why a salt dome often makes a good oil trap.

20. (5 pts) What did Jennie Butchart do with an exhausted limestone quarry, and what does the 1977 law require of a coal mine today?

Answer key

1. Ore is rock from which a metal can be extracted at a profit; gangue is the worthless mineral matter, such as quartz or calcite, that comes out mixed with it and must be separated and discarded.
2. Any three: hydrothermal veins (Comstock Lode silver), magmatic segregation (Stillwater platinum and chromite), placers (California gold), banded iron formations (Mesabi Range iron), evaporites (Carlsbad potash), laterites (Jamaican bauxite).
3. $1 \div 0.005 = 200$ tons of ore per ton of copper. For 50,000 tons of copper, $50,000 \times 200 = 10,000,000$ tons of ore.
4. An open pit is cheaper per ton and is used when the ore body is large, low-grade, and near the surface, so that removing the overburden pays. Underground mining follows a narrow, rich vein deep in the rock, where stripping everything above it would cost far more than the ore is worth.
5. The Davy lamp of 1815 enclosed the flame in wire gauze so it would not ignite explosive mine gas. The 1977 act requires surface coal mines to post a bond and reclaim the land, restoring it to approximately its original contour after mining.
6. Beauty, durability, and rarity. Fluorite is beautiful but too soft, hardness 4, to survive wear in jewelry.
7. Corundum, aluminum oxide. Traces of chromium make it red (ruby); iron and titanium make it blue, and every non-red color is called sapphire.
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10. Ancient stone names were applied by color and appearance, not chemistry. The word most likely referred to lapis lazuli, the opaque blue stone widely used in the ancient Near East, though this remains uncertain.
11. Peat, lignite, bituminous, anthracite. The Powder River Basin of Wyoming and Montana.
12. A source rock rich in kerogen, a porous reservoir rock, an impermeable cap rock, and a trap such as an anticline, fault, or salt dome.
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14. Both models accept the observations, plant fossils, flat seams, and the presence or absence of soil beneath. The disagreement is over the unobserved history: whether plants grew in place in a swamp over a long time or were transported and dumped rapidly as a log mat. The seam is observation; the story of how it got there is inference.
15. Benefit: it made the United States the world's largest oil and gas producer and lowered fuel costs. Cost: any of water use of several million gallons per well, salty wastewater that must be handled, small earthquakes linked to deep wastewater injection, truck traffic and noise.
16. Granite (Mount Rushmore, Bunker Hill Monument), marble (the Lincoln Memorial exterior), limestone (the Empire State Building, the National Cathedral), sandstone (New York brownstones), slate (roofs and blackboards).

17. Cement is the gray powder made by burning limestone and clay; concrete is cement mixed with sand, gravel, and water; mortar is cement or lime mixed with sand and water to bond bricks or stones.
18. $2.5 \text{ billion} \div 335 \text{ million} \approx 7.5 \text{ tons per person per year}$, or roughly 15,000 pounds.
19. As the salt plug rises it bends the surrounding layers upward and seals against them, and salt itself is impermeable; oil migrating upward through the tilted reservoir rock is caught against the dome and held there.
20. She filled it with topsoil and planted it as the Sunken Garden, now Butchart Gardens. The 1977 act requires that mined land be regraded to approximately its original contour and reclaimed, backed by a bond posted before mining begins.

MAPS, FIELD GEOLOGY, AND THE GREAT GEOLOGISTS

A geologist's two most important tools are a good map and a good pair of eyes. This unit teaches you to read the two maps every geologist carries, the topographic map and the geologic map, and then to make simple versions of each yourself. In the second half we meet four men who taught the world how to look at rocks: Nicolaus Steno, James Hutton, William Buckland, and Louis Agassiz. Each of them was a careful observer, each made real mistakes, and each left behind writings you can still read. By the end you should be able to find your own house on a free government map and tell what rock it sits on.

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 8.1, Topographic Maps and Landforms, and define contour line, contour interval, magnetic declination.
- I can explain the main ideas of Lesson 8.2, Geologic Maps and Cross-Sections, and define formation, strike, dip.
- I can explain the main ideas of Lesson 8.3, The Founders: Nicolaus Steno and James Hutton, and define glossopetrae, unconformity, deism.
- I can explain the main ideas of Lesson 8.4, The Founders: William Buckland and Louis Agassiz, and define erratic, moraine, Bridgewater Treatise.

8.1 TOPOGRAPHIC MAPS AND LANDFORMS

Video. Videos coming.

KEY VOCABULARY

contour line

A line on a map joining all points at the same elevation above sea level.

contour interval

The fixed difference in elevation between one contour line and the next.

magnetic declination

The angle between true north and the direction a compass needle points, which differs from place to place.

CORE IDEAS

What a topographic map shows. A road map tells you where things are; a topographic map tells you the shape of the land as well. It does this with contour lines: brown lines that connect every point on the ground that stands at the same height above sea level. Walk along one and you never go up or down; cross one and you have climbed or descended a fixed amount, the contour interval. On most USGS maps the interval is 20 or 40 feet; flatter country uses less, mountains more. Every fifth line is printed heavier and labeled with its elevation. These index contours let you read heights quickly.

Contour lines obey a few rules that make the map readable.

1. Lines never cross. A point cannot have two elevations.
2. Close spacing means steep ground; wide spacing means gentle ground.
3. Where a contour crosses a stream it bends into a V, and the V points upstream, toward higher ground.
4. A closed circle with no larger circle inside it is a hilltop.
5. A closed circle with short tick marks pointing inward, called hachures, is a depression such as a sinkhole or a crater.

With these rules you can read landforms off the paper. A ridge shows as a long tongue of contours with the bends pointing downhill. A valley shows as a long tongue with the V's pointing uphill, usually with a blue stream line down its middle. A saddle is the pinched place between two hilltops, shaped like an hourglass. A cliff shows as lines bunched so tightly they nearly touch. A floodplain is a wide area with almost no lines at all, a looping river wandering across it.

Scale, grid, and north. The standard USGS map is the 7.5-minute quadrangle at a scale of 1:24,000. The ratio means that one unit on the map equals 24,000 of the same unit on the ground. One inch on the map is 24,000 inches, which is 2,000 feet. The sheet covers 7.5

minutes of latitude and longitude, so its corners are labeled in degrees and minutes. Latitude lines run east and west and measure distance north or south of the equator, 0 to 90 degrees. Longitude lines run north and south and measure distance east or west of Greenwich, England, 0 to 180 degrees. Each degree has 60 minutes and each minute 60 seconds.

In most states west of the Appalachians you will also see a grid of red squares six miles on a side. These are townships of the Public Land Survey System, each divided into 36 sections of one square mile, or 640 acres.

At the bottom of the sheet is a diagram of three arrows. The star marks true north, toward the North Pole. "GN" marks grid north. "MN" marks magnetic north, where a compass needle actually points. The angle between true and magnetic north is the magnetic declination, and it changes with place and slowly with time. In the Pacific Northwest the needle points roughly 15 degrees east of true north; in Maine it points roughly 15 degrees west.

Drawing a profile. A topographic profile is a side view of the land along a chosen line, and drawing one proves you can read contours.

1. Draw a straight line across the map between two points, A and B.
2. Lay the edge of a strip of paper along the line. Wherever a contour crosses the strip, make a tick and write the elevation.
3. On graph paper, draw a horizontal axis as long as the strip and a vertical axis marked in elevation, with the lowest contour near the bottom.
4. Lay the strip along the horizontal axis and, above each tick, place a dot at the matching height.
5. Connect the dots with a smooth curve, rounding over hilltops and dipping gently through valleys.

If the vertical scale is larger than the horizontal, the hills look taller than they are; this is vertical exaggeration, and you should note it on the drawing.

Getting a map of your home. Every USGS quadrangle ever printed is free. On the USGS National Map website, open the tool called topoView, type your town, and download the sheet. You can get the current US Topo map and the old editions back to the 1880s, a wonderful record of how your town has grown.

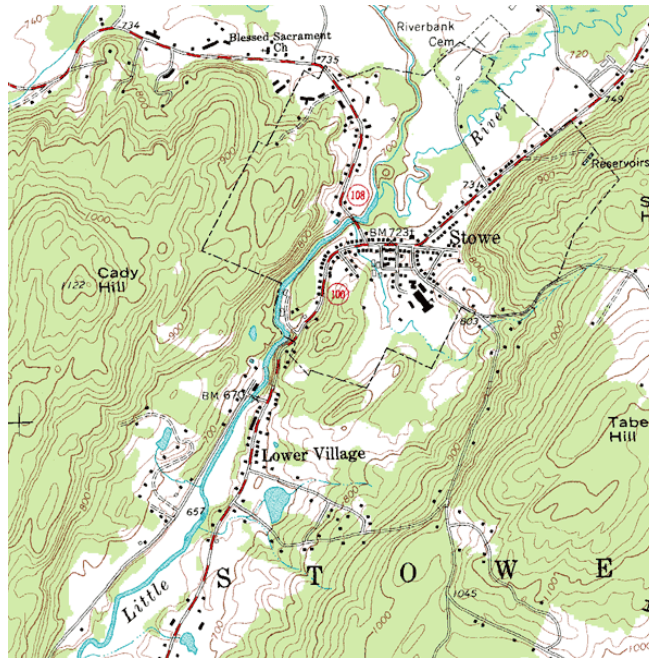
The surveys that made the maps. American mapping began on foot. In 1804 Meriwether Lewis and William Clark set out from St. Louis, and Clark's map of the West, published in 1814, was the first good picture of the Missouri and Columbia drainages. In 1871 Ferdinand Hayden led a government survey into the Yellowstone country with painter Thomas Moran and photographer William Henry Jackson, whose pictures helped persuade Congress to make Yellowstone the first national park in 1872. The USGS was founded in 1879 and spent the next century mapping the country at 1:24,000, more than 50,000 sheets.

The prophet Isaiah used the language of land shaping to describe God's coming: "Every valley shall be exalted, and every mountain and hill shall be made low: and the crooked shall

be made straight, and the rough places plain:" (Isaiah 40:4, KJV). A topographic map is those valleys and hills, measured.

Reading a figure like this is exactly what the ACT Science section and AP Environmental Science ask of you: look at a diagram with a scale and a key, pull a number from it, and reason about it. Practice on real maps now and those questions will feel easy.

PICTURE STUDY



Inset of the USGS topographic map of Stowe, Vermont, United States Geological Survey, 1:24,000 with 20-foot contours,

Find the heavier index contours and read their elevations. Then find a place where the lines bunch tightly and a place where they spread apart, and say which slope you would rather climb.

Look closely

Talk about it

Safety first. An adult handles or supervises the knife; cut away from your fingers on a stable board.

HANDS-ON ACTIVITY: POTATO MOUNTAIN

Materials. One large potato or a lump of modeling clay shaped like a hill, a kitchen knife, a cutting board, a sheet of paper, a pencil, a ruler.

Steps. (1) Set the potato on the board flat side down so it looks like a hill. (2) Measure and mark lines around it every half inch of height. (3) Slice straight across at each mark, keeping the slices in order. (4) Starting with the bottom slice, set it on the paper and trace around it;

then set the next slice on top of the first, centered as it was in the whole potato, and trace it inside the first outline; continue to the top. (5) Label each outline with its height.

What to notice. You have just drawn a contour map with a half-inch interval. Where the potato was steep the lines sit close together; where it was gently rounded they spread out. Cut a little notch in one side of the potato before slicing and watch the V's point uphill.

You will need

Steps

PRACTICE

1. State three rules that contour lines always obey.
2. On a 1:24,000 map, two farmhouses are 3.5 inches apart. How far apart are they on the ground, in feet and in miles?
3. Read this described map. The contour interval is 40 feet. A heavy index contour labeled 1,200 runs across the middle. Just north of it four thin contours are packed within a quarter inch; south of it the next thin contour is a full inch away. A blue stream crosses the index line, and the contours bend into V's that point north. In which direction is uphill, which side is steeper, and what is the elevation of the fourth thin line north of the index contour?
4. Explain why a hiker who ignores magnetic declination can walk the wrong way even with a good compass and a good map.
5. Describe how you would draw a topographic profile along a line from point A to point B.

Exam connection. Contour-map and scale questions appear on the ACT Science section as figure-reading passages and in the AP Environmental Science units on earth systems and land use; the SAT math section tests the same unit-conversion skill, such as inches to feet to miles.

For families. At the table, pull up topoView and find the oldest map of your town; ask what has changed and what has not. The potato activity is quick, but the real learning comes when the student sets the outline map beside the sliced potato and explains, slice by slice, why the lines fall where they do. If someone in the family hikes or hunts, ask them how they correct for declination; many never do, and it makes a good discussion.

Practice answers

1. Any three of: they never cross; close spacing means steep ground and wide spacing means gentle ground; they bend into a V pointing upstream where they cross a stream; a closed circle is a hilltop; a closed circle with hachures is a depression.
2. $3.5 \times 2,000 \text{ feet} = 7,000 \text{ feet}$, which is about 1.3 miles ($7,000 \div 5,280 = 1.33$).
3. The V's point upstream, so uphill is north. The north side is steeper because the lines are packed close. The fourth thin line north is $1,200 + 4 \times 40 = 1,360 \text{ feet}$.

4. The compass needle points to magnetic north, not true north. A map bearing is measured from true north, so unless the hiker adds or subtracts the local declination, which can be 15 degrees or more, the bearing will be off by that angle and the error grows with every mile walked.
5. Lay a strip of paper along the line, mark each contour crossing with its elevation, transfer the marks to graph paper with elevation on the vertical axis, plot a dot above each mark at its height, and connect the dots with a smooth curve, noting any vertical exaggeration.

8.2 GEOLOGIC MAPS AND CROSS-SECTIONS

Video. Videos coming.

KEY VOCABULARY

formation

A body of rock with a distinctive character that can be traced and mapped across the countryside.

strike

The compass direction of a horizontal line drawn on a tilted rock layer.

dip

The angle, measured from horizontal, at which a tilted rock layer slopes downward, measured at right angles to the strike.

CORE IDEAS

A map of what is under the soil. A geologic map is a topographic map painted over. Each color is a formation, a body of rock with a recognizable character that a geologist can trace across the countryside, such as the Kaibab Limestone of the Grand Canyon. Each formation also gets a short letter code, such as Pk for the Kaibab or Qal for recent stream gravel. The thin lines between colors are contacts, where one rock type meets another. Heavier lines are faults; teeth along a fault line mark a thrust, pointing toward the block shoved up and over.

The key small symbol is strike and dip: a long line with a short tick on one side and a number beside it. The long line is the strike, the compass direction of a horizontal line drawn on a tilted bed. The tick points the direction the bed slopes down, and the number is the dip, the angle of that slope in degrees from horizontal. Tilt a hardcover book so one corner is higher: the level edge of the cover is the strike, the downhill direction is the dip direction, and the angle between cover and table is the dip. A symbol with a circle and a cross means the bed is horizontal. In the field both are measured with a Brunton compass, a pocket instrument with a mirror, needle, and level, invented by David Brunton in 1894.

The legend of a geologic map lists the formations in a column, youngest at the top and oldest at the bottom, with the museum names of the time scale alongside: Quaternary, Tertiary, Cretaceous, Jurassic, Permian, Cambrian, Precambrian. Remember that the colors and contacts are things someone walked out and saw. The order in the column is a reasoned judgment, usually from superposition and fossils. The ages in years are an inference layered on top of that.

Three map patterns. Rocks make only a few basic patterns on a map.

- Horizontal layers follow the contour lines. On a flat mesa the top formation covers the whole surface, its edge winds around like a contour, and lower formations appear as

bands down the slopes. The Grand Canyon's map looks like a topographic map colored in.

- Tilted layers make bands. Each formation crops out as a stripe running parallel to the strike. Steeply dipping beds make narrow stripes; gently dipping beds make wide ones.
- Folded layers make repeating bands. An arch, called an anticline, shows its oldest rock in the middle with younger stripes repeating on each side; a trough, called a syncline, shows the youngest in the middle.

One special pattern is the rule of V's. Where a tilted bed crosses a valley, its outcrop bends into a V, and in the usual case the V points in the direction the bed dips. Horizontal beds, by contrast, make V's that point upstream, because they simply follow the contours.

From map to cross-section. A cross-section is the slice you would see if you cut the land along a line and looked at the cut face. To draw one, first draw a topographic profile along the line, as in Lesson 8.1. Then mark on the profile every contact the line crosses. At each contact, read the nearest strike-and-dip symbol, measure that angle below the surface with a protractor, and draw the contact down into the ground at that angle. Continue each formation until it runs into a fault or off the bottom of the drawing. Horizontal beds come out flat, tilted beds slanted, folds as arches and troughs.

William Smith's great map. The first true geologic map of a whole country was drawn by a canal surveyor. William Smith was born in 1769 in Churchill, Oxfordshire. In the 1790s he was hired to survey the route of the Somerset Coal Canal, and as the cuttings opened the ground he noticed that the layers lay in a fixed order and that each carried its own fossils, so a bed could be recognized wherever it appeared. He spent twenty years walking England, drawing, and running out of money. In 1815 he published a hand-colored map more than eight feet tall whose title begins *A Delineation of the Strata of England and Wales, with part of Scotland*; the full title runs on for several more lines, and the exact wording varies a little between copies. Rivals copied his work, and in 1819 he spent weeks in a debtors' prison. In 1831 the Geological Society of London gave him its first Wollaston Medal, its highest honor, and hailed him as the father of English geology. He died in 1839.

The Geologic Map of North America, published by the Geological Society of America in 2005 at a scale of 1:5,000,000, is the modern descendant of Smith's sheet. Nearly every state keeps its own geological survey, and the USGS National Geologic Map Database, at ngmdb.usgs.gov, gives free maps of every county. Find your house and read the letter code under it.

What the map does and does not say. A geologic map is honest if you know what it claims: that the mapper saw these rocks at these places, measured these dips, and traced these contacts, dashing the line where soil hid it. It also claims an order of formations. It does not, by itself, tell you how many years each took or how long the gaps between them lasted. The wise king searches out a matter (Proverbs 25:2); the wise map reader keeps the observed and the inferred in separate columns.

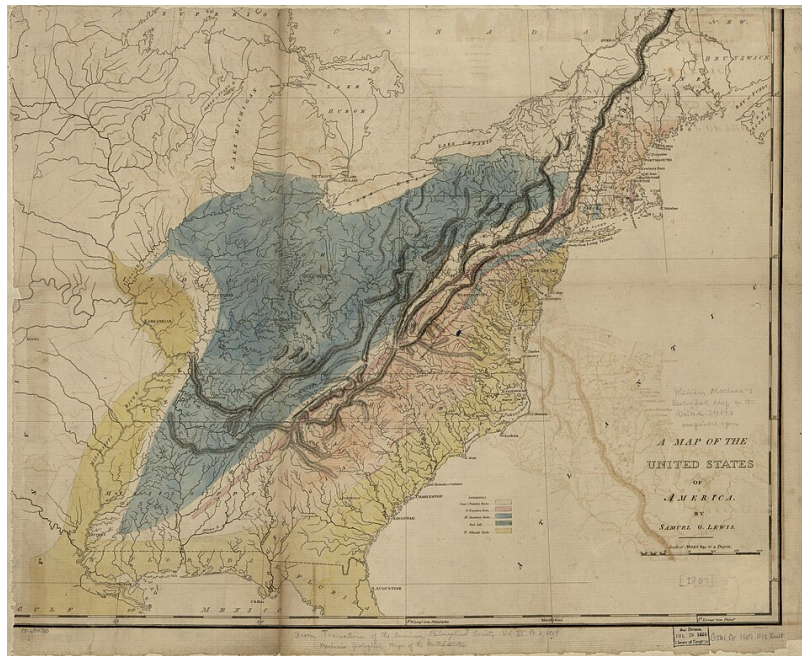
Thinking About Time

What the sign says. A legend labels the Kaibab Limestone “Permian, about 270 million years old.”

What we observe. A thick, pale, fossil-bearing limestone lying above the Toroweap and Coconino beds, traceable for miles along the rim, and a column of layers whose order from bottom to top anyone can check.

How Christians read it. Many Christian families understand these layers as laid down rapidly within a young earth, largely during the Flood of Genesis 6–9, and read the museum ages as inferences built on assumed slow rates. Other Christians hold an older earth, read the days of Genesis 1 differently, and accept the long ages while confessing the same Creator. Both agree that the order of the layers is observed and that the number of years is inferred, and neither treats Scripture as myth.

PICTURE STUDY



Maclure's Geological Map of the United States, William Maclure, 1809, printed on a base map by Samuel Lewis,

This is the earliest attempt to map the geology of America, six years before William Smith's map of England (Unit 5, Lesson 5.3 picture study). Maclure crossed the Alleghenies many times on foot and horseback to draw it. Notice the long colored belts running northeast to southwest parallel to the Appalachians: tilted and folded layers cropping out as stripes, the second map pattern described above.

Look closely

Talk about it

Safety first. Keep the knife blunt and cut on a board.

HANDS-ON ACTIVITY: PLAY-DOUGH GEOLOGY MAP

Materials. Four or five colors of play dough or modeling clay, a rolling pin, a butter knife or dental floss, a ruler, paper and colored pencils.

Steps. (1) Roll each color into a flat sheet and stack them in order, bottom to top, writing down the order. (2) Press the stack firmly, then tilt it by propping one end on a book so it slopes about 30 degrees. (3) With the floss or butter knife, slice the top off flat, parallel to the table, as erosion would. (4) Look straight down at the cut surface and draw what you see: bands of color. (5) Now bend a fresh stack into an arch before slicing, and draw the repeating bands. (6) Finally, label each band with a letter code and draw a legend with the youngest at the top.

What to notice. The band width changes with the tilt; the arch shows the bottom color in the middle.

Alternative. Print the free geologic map of your county from ngmdb.usgs.gov and find the formation your house sits on.

You will need

Steps

PRACTICE

1. What do the colors, the thin lines, and the heavy lines on a geologic map represent?
2. A strike-and-dip symbol shows a long line running north to south, a tick on the east side, and the number 25. Describe the bed in words, and say whether this bed would make a narrower or wider band on the map than one marked 70.
3. Explain, using the tilted book, why strike and dip are always measured at right angles to each other.
4. On a map, a formation's outcrop follows the contour lines closely around a flat-topped hill. What does that tell you about the layers, and what would tilted layers look like instead?
5. What on a geologic map is directly observed, and what is inferred? Give one example of each.

Exam connection. AP Environmental Science asks students to interpret maps and diagrams of rock layers in its earth-systems unit, and the ACT Science section often presents a labeled cross-section or a table of dip measurements and asks you to draw a conclusion from it.

For families. Ask at dinner: what rock is our house built on, and how do we know? The county geologic map answers the first part and the lesson answers the second. Be aware that the museum ages in the legend will raise the question of time; use the Thinking About Time box to talk through what is observed and what is inferred. Scholars still debate how fast some of the layers formed, and that debate is a fair subject for a family of careful observers.

Practice answers

1. Colors are formations, thin lines are contacts between formations, and heavy lines are faults.
2. The bed strikes north-south and dips 25 degrees down toward the east. A 25-degree bed makes a wider band on the map than a 70-degree bed, because gentle dips spread the outcrop out.
3. The strike is the level edge of the tilted cover; the steepest path down the cover is at right angles to that edge. Measuring dip anywhere else would give a smaller angle than the true slope, so dip is defined as the steepest angle, which is perpendicular to strike.
4. The layers are horizontal. Tilted layers would make bands or stripes running across the map parallel to the strike, cutting across the contours.
5. Observed: rock types, contacts seen in outcrop, measured strike and dip. Inferred: the ages in years in the legend, dashed contacts under soil cover, and the shape of layers underground in a cross-section.

8.3 THE FOUNDERS: NICOLAUS STENO AND JAMES HUTTON

Video. Videos coming.

KEY VOCABULARY

glossopetrae

“tongue stones,” the fossil shark teeth of Malta and Tuscany that Steno identified in 1666.

unconformity

A surface in the rock record where layers were eroded or tilted before new layers were laid on top, representing a gap in deposition.

deism

Belief in a Creator who made the world and its laws but does not act within it or reveal himself in Scripture.

CORE IDEAS

Steno: the anatomist who read the hills. Niels Stensen, Nicolaus Steno in Latin, was born in Copenhagen in 1638, a goldsmith’s son. He studied medicine, and before twenty-five he had found the duct carrying saliva from the parotid gland into the mouth, still called Stensen’s duct. In 1666 he settled in Florence under Grand Duke Ferdinando II de’ Medici.

That October fishermen landed a huge shark near Livorno, and the Duke sent its head to Steno. Steno saw at once that its teeth matched the glossopetrae, the “tongue stones” dug from the hills of Malta and Tuscany. People thought tongue stones fell from the sky or grew in the ground. Steno said they were shark teeth turned to stone inside rock that had once been soft sediment; if so, the hills had a history that could be read.

He wrote that history out in 1669 in a short book, the preface to a larger one he never finished: *De solido intra solidum naturaliter contento dissertationis prodromus*, usually called the *Prodromus*. It laid down three principles every geology student still learns. Superposition: lower layers were laid first. Original horizontality: layers settle flat, so a tilted layer was tilted afterward. Lateral continuity: a layer extends sideways until it thins or meets a barrier, so matching layers across a valley were once joined.

The *Prodromus* ends with six small panels showing how Tuscany got its shape, read from the bottom up. First, flat layers settled out of water. Second, water or fire hollowed caverns beneath them. Third, the roof fell in, tilting the broken layers into the first mountains and valleys. Fourth, water laid new flat layers in the valleys, these full of shells. Fifth, caverns opened under these too. Sixth, they collapsed in turn, leaving the hills of his own day. Steno held the Flood of Genesis as real history: the lower, shell-free layers he assigned to the Creation, before living things, and the upper, shell-bearing layers to the universal Deluge. His often-quoted aphorism about the beautiful things we see and the more beautiful things we understand is given here only as “translation varies.”

Raised a Lutheran, Steno entered the Catholic Church in November 1667 after long study. He was ordained a priest in 1675 and made a bishop in 1677, serving the scattered Catholics of northern Germany and Scandinavia. He gave away nearly all he owned and died poor in Schwerin in 1686, aged forty-eight; in 1988 Pope John Paul II beatified him. A brilliant scientist gave up science and comfort for his faith; his three principles outlived him.

Hutton: the farmer who saw no beginning. James Hutton was born in Edinburgh in 1726 and trained as a physician at Leiden, but never practiced. Instead he farmed at Slighhouses in Berwickshire, watching soil wash off his fields into the streams and wondering where new soil would come from. He returned to Edinburgh in 1767 and joined the circle we call the Scottish Enlightenment, a close friend of the chemist Joseph Black and the economist Adam Smith.

Hutton's idea was that the earth is a self-repairing machine. Rivers wear the land down into the sea; the sediment hardens into rock; heat from below lifts it into new land; and the cycle begins again. He read his *Theory of the Earth* to the Royal Society of Edinburgh in 1785 and published it in its *Transactions* in 1788. In Glen Tilt in 1785 he saw granite veins shot through older schist, proof the granite had been molten and forced its way in. In June 1788, sailing along the Berwickshire coast with John Playfair and James Hall, he found Siccar Point, where nearly vertical gray layers are cut off flat and covered by gently tilted red ones. Here were layers laid, hardened, tilted, worn flat, and buried again. Playfair later wrote of growing giddy looking so far into the abyss of time (paraphrase).

The 1788 paper ends with the most famous sentence in geology: "The result, therefore, of our present enquiry is, that we find no vestige of a beginning,—no prospect of an end." He did not mean the earth was strictly eternal, but that the rocks show cycle after cycle and no observation reveals a first one. He also wrote as a deist, believing in a wise Designer but not the God of Scripture who acts in history. Scripture says, "In the beginning God created the heaven and the earth" (Genesis 1:1, KJV), and "Through faith we understand that the worlds were framed by the word of God, so that things which are seen were not made of things which do appear" (Hebrews 11:3, KJV). A Christian can agree that the rocks do not show Day One and still know on better authority that there was one.

Hutton expanded his work into two volumes in 1795, but his prose was so tangled few read it. After his death in 1797, Playfair's 1802 *Illustrations of the Huttonian Theory of the Earth*, clear and well argued, carried it to the world.

A fair evaluation. Hutton's observations were careful and real: granite veins do cut older rock, unconformities do record tilting and erosion, rivers do carry the land to the sea. His inference of unlimited time was an inference, built on the assumption that the slow processes of his farm were the only ones that ever operated. Later geologists found that ice and great floods can do in a season what rivers do in an age. Observation stands; inference can be corrected.



What the sign says. “Hutton’s unconformity at Siccar Point records a gap of about 65 million years.”

What we observe. Vertical gray layers, a flat erosion surface, and red layers lying across them at a gentle angle. The order of events is certain: deposit, tilt, erode, deposit.

How Christians read it. Many Christian families understand such surfaces as cut quickly by moving water during the Flood of Genesis 6-9, between stages of deposition, and read the millions as an inference from assumed slow rates. Other Christians accept the long ages and read the days of Genesis 1 differently. Both honor the observation and both hold that the world had a beginning, which Hutton’s method could not see.

PICTURE STUDY



Portrait of Nicolaus Steno, attributed to Justus Sustermans, about 1666-1677, Uffizi Gallery, Florence,

Look at the plain dark clothing and the quiet face of a man at the busiest court in Italy. For comparison, see Henry Raeburn’s portrait of James Hutton, painted before 1798: commons.wikimedia.org/wiki/File:Hutton_James_portrait_Raeburn.jpg (PD-old). Hutton sits with fossils and papers at his elbow; what does each painter want you to think the man cared about?

Look closely

Talk about it

HANDS-ON ACTIVITY: SICCAR POINT IN A SHOEBOX

Materials. A shoebox or clear plastic container, three colors of sand, soil, or flour and cocoa, a ruler, a spoon, a small book.

Steps. (1) Lay three flat layers of alternating color in the box, about half an inch each. (2) Tilt the box steeply by propping one end on the book and tap it gently; or, with damp sand, cut the layers out as a block, stand it on end, and pack it back in so the layers stand nearly vertical. (3) With the ruler, scrape the top flat as if erosion had planed it off. (4) Lay two new flat layers of a different color on top. (5) Look at the side of the box and draw what you see, labeling each layer in order from oldest to youngest.

What to notice. You have made an unconformity.

Alternative. Do a Steno and draw six panels, in order, showing how the layers under your own backyard could have been laid, hollowed, collapsed, re-covered, and collapsed again.

You will need

Steps

PRACTICE

1. What did Steno conclude from the shark's head of 1666, and why did that conclusion matter for the hills?
2. Name and explain Steno's three principles from the *Prodromus* of 1669.
3. Put Steno's six Tuscany panels in order and say which layers he connected to the Creation and which to the Flood.
4. Hutton saw red layers resting on vertical gray layers at Siccar Point. List the sequence of events this proves, and then explain why the number of years it took is not proven by the same observation.
5. Steno died in 1686 and Hutton read his theory in 1785. How many years separate the two events, and name one historical event from the brief that falls between them.

Exam connection. Superposition, original horizontality, and unconformities appear in AP Environmental Science's earth-systems unit and in ACT Science passages that show a labeled rock column and ask which layer is oldest.

For families. Steno's conversion and Hutton's deism will come up; talk about both honestly. A Protestant family can honor Steno's integrity and his principles without sharing every Catholic conclusion, and can admire Hutton's eye while rejecting his picture of a God who never speaks. Ask: what did each man see with his eyes, and what did he conclude by reasoning? That is the habit this whole course is trying to build.

Practice answers

1. The shark's teeth matched the tongue stones found in rock, so tongue stones were real shark teeth buried in what had once been soft sediment. That meant the rock layers had formed from loose material in water and so had a readable history.
2. Superposition: lower layers were laid first. Original horizontality: layers settle flat, so tilted layers were tilted afterward. Lateral continuity: a layer extends sideways until it thins or meets a barrier, so matching layers across a valley were once connected.

3. Flat layers laid; caverns hollowed beneath; collapse and tilting; new flat shell-bearing layers laid in the valleys; new caverns; second collapse making today's landscape. He connected the lower shell-free layers to the Creation and the upper shell-bearing layers to the Deluge.
4. The gray layers were deposited flat, hardened, tilted to near vertical, eroded flat, and then covered by the red layers. The order is proven by superposition and original horizontality, but the time required depends on assumed rates of tilting and erosion, which the rock itself does not record.
5. 99 years. The Lisbon earthquake of 1755 falls between them.

8.4 THE FOUNDERS: WILLIAM BUCKLAND AND LOUIS AGASSIZ

Video. Videos coming.

KEY VOCABULARY

erratic

A boulder carried by a glacier and left far from the bedrock it came from.

moraine

A ridge or sheet of unsorted rock and gravel dropped at the edge or end of a glacier.

Bridgewater Treatise

One of a series of books, funded by the Earl of Bridgewater's will, written in the 1830s to show the wisdom of God in creation; Buckland wrote the one on geology in 1836.

CORE IDEAS

Buckland: the parson in the cave. William Buckland was born in 1784 at Axminster in Devon, a clergyman's son, and went up to Oxford, where he was ordained and spent most of his life. Oxford had no geology; Buckland invented it there. A Readership in Geology was created for him in 1818, and his inaugural lecture, delivered in 1819 and printed in 1820, was titled *Vindiciae Geologicae; or, the Connexion of Geology with Religion Explained*. He argued that the new science, honestly done, confirmed Genesis, and that the surface of the earth showed the marks of a great flood.

In 1821 workmen at Kirkdale in Yorkshire broke into a cave floored with bones. Buckland crawled in and found gnawed bones of elephant, rhinoceros, hippopotamus, and deer, with hyena bones and droppings among them. He argued, correctly, that the cave had been a hyena den, and that the animals had lived in England before a flood sealed it with mud. The Royal Society gave him its Copley Medal for it in 1822. In January 1823 he dug a red-ochre-stained skeleton from a cave at Paviland in Wales and called it the Red Lady; it was in fact a young man. That year he gathered his cave work into *Reliquiae Diluvianae; or, Observations on the Organic Remains contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, attesting the Action of an Universal Deluge*. In 1824 he described a huge jaw and limb bones from Stonesfield and named the animal *Megalosaurus*, the first dinosaur ever named, though the word dinosaur was not coined until 1842.

Buckland was a famous eccentric, and the stories are well attested: he kept a tame bear named Tiglath-Pileser, lectured on horseback, and set himself to eat his way through the animal kingdom, reporting that mole was the worst.

His views changed as the evidence did. In his 1836 Bridgewater Treatise, *Geology and Mineralogy Considered with Reference to Natural Theology*, he no longer tied the gravel and caves to a single recent Deluge, and read the days of Genesis as long ages. Then in the

autumn of 1840 Louis Agassiz toured Scotland and England with him, and Buckland saw that the scratched bedrock and scattered boulders he had credited to flood water were better explained by ice; he said so before the Geological Society that November. In 1845 he was made Dean of Westminster. His mind failed in his last years, and he died in 1856. A fair word: Buckland never hid behind a position. He followed the evidence as he understood it, and twice in public said he had been wrong, a Christian virtue as well as a scientific one.

Agassiz: the man who discovered the Ice Age. Louis Agassiz was born in 1807 at Môtier on Lake Morat, Switzerland, a Protestant pastor's son. He studied in Zürich, Heidelberg, and Munich, and in 1831 went to Paris to work under Georges Cuvier, the greatest anatomist of the age, who gave him his fossil-fish notes before dying the next year. From 1833 to 1843 Agassiz published *Recherches sur les poissons fossiles*, five volumes on more than a thousand species. In 1832 he became professor at Neuchâtel.

Swiss farmers had long said the glaciers once reached far down the valleys, pointing to polished rock and to great boulders, called erratics, lying where no river could have carried them. In July 1837, as president of the Swiss Society of Natural Sciences at Neuchâtel, Agassiz told the assembled scientists that a vast sheet of ice had once covered much of Europe (paraphrase). The idea met laughter; he answered with work. In 1840 he published *Études sur les glaciers*, and that summer he and his friends camped under a huge boulder on the Unteraar glacier, which they named the Hôtel des Neuchâtelois, driving stakes into the ice to measure how fast it moved. That autumn he carried the theory to Britain and won Buckland over.

In 1846 Agassiz sailed to lecture in Boston and never went home. Harvard made him a professor in 1847, and in 1859 he founded its Museum of Comparative Zoology. He taught by setting a fish before a student and leaving him alone with it for days. "Study nature, not books" is the motto attributed to him and to the summer school he opened on Penikese Island in 1873, his last year.

Agassiz believed that every species was a separate thought of the Creator, and when Darwin's *Origin of Species* appeared in 1859 he opposed it to the end, the most famous scientific critic of evolution in America. He also held views on the separate origins of human races that scientists and Christians reject today. He died in Cambridge, Massachusetts, in December 1873; on his grave at Mount Auburn Cemetery stands a boulder brought from the moraine of the Aar glacier, near where his hut once stood.

What the four men share. Steno left science for the Church; Hutton kept God at a distance; Buckland fitted geology to Genesis and changed his mind twice; Agassiz fought Darwin and found the Ice Age. They disagreed about much, but they shared three habits. They looked carefully at real rocks. They wrote down what they saw so others could check it. And when the evidence turned, the best of them were willing to be corrected. "The works of the LORD are great, sought out of all them that have pleasure therein" (Psalm 111:2, KJV). Seeking out His works with pleasure and honesty is field geology.



What the sign says. “The Pleistocene ice age lasted from about 2.6 million to 11,700 years ago.”

What we observe. Polished and scratched bedrock, boulders far from their source, long ridges of unsorted gravel, and glaciers today that move and leave the same marks.

How Christians read it. Many Christian families understand a single ice age following the Flood of Genesis 6–9, lasting a few centuries, driven by warm oceans and cold continents. Other Christians accept the longer sequence of ice advances the museum describes. Both agree that ice, not Noah’s floodwater, made the scratches, as Buckland came to see.

PICTURE STUDY



William Buckland entering Kirkdale Cave, William Conybeare, 1822 cartoon,

A fellow geologist drew Buckland crawling by candlelight into a cave full of living hyenas; it is a joke, but it shows how famous the discovery was. For Agassiz, see J. Bettannier’s 1840 lithograph of the lower Aar glacier from *Études sur les glaciers*: commons.wikimedia.org/wiki/File:Agassizaar.jpg (PD-old), and find the dark stripe of moraine running down the ice.

Look closely

Talk about it

HANDS-ON ACTIVITY: GEOLOGIST’S PROFILE AND TIMELINE

Materials. Paper, pencil, a ruler, access to the free scans of Steno’s *Prodromus* in English, Hutton’s 1788 paper, Buckland’s *Reliquiae Diluvianae*, or Agassiz’s *Études sur les glaciers* on

Internet Archive or Wikimedia Commons.

Steps. (1) Choose one of the four men. (2) Read at least two pages of his own writing and copy out one sentence exactly, with the page number. (3) Write a one-page profile: where he was born, what he saw, what he concluded, what he believed about God, and one thing he got wrong. (4) On a separate sheet, draw a timeline from 1630 to 1990 with a tick every ten years, and place the births and deaths of all four men, plus the Lisbon earthquake of 1755, the 1815 Smith map, the 1859 *Origin of Species*, the founding of the USGS in 1879, and the Mount St. Helens eruption of 1980.

What to notice. How much of the subject was settled in a single century, from Hutton's 1788 paper to Agassiz's death in 1873.

You will need

Steps

PRACTICE

1. What did Buckland find at Kirkdale Cave in 1821, and what did he conclude?
2. Give the full title of Buckland's 1823 book and explain in one sentence what the title claims.
3. Explain why Buckland changed his mind in 1840, and say what evidence persuaded him.
4. Agassiz was born in 1807 and died in 1873. Buckland was born in 1784 and died in 1856. How many years did their lives overlap, and in which year did they work together in Britain?
5. Name the three habits the four founders shared, and give one example from the lesson of a man being corrected.

Exam connection. The CLT and SAT reading sections use passages from nineteenth-century scientific writers of exactly this kind, and AP Environmental Science covers glaciers and the evidence they leave in its earth-systems unit.

For families. This lesson has two sensitive points: Agassiz's views on race and Buckland's late-life illness. Both are stated plainly and briefly in the reading and need no lecture. At the table, ask which of the four men the student would most like to have met, and why. The profile activity needs a primary source; the English *Prodromus* and the *Reliquiae Diluvianae* are both scanned free on Wikimedia Commons, and a parent may want to open them first and find a readable page.

Practice answers

1. Gnawed bones of elephant, rhinoceros, hippopotamus, deer, and other animals, together with hyena bones and droppings. He concluded the cave had been a hyena den and the animals had lived in England before a flood sealed it with mud.

2. *Reliquiae Diluvianae; or, Observations on the Organic Remains contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, attesting the Action of an Universal Deluge.* It claims that cave bones and surface gravels are evidence of a worldwide flood.
3. Agassiz showed him that scratched and polished bedrock, erratic boulders, and ridges of unsorted gravel in Britain matched exactly what living glaciers produce in Switzerland, so ice explained them better than flood water.
4. From 1807 to 1856 is 49 years of overlap. They toured Britain together in 1840.
5. Careful looking, honest recording, and willingness to be corrected. Buckland gave up the single-Deluge explanation of gravel and caves after seeing Agassiz's glacial evidence in 1840.

UNIT 8 TEST

Answer every question in complete sentences, and show your work on any calculation. Each question is worth 5 points (100 points in all). The questions come from the lessons of this unit; study your corrected answers first.

1. (5 pts) State three rules that contour lines always obey.
2. (5 pts) On a 1:24,000 map, two farmhouses are 3.5 inches apart. How far apart are they on the ground, in feet and in miles?
3. (5 pts) Read this described map. The contour interval is 40 feet. A heavy index contour labeled 1,200 runs across the middle. Just north of it four thin contours are packed within a quarter inch; south of it the next thin contour is a full inch away. A blue stream crosses the index line, and the contours bend into V's that point north. In which direction is uphill, which side is steeper, and what is the elevation of the fourth thin line north of the index contour?
4. (5 pts) Explain why a hiker who ignores magnetic declination can walk the wrong way even with a good compass and a good map.
5. (5 pts) Describe how you would draw a topographic profile along a line from point A to point B.
6. (5 pts) What do the colors, the thin lines, and the heavy lines on a geologic map represent?
7. (5 pts) A strike-and-dip symbol shows a long line running north to south, a tick on the east side, and the number 25. Describe the bed in words, and say whether this bed would make a narrower or wider band on the map than one marked 70.
8. (5 pts) Explain, using the tilted book, why strike and dip are always measured at right angles to each other.
9. (5 pts) On a map, a formation's outcrop follows the contour lines closely around a flat-topped hill. What does that tell you about the layers, and what would tilted layers look like instead?
10. (5 pts) What on a geologic map is directly observed, and what is inferred? Give one example of each.
11. (5 pts) What did Steno conclude from the shark's head of 1666, and why did that conclusion matter for the hills?
12. (5 pts) Name and explain Steno's three principles from the *Prodromus* of 1669.
13. (5 pts) Put Steno's six Tuscany panels in order and say which layers he connected to the Creation and which to the Flood.
14. (5 pts) Hutton saw red layers resting on vertical gray layers at Siccar Point. List the sequence of events this proves, and then explain why the number of years it took is not proven by the same observation.
15. (5 pts) Steno died in 1686 and Hutton read his theory in 1785. How many years separate the two events, and name one historical event from the brief that falls between them.
16. (5 pts) What did Buckland find at Kirkdale Cave in 1821, and what did he conclude?

17. (5 pts) Give the full title of Buckland's 1823 book and explain in one sentence what the title claims.
18. (5 pts) Explain why Buckland changed his mind in 1840, and say what evidence persuaded him.
19. (5 pts) Agassiz was born in 1807 and died in 1873. Buckland was born in 1784 and died in 1856. How many years did their lives overlap, and in which year did they work together in Britain?
20. (5 pts) Name the three habits the four founders shared, and give one example from the lesson of a man being corrected.

Answer key

1. Any three of: they never cross; close spacing means steep ground and wide spacing means gentle ground; they bend into a V pointing upstream where they cross a stream; a closed circle is a hilltop; a closed circle with hachures is a depression.
2. $3.5 \times 2,000$ feet = 7,000 feet, which is about 1.3 miles ($7,000 \div 5,280 = 1.33$).
3. The V's point upstream, so uphill is north. The north side is steeper because the lines are packed close. The fourth thin line north is $1,200 + 4 \times 40 = 1,360$ feet.
4. The compass needle points to magnetic north, not true north. A map bearing is measured from true north, so unless the hiker adds or subtracts the local declination, which can be 15 degrees or more, the bearing will be off by that angle and the error grows with every mile walked.
5. Lay a strip of paper along the line, mark each contour crossing with its elevation, transfer the marks to graph paper with elevation on the vertical axis, plot a dot above each mark at its height, and connect the dots with a smooth curve, noting any vertical exaggeration.
6. Colors are formations, thin lines are contacts between formations, and heavy lines are faults.
7. The bed strikes north-south and dips 25 degrees down toward the east. A 25-degree bed makes a wider band on the map than a 70-degree bed, because gentle dips spread the outcrop out.
8. The strike is the level edge of the tilted cover; the steepest path down the cover is at right angles to that edge. Measuring dip anywhere else would give a smaller angle than the true slope, so dip is defined as the steepest angle, which is perpendicular to strike.
9. The layers are horizontal. Tilted layers would make bands or stripes running across the map parallel to the strike, cutting across the contours.
10. Observed: rock types, contacts seen in outcrop, measured strike and dip. Inferred: the ages in years in the legend, dashed contacts under soil cover, and the shape of layers underground in a cross-section.
11. The shark's teeth matched the tongue stones found in rock, so tongue stones were real shark teeth buried in what had once been soft sediment. That meant the rock layers had formed from loose material in water and so had a readable history.
12. Superposition: lower layers were laid first. Original horizontality: layers settle flat, so tilted layers were tilted afterward. Lateral continuity: a layer extends sideways until it thins or meets a barrier, so matching layers across a valley were once connected.
13. Flat layers laid; caverns hollowed beneath; collapse and tilting; new flat shell-bearing layers laid in the valleys; new caverns; second collapse making today's landscape. He connected the lower shell-free layers to the Creation and the upper shell-bearing layers to the Deluge.

14. The gray layers were deposited flat, hardened, tilted to near vertical, eroded flat, and then covered by the red layers. The order is proven by superposition and original horizontality, but the time required depends on assumed rates of tilting and erosion, which the rock itself does not record.
15. 99 years. The Lisbon earthquake of 1755 falls between them.
16. Gnawed bones of elephant, rhinoceros, hippopotamus, deer, and other animals, together with hyena bones and droppings. He concluded the cave had been a hyena den and the animals had lived in England before a flood sealed it with mud.
17. *Reliquiae Diluvianae; or, Observations on the Organic Remains contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, attesting the Action of an Universal Deluge*. It claims that cave bones and surface gravels are evidence of a worldwide flood.
18. Agassiz showed him that scratched and polished bedrock, erratic boulders, and ridges of unsorted gravel in Britain matched exactly what living glaciers produce in Switzerland, so ice explained them better than flood water.
19. From 1807 to 1856 is 49 years of overlap. They toured Britain together in 1840.
20. Careful looking, honest recording, and willingness to be corrected. Buckland gave up the single-Deluge explanation of gravel and caves after seeing Agassiz's glacial evidence in 1840.

FIELD LAB: DOING GEOLOGY WHERE YOU LIVE

Eight units have given you the vocabulary of the earth: minerals and rocks, plates and volcanoes, rivers and glaciers, groundwater and caves, fossils and layers, the Flood and the Ice Age, mines and gems, maps and the men who drew them. Now you will do what every geologist in this course did before he wrote a book. You will go outside with a hammer and a notebook and read the ground under your own feet. The four lessons of the Field Lab build toward one capstone: a written field report on your own place, with a specimen collection, a map, a sketch, and a presentation to your family. *Fabricando fit faber: the maker is made by making.*

BEFORE YOU BEGIN

- Has finished the earlier units of this course
- A notebook, pencil and the household materials listed in each Hands-On Activity

MASTERY CHECKLIST

- I can explain the main ideas of Lesson 9.1, The Geologist's Kit and the Field Notebook, and define field notebook, hand specimen, catalog.
- I can explain the main ideas of Lesson 9.2, Reading Your Local Landscape, and define strike and dip, contact, stratigraphic section.
- I can explain the main ideas of Lesson 9.3, Catastrophe and Calm: Experiments on Rates, and define flume, scaling.
- I can explain the main ideas of Lesson 9.4, The Geology Field Report (Capstone), and define field report, rubric, primary source.

9.1 THE GEOLOGIST'S KIT AND THE FIELD NOTEBOOK

Video. Videos coming.

KEY VOCABULARY

field notebook

The dated, sketched, measured record a geologist keeps on site, with observations kept separate from interpretations.

hand specimen

A fist-sized rock sample that can be identified with simple tests and a hand lens.

catalog

The numbered list of samples with location, date, test results, and tentative identification, matching the labels on the samples.

CORE IDEAS

Why a kit at all. Everything in Units 1 through 8 was first learned by someone standing on a hillside with a hammer. Steno climbed Tuscan hills, Hutton walked the Scottish coast to Siccar Point, and Powell went down the Colorado in a wooden boat, with eyes, simple tools, and a notebook. “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter” (Proverbs 25:2, KJV). The searching-out begins with a kit you can assemble for the price of a few pizzas.

The kit. Keep them in one bag.

1. Safety glasses. Not sunglasses. Rock chips fly.
2. A hammer. A geologist's hammer costs about thirty to forty dollars; a brick hammer and cold chisel from any hardware store cost less and work nearly as well. Add a short cord so the chisel cannot fly off a ledge.
3. A hand lens, 10x. Hold it close to your eye and bring the rock up to it.
4. A streak plate, or the unglazed back of a white bathroom tile. Hardness about 7.
5. A steel nail (hardness about 5.5), a copper penny (about 3.5), and your fingernail (about 2.5). This is your whole Mohs kit, as in Unit 1.
6. A small magnet. Magnetite pulls; most other black minerals do not.
7. A dropper bottle of white vinegar. Calcite fizzes. Vinegar is the only acid you will ever use; never muriatic acid.
8. Small zip bags, a permanent marker, and masking tape for labels.
9. A tape measure and a compass. A phone compass and level app will serve.
10. A notebook with waterproof or stiff pages, and pencils, since pens bleed in rain.
11. A phone camera. Include something for scale in every photograph: a coin, a hammer, or a person.

The notebook tradition. The notebook is geology's oldest tool and still its most important. Hutton carried notes and sketches on his walks; Agassiz drilled his students with the motto attributed to him, "Study nature, not books"; and Powell wrote his journal by firelight on the river. Powell's 1869 entry for August 13 reads, "We are now ready to start on our way down the Great Unknown." His journals were later published; yours may not be, but they will be the only record of what you saw, and memory is a poor geologist.

A good entry has a fixed shape. At the top: the date, the place with coordinates from your phone, and the weather. Then a sketch, always with a scale bar and a north arrow. Then measured dimensions: layer thickness, crack width, distance from the road. Then two columns. Label the left column **Observed** and the right column **Inferred**. In the left column write only what you can see, touch, or measure: "grey limestone, fizzes in vinegar, beds 20 to 40 cm thick, tilted about 15 degrees to the east, one bed full of shell fragments." In the right column write what you think it means: "marine deposit; tilted after it hardened; possibly the same formation as the quarry on Route 9." The whole discipline of this course lives in that line down the middle of the page.

Samples and the catalog. Each sample gets a number the moment you bag it: FL-001, FL-002, and so on, written on tape on the sample, on the bag, and in the notebook with place, date, and a tentative name. At home, copy each entry into a catalog, a single sheet with columns: number, date, location, tentative name, luster, hardness, streak, cleavage, vinegar test, notes. Ten well-labelled samples are worth more than a bucket of unlabelled ones, and the catalog is a required part of your FL.4 report.

Where you may and may not collect. On private land, including a neighbor's creek bank, ask first and say how little you will take. In national parks and national monuments, collecting anything is forbidden by federal regulation. In most national forests and on most Bureau of Land Management lands, small amounts of common rock for personal use are allowed without a permit, but some districts have closures, so call the ranger station. State parks and state forests vary widely; many forbid it. Road cuts are usually state highway right-of-way, and rules differ; interstate shoulders are never permitted. Working quarries require written permission. Landscaping and stone yards are the easiest source of all: they often sell or give away broken granite, basalt, limestone, slate, marble, and sandstone.

The flowchart in words. Walk one step at a time and record each answer before moving on.

Step 1, luster: metallic or non-metallic? Step 2, hardness: does a fingernail scratch it (under 2.5)? A penny (under 3.5)? A nail (under 5.5)? Does it scratch the streak plate (over 7)? Step 3, streak: rub it on the tile and name the color of the powder. Step 4, cleavage: does it break along flat faces, and in how many directions? Or does it fracture irregularly or like glass? Step 5, the vinegar test: a drop of vinegar fizzes on calcite and on limestone and marble. Step 6, grain size and arrangement: interlocking crystals point to igneous or metamorphic; parallel bands or shiny flat sheets point to foliated metamorphic; rounded grains, layers, or fossils point to sedimentary; a glassy or bubbly texture points to volcanic. Step 7: name the rock, and write the evidence beside the name. "The works of the LORD are great, sought out of all them that have pleasure therein" (Psalm 111:2, KJV).

PICTURE STUDY



The camp of the survey party, San Francisco Mountain, Coconino County, Arizona, Elias Olcott Beaman, James Fennemore, and John K. Hillers, Powell Survey photographers, between 1871 and 1878,

Look for how little the survey party carried: tents, a wagon, instruments, and notebooks. The maps and reports that came out of this camp were built from exactly the kind of entries you will write.

Look closely

Talk about it

Safety first. Wear safety glasses when breaking a rock, strike away from everyone, and do not break rocks on concrete or near windows. Wash hands after handling samples and never taste any specimen.

HANDS-ON ACTIVITY: ASSEMBLE, CATALOG, IDENTIFY

Materials. The eleven-item kit above; five rocks from the yard, driveway gravel, a creek, or a landscaping yard; a catalog sheet.

Steps. (1) Lay out the kit and photograph it for your report. (2) Rule a catalog sheet with the columns named in the reading. (3) Number each rock FL-001 to FL-005 with tape and marker. (4) For each rock, walk the seven flowchart steps in order and write each result in the catalog before going to the next step. (5) Give each a name and one sentence of evidence.

What to notice. How often your first guess changes at step 5 or 6, and how a hand lens turns a dull grey rock into a mosaic of crystals or grains.

You will need

Steps

PRACTICE

1. Name the four items in the kit that together let you test Mohs hardness, and give the approximate hardness of each.
2. What are the two columns every good notebook entry must have, and what goes in each?
3. Explain why a sample with no number and no catalog entry is nearly worthless to a geologist, even if it is a beautiful rock.
4. A sample is non-metallic, is scratched by a penny but not by a fingernail, has a white streak, breaks along three directions that are not at right angles, and fizzes in vinegar. Walk the flowchart and name the mineral.
5. Where is rock collecting always forbidden, and where is it usually allowed in small amounts for personal use?

Exam connection. The observed-versus-inferred habit is exactly what the ACT science section rewards: the passages give data, and the questions ask which conclusion the data supports. AP Environmental Science free-response question 1 asks you to design an investigation with a clear method and measurements, which is what a notebook protocol is.

For families. Help your student price the kit; a brick hammer, chisel, loupe, and tile cost less than a video game. Talk at the table about why the two-column notebook matters beyond geology: in medicine, law, and business, the people who keep what they saw separate from what they concluded are the ones others trust. Before the activity, decide together where you may collect, and make the phone call to a ranger station if a national forest is nearby.

Practice answers

1. Fingernail (about 2.5), copper penny (about 3.5), steel nail (about 5.5), and streak plate or unglazed tile (about 7).
2. Observed and Inferred. Observed holds only what can be seen, touched, or measured; Inferred holds what the observer thinks the observations mean.
3. Its value lies in where it came from and what was around it. Without a location and context recorded at the time, it cannot be tied to a formation, a map, or any inference, so it is only a pretty stone.
4. Hardness between 2.5 and 3.5, so about 3; white streak; three cleavage directions forming rhombs; fizzing in vinegar. These identify calcite (Mohs 3).
5. Always forbidden in national parks and national monuments. Usually allowed in small, non-commercial amounts in national forests and on most BLM land, subject to local closures; state lands vary.

9.2 READING YOUR LOCAL LANDSCAPE

Video. Videos coming.

KEY VOCABULARY

strike and dip

The compass direction of a horizontal line on a tilted bed (strike) and the angle and direction of its steepest slope (dip).

contact

The surface where one rock unit meets another.

stratigraphic section

A measured record of layers from bottom to top, drawn as a column at a fixed scale.

CORE IDEAS

Everywhere is somewhere. Nothing geological happens where you live? That is never true. A creek bank, a road cut, the edge of a quarry, a beach, a gravel pit, or the stone walls of an old courthouse all show rock or sediment doing something. “In his hand are the deep places of the earth: the strength of the hills is his also. The sea is his, and he made it: and his hands formed the dry land” (Psalm 95:4–5, KJV). This lesson is a guided walk you can take anywhere, with a checklist for what to look for at each kind of site.

Before you go: the two free maps. First, download the USGS topographic quadrangle for your spot. The USGS makes every quad free through its topoView and National Map websites; search by town name and pick the 7.5-minute sheet. Contour lines show slope and blue lines are streams. Second, find the geologic map. Every state geological survey publishes one online, the USGS National Geologic Map Database collects them, and free phone apps built on those maps name the formation under your feet. Write the formation name and its described rock type in your notebook before you go. Then the field walk becomes a test: does the ground agree with the map?

What to look for. At any outcrop, start with the big picture before the hand lens. Are there layers? If so, what is their attitude: horizontal, as Steno said they began, or tilted? To measure, lay your phone’s level app flat on a bedding surface and read the angle of dip, then use the compass to record the direction a ball would roll down that surface. The line at right angles to that is the strike. “Dips 12 degrees toward the northeast” is a complete measurement.

Then look for contacts, the surfaces where one rock type ends and another begins. Is the contact sharp or gradual? Do the grains get coarser or finer as you go up? Coarse to fine usually means a current slowing down. Look for cross-beds, which are sloping laminae inside a thicker layer, and ripple marks on bedding surfaces; both record moving water or wind, and the direction they lean records the direction of flow. Look for fossils, especially shell

fragments in limestone, leaf impressions in shale, and burrows. Note joints, which are cracks with no movement, and faults, where layers on one side are offset from the other. Measure the offset if you can.

At a road cut or bank, look for the weathering rind, the discolored outer shell where air and water have altered fresh rock; chip through it to see the true color. At a soil bank, read the profile from top down: dark organic topsoil, lighter leached layer, reddish or clay-rich subsoil, then broken parent rock. Measure each. At a creek, find the point bar, the gravel deposited on the inside of a bend, and the cut bank, the steep eroded outside of the bend, then the alternating riffles and pools. If you live where glaciers reached in the Ice Age of Unit 6, look for till, an unsorted mix of clay to boulders, and for erratics, boulders of a rock type not found in the local bedrock. If your bedrock is limestone, look for karst from Unit 4: sinkholes, springs, disappearing streams, and fluted surfaces.

In a city, building stones are an outcrop too: granite steps show interlocking crystals, limestone facades hold fossils, marble shows veins, slate roofs show foliation. Old courthouses and banks are a free museum.

Sketching and measuring. A sketch beats a photograph because it forces you to decide what matters. Draw the outcrop in pencil, put a scale bar in the corner, add a north arrow or a note of which way you are facing, and number each layer. Then measure a stratigraphic section: start at the lowest exposed bed, hold the tape vertically, and record each layer's thickness, rock type, color, grain size, and any features, working upward. At home redraw it as a column at a fixed scale, oldest at the bottom according to superposition, with the thickness of each band proportional to the measured thickness. A column with a scale is the standard language of Unit 5, and it will go in your report.

Keep the FL.1 discipline. "Bed 4: 35 cm, tan sandstone, cross-beds dipping south" is observed. "Deposited by a current flowing south" is inferred, and belongs in the right-hand column. "Deposited over ten thousand years" or "deposited in a day" is also inferred, and the sign at a park will usually give you only one of those. Write what you can measure; then write what you conclude; then write what the map or the sign claims, and note which column each belongs in.

Safety. Never stop on a highway or interstate. Choose a quiet road with a wide shoulder, park fully off the pavement, wear high-visibility clothing, and go with a parent. Stand back from the face of any cut; loose rock falls without warning, especially after rain or frost. At creeks, watch the water level and never enter fast water above the knee. At quarries, stay outside the fence unless you have written permission and an escort. Wear safety glasses whenever you strike rock. "I tell you that, if these should hold their peace, the stones would immediately cry out" (Luke 19:40, KJV). The stones speak; listen carefully, which means safely.

PICTURE STUDY



A USGS scientist beside the mudline on the Muddy River, southeast of Mount St. Helens, Lyn Topinka, USGS, October 23, 1980,

Look for the pale line on the trees and the small figure standing below it for scale. The line is an observation; the depth of the May 18 lahar that left it is a measurement you can make from the photograph; and what that depth means for how fast the valley changed is an inference.

Look closely

Talk about it

Safety first. As in the reading; safety glasses, off the pavement, parent present, stay back from cut faces, caution near water.

HANDS-ON ACTIVITY: THE FIELD WALK

Materials. The FL.1 kit, the printed quad and geologic map, a clipboard, high-visibility vests, and this checklist.

Steps. (1) Choose a site: creek bank, legal road cut, beach, gravel pit edge, or a downtown block of stone buildings. (2) At the site, write the header entry: date, place with coordinates, weather, formation name from the map. (3) Work the checklist and tick what you find: layers; attitude with strike and dip; contacts; grain-size changes; cross-beds; ripple marks; fossils; joints; faults; weathering rind; soil profile; point bar and cut bank; riffle and pool; till or erratics; karst features; building stones. (4) Make an outcrop sketch with scale bar and north arrow, or measure a stratigraphic section with the tape, bed by bed. (5) Collect no more than five labelled samples where permitted. (6) At home, redraw the section as a column at a fixed scale and write up the two columns.

What to notice. Whether the ground agreed with the map, and which features you would have walked past without the checklist.

You will need

Steps

PRACTICE

1. What two free maps should you obtain before a field walk, and what does each tell you?
2. What is the difference between a joint and a fault?
3. Explain why cross-beds and ripple marks are useful to a geologist beyond simply being pretty.
4. You measure a section 4.6 meters thick with four beds: 1.2 m shale, 0.4 m limestone, 2.0 m sandstone, and 1.0 m shale, from bottom to top. At a drawing scale of 1 cm = 20 cm, how tall is the whole column, and how tall is the limestone band?
5. Name three safety rules for a road cut.

Exam connection. Reading a geologic map and a stratigraphic column is a standard ACT science passage type: a diagram with layers and a set of questions about order and thickness. AP Environmental Science tests soil profiles and horizons directly, so the soil-bank step of this walk is exam material.

For families. Choose the site together, and call ahead if there is any doubt about permission. Scholars genuinely disagree about how long many sedimentary layers took to form, and the local sign or brochure will give one answer; this is a good evening to practice saying “that is the sign’s inference” without heat. Bring water and a snack; a good field day runs two to three hours.

Practice answers

1. The USGS topographic quadrangle, which shows elevation contours, streams, and features; and the state geologic map, which names the rock formation and its rock type at your location.
2. A joint is a crack with no movement across it; a fault is a break along which the rock on one side has moved relative to the other.
3. They record moving water or wind and the direction it flowed, which lets the geologist infer the environment and current direction at the time the sediment was deposited.
4. $460 \text{ cm} \div 20 = 23 \text{ cm}$ for the whole column; $40 \text{ cm} \div 20 = 2 \text{ cm}$ for the limestone. The lowest shale goes at the bottom by superposition.
5. Any three: never on a highway or interstate; park fully off the pavement; wear high-visibility clothing; go with a parent; stand back from the face because of rockfall; wear safety glasses when striking rock.

9.3 CATASTROPHE AND CALM: EXPERIMENTS ON RATES

Video. Videos coming.

KEY VOCABULARY

flume

A channel of flowing water used to study how currents carry and deposit sediment.

scaling

The step of applying a result from a small model to a large natural feature; an inference that must be defended.

CORE IDEAS

The question of speed. Geology's great argument, from Hutton and Lyell to Bretz and Mount St. Helens, has been about rates. Lyell's subtitle promised to explain the earth's former changes "by Reference to Causes Now in Operation," and the question has always been how fast those causes can run. "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). You cannot settle the question of the Flood on a kitchen table, but you can measure how fast layers, canyons, and crusts form in a model and think clearly about what a model can tell you.

Experiment 1: layers in a flume. A flume is a channel with water flowing through it. Build one from a long clear plastic storage box tilted a few degrees on a block, with an outlet at the low end into a bucket. Mix fine sand, coarse sand, crushed gravel, and a little silt, in different colors if you can find them. Feed it steadily into the upstream end under a steady flow of water from a pitcher or slow hose. Watch the side of the box. Rather than one layer settling at a time, several thin laminae form at once along a sloping front as the current sorts grains by size and carries the deposit forward. In the 1980s and 1990s the French engineer Guy Berthault, working with Pierre Julien and colleagues at the hydraulics laboratory of Colorado State University, ran flume experiments of this kind and reported that laminations built sideways and simultaneously under a moving current rather than one on top of another in still water. That is a paraphrase; sedimentologists agree that laminae can form rapidly in currents while disagreeing about how widely that applies to the rock record. Record time, flow, deposit thickness, and the number of laminae in a table, and compute a deposition rate.

Experiment 2: a canyon in a sand box. Fill a plastic tub or a wooden box with damp sand, sloped from one end to the other. Run two trials. In the first, let water trickle from a jug at the top at the slowest steady rate you can manage and measure the depth of the channel every minute for ten minutes. In the second, dam a few liters of water behind a sand wall at the top, then breach the dam and measure the depth of the channel cut, again by the minute. The breach cuts in seconds what the trickle cannot match in ten minutes. After the 1980

eruption of Mount St. Helens, deposits up to about 600 feet thick filled the upper North Fork Toutle valley. On March 19, 1982, an eruption melted snow in the crater and sent a mudflow across the deposits, and the breakout of ponded water cut channels through them, in places up to about 100 feet deep, in a single day. USGS geologists have photographed those canyons ever since; they show side canyons and terraces, and they were cut through soft, fresh deposits. By contrast, the gorge below Niagara Falls has been retreating upstream at measured rates of about 3 to 4 feet per year through the 1800s and early 1900s, and only a few inches to a foot per year since water was diverted for power in the 1950s, through hard dolomite over soft shale. Both are observations of rate. Which one applies to a canyon you are looking at is an inference, and the rock type, the water supply, and the slope all matter.

Experiment 3: mineral crusts and petrifying. Stalactites in Unit 4 grow by precipitation of calcite from dripping water; model it with Epsom salt or borax. Dissolve as much as will dissolve in hot water, soak a length of cotton yarn in it, and hang the yarn between two jars with the ends in the solution and a dip in the middle over a saucer. Crystals form along the yarn and a drip-point in a few days. For a “petrifying” variant, soak a sponge, a pine cone, or a leaf in the saturated solution and let it dry on a plate; the pores fill with crystals. Measure the crust each day and tabulate it. Most cave formations grow more slowly, and museum signs often give rates of a fraction of an inch per century, but stalactites inches long have formed under bridges and in mine tunnels within decades. Safety: borax is a cleaning product and is not for eating; wash hands, keep solutions away from small children, and have a parent handle the hot water.

Models and scale. Each experiment is small. A sand box is not a canyon, and a storage tub is not a sea. Scaling up a result is itself an inference, and an honest notebook says so. The fair statement is this: laminae, canyons, and mineral crusts can form quickly under the right conditions, and that is an observation; whether a particular formation did form quickly is an inference that must be argued from the formation itself. Mainstream geologists say Mount St. Helens shows what fresh volcanic deposits do and does not by itself tell how the Grand Canyon formed. Many Christian geologists say the same site shows that rapid processes deserve a larger place in explaining the rock record than they were given for a century. Both are drawing inferences from the same observed canyon. “Thou hast set a bound that they may not pass over; that they turn not again to cover the earth” (Psalm 104:9, KJV).

Thinking About Time

What the sign says. The sign at Niagara reports that the falls have retreated about seven miles from the escarpment in roughly twelve thousand years since the Ice Age glaciers melted back; a canyon sign elsewhere may say millions of years.

What we observe. A measured retreat rate at Niagara of about 3 to 4 feet per year in the 1800s, reduced today by water diversion to a few inches to a foot per year; at Mount St. Helens, a canyon up to about a hundred feet deep cut in one day through loose deposits; in a sand box, a dam breach cutting deeper in seconds than a trickle does in minutes.

How Christians read it. Many Christian families understand canyons and layers within a young earth shaped largely by the Flood of Genesis 6–9 and its aftermath, where rapid processes did most of the work. Other Christians hold an older earth and read the days of Genesis 1 differently, accepting slow measured rates as the normal case with catastrophes as exceptions. Both honor Scripture, and both must say honestly which rate they are assuming when they move from a measured rate to an age.

PICTURE STUDY



North Fork Toutle River valley, downstream view, debris avalanche deposit from the May 18, 1980 eruption of Mount St. Helens, Lyn Topinka, USGS Cascades Volcano Observatory, November 30, 1983,

Look at the hummocky surface of the avalanche deposit and the channels already cut into it three years after the eruption. Ask which parts of the picture are observations and which statements about them would be inferences.

Look closely

Talk about it

Safety first. Borax and Epsom salt are not for eating; a parent handles the hot water; keep solutions away from young children; mop up spills, since wet sand and water on a floor cause falls.

HANDS-ON ACTIVITY: THREE RATE EXPERIMENTS WITH TABLES AND A GRAPH

Materials. Clear plastic storage box, block, bucket, pitcher or hose, mixed sand and gravel of different colors; plastic tub of damp sand and a jug; Epsom salt or borax, jars, cotton yarn, a sponge or leaf, saucer; ruler, timer, notebook.

Steps. (1) Flume: tilt the box, feed sediment and water steadily, and record deposit thickness at a marked line every 2 minutes for 12 minutes along with the lamina count; photograph the side. (2) Sand box: run the trickle trial and the dam-breach trial, recording channel depth at the same point every minute for 10 minutes each. (3) Crystals: set up the yarn and the soaked sponge, and measure crust thickness or crystal length once a day for five days. (4) Graph depth or thickness against time for all three on one sheet, each as its own line. (5) Write each up with an Observed column and an Inferred column and a short paragraph comparing to Mount St. Helens and Niagara.

What to notice. The shape of each curve, and especially whether the dam-breach line is a jump followed by a flat line.

You will need

Steps

PRACTICE

1. In the flume, how do laminae form under a moving current, according to your observation and the paraphrased Colorado State experiments?
2. Your flume data: at 0 minutes the deposit at the marked line is 0 cm thick; at 4 minutes, 1.0 cm; at 8 minutes, 2.1 cm; at 12 minutes, 3.0 cm, with 9 laminae counted. What is the average deposition rate in centimeters per minute, and in centimeters per hour?
3. Compare the two canyon trials. Which cut deeper per minute, and why?
4. Explain why “scaling up is itself an inference” is a fair statement rather than a dodge.
5. The Niagara gorge is about 7 miles long. At a retreat rate of 3 feet per year, how many years would the full length take, and what assumptions does that number rest on?

Exam connection. This lesson is pure ACT science practice: you will build tables, plot lines, read slopes, and interpolate. The SAT and ACT math sections include rate and unit-conversion problems like question 2 and question 5. AP Environmental Science free-response question 3 requires a calculation from given data with units shown.

For families. This is the messiest lesson in the course; do the flume outdoors or in a garage. Expect the student to ask what the experiments prove about the Flood or the Grand Canyon, and the honest answer is that they prove what water can do, not what it did; the family’s reading of Genesis supplies the history, and the experiment supplies the possibility. Scholars still debate how much of the rock record formed rapidly, and the paraphrased Colorado State flume work is accepted as an observation while its reach is disputed.

Practice answers

1. Several laminae form at the same time along a sloping front, sorted by grain size, rather than one layer settling after another in still water.

2. $3.0 \text{ cm} \div 12 \text{ min} = 0.25 \text{ cm per minute}$, which is 15 cm per hour. About 9 laminae in 12 minutes, roughly one every 80 seconds.
3. The dam breach cut far deeper per minute because a large volume of water moving fast carries much more energy and sediment than a slow trickle; erosion rises steeply with flow.
4. The model shows that a process can act quickly under certain conditions; whether those conditions held for a real formation must be argued from the formation's own rock type, water supply, slope, and features. The model proves possibility, not history.
5. $7 \text{ miles} \times 5,280 \text{ feet} = 36,960 \text{ feet}$; $\div 3 \text{ feet per year} \approx 12,300 \text{ years}$. It assumes a constant rate, the same rock, and the same water flow throughout, none of which is guaranteed; the rate today, after diversion, is lower, and rates during meltwater floods may have been far higher.

9.4 THE GEOLOGY FIELD REPORT (CAPSTONE)

Video. Videos coming.

KEY VOCABULARY

field report

A written account of a place's geology built on the writer's own observations, measurements, maps, and samples.

rubric

A scoring table that states what each part of an assignment is worth and what earns full marks.

primary source

A document written by a participant or original investigator, such as Powell's journal or a USGS bulletin, as opposed to a textbook summary.

CORE IDEAS

What you are making. The capstone of this course is a written field report on your own place, or on a park you have visited, with a specimen display and a ten-minute presentation to your family. It is what a geologist writes after a season in the field, and the kind of project an admissions reader remembers. "The heavens declare the glory of God; and the firmament sheweth his handywork" (Psalm 19:1, KJV). Your report declares what the ground under your house says, in your own words and measurements.

The required parts. The report runs 1,500 to 2,500 words, not counting the catalog and bibliography, and contains these parts in this order.

1. A title page with the report title, your name, the date, and the location with coordinates.
2. A location map, hand-drawn or traced from the USGS quad, with a scale bar, a north arrow, and your sites marked.
3. An outcrop sketch or a measured stratigraphic section, drawn to scale, from FL.2.
4. A rock and mineral catalog of at least ten specimens, each with number, location, test results, and your identification, from the FL.1 flowchart. Gravel-pit and landscaping-yard pieces count if their source is recorded honestly.
5. A section on the processes that shaped your place. Choose from the units: tectonics and volcanism from Unit 2; weathering, rivers, and glaciers from Unit 3; groundwater and karst from Unit 4; fossils and layers from Unit 5; the Flood and the Ice Age from Unit 6; mining and resources from Unit 7. Most places need two or three of these.
6. A "Thinking About Time" section on one feature, written in the three-part form you have read all year: What the sign says, What we observe, How Christians read it. State both readings fairly and keep observation and inference separate.

7. One primary source, quoted exactly from a text you can cite or clearly labelled as paraphrase. Powell's 1869 journal, Lyell's title, Hutton's closing sentence, a USGS bulletin, or a state survey report all qualify.
8. A bibliography with at least four sources, including the geologic map and the quad you used.

The presentation lays the labelled specimens on a table, walks the family through the map and sketch, and ends with the time section and a question from each listener.

The rubric.

Part	Points	What earns full marks
Observation quality	20	Entries dated, measured, sketched; Observed and Inferred in separate columns
Identification accuracy	15	Ten or more specimens with flowchart steps recorded and a defensible name
Map and sketch	15	Scale bar, north arrow, sites marked; section drawn to a stated scale with beds in order
Writing	15	Clear, full sentences; 1,500 to 2,500 words; correct vocabulary from the units
Sources	10	At least four, including the map and quad; one primary source quoted exactly or labelled paraphrase
Time section fairness	15	Both Christian readings stated accurately and without sneering; observation and inference separated
Presentation	10	Ten minutes, specimens displayed and labelled, questions answered from evidence
Total	100	90 and above is an A; 80 to 89 a B; 70 to 79 a C

Transcript and portfolio. The parent issues the transcript; this course earns one science credit when the eight units and the Field Lab are complete. Record it as "Geology with Laboratory" and note that the laboratory included a field report; colleges want to see lab science, and a field report with a specimen catalog is stronger than a kit of pre-packaged experiments. Keep the report, maps, display photographs, and notebook together as a portfolio. Many colleges accept a graded writing sample or a project description, and a field report with a rubric score, a map, and primary sources is an unusual and persuasive one.

Transfer to the exams. The ACT science section is built from passages with data tables, graphs, and competing viewpoints; your report has trained you to read a column, compute a rate, and separate what is measured from what is claimed. The "conflicting viewpoints" passage format, in which two scientists interpret the same evidence differently, is the three-part time section under another name. AP Environmental Science free-response questions ask you to design an investigation, analyze a problem and propose a solution, and do a calculation from given data; your notebook protocol, your process section, and your rate

tables from FL.3 are practice for all three. The CLT and SAT reward the clear sentences and exact vocabulary your writing score demands.

Why it matters. “For the invisible things of him from the creation of the world are clearly seen, being understood by the things that are made, even his eternal power and Godhead; so that they are without excuse” (Romans 1:20, KJV). The things that are made include the gravel in your driveway and the bank of the creek down the road. To read them carefully, to say exactly what you saw and what you concluded, and to tell honestly where Christians differ on the ages, is to do geology as the best of its founders did it: Steno the bishop, Buckland the dean, Agassiz the creationist, Powell the one-armed major with his journal. Write the report so that a stranger could follow you to your outcrop with your map, check your measurements, and see what you saw.

PICTURE STUDY



The Chasm of the Colorado, Thomas Moran, 1873-1874,

Moran traveled with Powell’s survey in 1873 and painted this canvas afterward from his field sketches; it was purchased by Congress. Look for the horizontal layers in the canyon walls and the storm that Moran uses to show water at work. His field sketches were his notebook, and the painting was his report.

Look closely

Talk about it

Safety first. None beyond the usual care with samples; wash hands after handling specimens.

HANDS-ON ACTIVITY: THE REPORT AND THE PRESENTATION

Materials. Your notebook, catalog, specimens, the quad and geologic map, tracing paper, pencils, ruler, a word processor, a table for the display.

Steps and checklist. (1) Title page with name, date, location, coordinates. (2) Location map traced from the quad, with scale bar, north arrow, sites. (3) Outcrop sketch or measured section redrawn to a stated scale. (4) Catalog of ten or more specimens with flowchart results and names. (5) Processes section drawing on two or three units by number. (6) Thinking About Time section in the three-part form, both readings stated fairly. (7) One primary source, quoted exactly with page or date, or labelled paraphrase. (8) Bibliography of four or more sources. (9) Word count between 1,500 and 2,500. (10) Specimens labelled and arranged on the table. (11) Ten-minute presentation rehearsed once with a timer. (12) Parent scores the rubric table above and writes two sentences of comment.

What to notice. How the report tightens when you cut every sentence that cannot be traced to a notebook entry or a source.

You will need

Steps

PRACTICE

1. List the eight required parts of the field report in order.
2. Using the rubric, a student scores 18 on observation, 12 on identification, 13 on map and sketch, 11 on writing, 8 on sources, 15 on the time section, and 9 on presentation. What is the total, what letter grade is it, and which part most needs work?
3. Explain why the “Thinking About Time” section is scored on fairness rather than on which reading the student holds.
4. How should this course appear on a homeschool transcript, and why is the field report an asset in a college application?
5. Which skill from the report matches the ACT “conflicting viewpoints” passage, and which matches AP Environmental Science free-response question 1?

Exam connection. The whole capstone is ACT science and AP Environmental Science practice in disguise: tables, rates, competing interpretations, investigation design, and a calculation with units. The writing and the bibliography serve the SAT, CLT, and any college application essay about a project you are proud of.

For families. Set the presentation date on the calendar before the report is written; a deadline makes the project real. Score the rubric honestly and let the student see the sheet; a B with clear comments teaches more than an unexplained A. The time section may spark the best conversation of the year, and the family’s own reading of Genesis belongs in that conversation alongside the course’s rule that the other reading be stated fairly. Keep everything in a folder; you will want it when application season comes.

Practice answers

1. Title page; location map; outcrop sketch or measured section; catalog of at least ten specimens; processes section; Thinking About Time section; primary source quoted exactly or labelled paraphrase; bibliography.
2. $18 + 12 + 13 + 11 + 8 + 15 + 9 = 86$, a B. Writing scored 11 of 15, the lowest fraction along with sources at 8 of 10; writing is the first place to improve.
3. The course's rule is that both Christian readings be stated accurately and without sneering, and that observation be separated from inference; the student is free to hold either reading, but is graded on representing both honestly and reasoning clearly.
4. As one science credit, "Geology with Laboratory," with a note that the lab included a field report. Colleges look for laboratory science, and an original field report with a map, catalog, rubric score, and primary sources is a concrete, verifiable portfolio piece.
5. The three-part time section matches conflicting viewpoints, since two readers interpret the same evidence differently. The notebook protocol and the processes investigation match AP question 1, which asks the student to design an investigation.