U·X·L

ENCYCLOPEDIA OF LANDFORMS AND OTHER GEOLOGIC FEATURES

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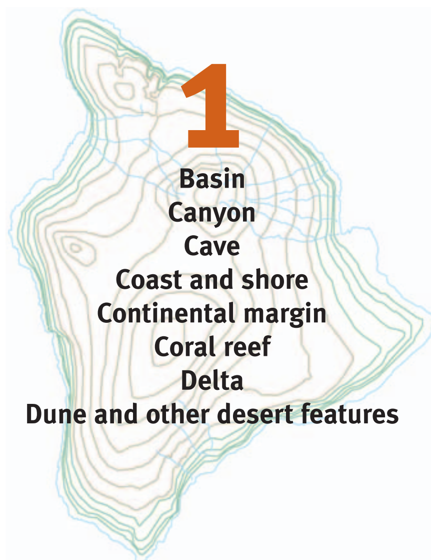

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Basin
Canyon
Cave
Coast and shore
Continental margin
Coral reef
Delta
Dune and other desert features

Rob Nagel

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U•X•L Encyclopedia of Landforms and Other Geologic Features

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Contents

Reader's Guide

From the perspective of human time, very little changes on the surface of Earth. From the perspective of geologic time, the period from Earth's beginning more than 4.5 billion years ago to the present day, however, the surface of the planet is in constant motion, being reshaped over and over. The constructive and destructive forces at play in this reshaping have helped create landforms, specific geomorphic features on Earth's land surface. Mountains and canyons, plains and plateaus, faults and basins: These are but a few of the varied and spectacular features that define the landscape of the planet.

U•X•L Encyclopedia of Landforms and Other Geologic Features explores twenty-two of these landforms: what they are, how they look, how they were created, how they change over time, and major geological events associated with them.

Scope and Format

In three volumes, *U•X•L Encyclopedia of Landforms and Other Geologic Features* is organized alphabetically into the following chapters:

- Basin
- Canyon
- Cave
- Coast and shore
- Continental margin
- Coral reef
- Delta
- Dune and other desert features
- Fault
- Floodplain
- Geyser and hot spring
- Glacial landforms and features
- Landslide and other gravity movements
- Mesa and butte

Meteorite crater	Mountain
Ocean basin	Plain
Plateau	Stream and river
Valley	Volcano

Each chapter begins with an overview of that specific landform. The remaining information in the chapter is broken into four sections:

- **The shape of the land** describes the physical aspects of the landform, including its general size, shape, and location on the surface of the planet, if applicable. A standard definition of the landform opens the discussion. If the landform exists as various types, those types are defined and further described.
- **Forces and changes: Construction and destruction** describes in detail the forces and agents responsible for the construction, evolution, and destruction of the landform. The erosional actions of wind and water, the dynamic movement of crustal plates, the influence of gravity, and the changes in climate both across regions and time are explained in this section, depending on their relation to the specific landform.
- **Spotlight on famous forms** describes specific examples of the landform in question. Many of these examples are well-known; others may not be. The biggest, the highest, and the deepest were not the sole criteria for selection, although many of the featured landforms meet these superlatives. While almost all chapters include examples found in the United States, they also contain examples of landforms found throughout the world.
- **For More Information** offers students further sources for research—books or Web sites—about that particular landform.

Other features include more than 120 color photos and illustrations, "Words to Know" boxes providing definitions of terms used in each chapter, sidebar boxes highlighting interesting facts relating to particular landforms, a general bibliography, and a cumulative index offering easy access to all of the subjects discussed in *U•X•L Encyclopedia of Landforms and Other Geologic Features*.

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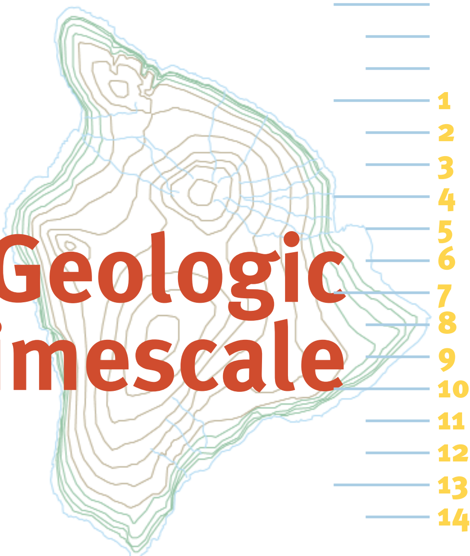
Comments and Suggestions

We welcome your comments on *U•X•L Encyclopedia of Landforms and Other Geologic Features*. Please write: Editors, *U•X•L Encyclopedia of Landforms and Other Geologic Features*, U•X•L, 27500 Drake Rd., Farmington Hills, MI 48331; call toll-free: 1-800-877-4253; fax: 248-699-8097; or send e-mail via http://www.gale.com.

Geologic Timescale



Era	Period		Epoch	Started (millions of years ago)
Cenozoic: 66.4 millions of years ago–present time	**Quaternary**		Holocene	0.01
			Pleistocene	1.6
	Tertiary	**Neogene**	Pliocene	5.3
			Miocene	23.7
		Paleogene	Oligocene	36.6
			Eocene	57.8
			Paleocene	66.4
Mesozoic: 245–66.4 millions of years ago	**Cretaceous**		Late	97.5
			Early	144
	Jurassic		Late	163
			Middle	187
			Early	208
	Triassic		Late	230
			Middle	240
			Early	245
Paleozoic: 570–245 millions of years ago	**Permian**		Late	258
			Early	286
	Carboniferous	**Pennsylvanian**	Late	320
		Mississippian	Early	360
	Devonian		Late	374
			Middle	387
			Early	408
	Silurian		Late	421
			Early	438
	Ordovician		Late	458
			Middle	478
			Early	505
	Cambrian		Late	523
			Middle	540
			Early	570
Precambrian time: 4500-570 millions of years ago				4500

Words to Know

A

Ablation zone: The area of a glacier where mass is lost through melting or evaporation at a greater rate than snow and ice accumulate.

Abrasion: The erosion or wearing away of bedrock by continuous friction caused by sand or rock fragments in water, wind, and ice.

Abyssal hill: A gently sloping, small hill, typically of volcanic origin, found on an abyssal plain.

Abyssal plain: The relatively flat area of an ocean basin between a continental margin and a mid-ocean ridge.

Accretionary wedge: A mass of sediment and oceanic rock that is transferred from an oceanic plate to the edge of the less dense plate under which it is subducting.

Accumulation zone: The area of a glacier where mass is increased through snowfall at a greater rate than snow and ice is lost through ablation.

Active continental margin: A continental margin that has a very narrow, or even nonexistent, continental shelf and a narrow and steep continental slope that ends in a deep trench instead of a continental rise; it is marked by earthquake and volcanic activity.

Alluvial fan: A fanlike deposit of sediment that forms where an intermittent, yet rapidly flowing canyon or mountain stream spills out onto a plain or relatively flat valley.

Alluvium: A general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Alpine glacier: A relatively small glacier that forms in high elevations near the tops of mountains.

Angle of repose: The steepest angle at which loose material on a slope remains motionless.

Anticline: An upward-curving (convex) fold in rock that resembles an arch.

Arête: A sharp-edged ridge of rock formed between adjacent cirque glaciers.

Arroyo: A steep-sided and flat-bottomed gully in a dry region that is filled with water for a short time only after occasional rains.

Asteroid: A small, irregularly shaped rocky body that orbits the Sun.

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Atmospheric pressure: The pressure exerted by the weight of air over a given area of Earth's surface.

Atoll: A ring-shaped collection of coral reefs that nearly or entirely enclose a lagoon.

B

Back reef: The landward side of a reef between the reefcrest and the land.

Backshore zone: The area of a beach normally affected by waves only during a storm at high tide.

Backswamp: The lower, poorly drained area of a floodplain that retains water.

Backwash: The return flow of water to the ocean following the swash of a wave.

Bajada: Several alluvial fans that have joined together.

Bar: A ridge or mound of sand or gravel that lies underwater a short distance from and parallel to a beach; also commonly known as a sand bar.

Barrier island: A bar that has been built up so that it rises above the normal high tide level.

Barrier reef: A long, narrow ridge of coral relatively near and parallel to a shoreline, separated from it by a lagoon.

Basal sliding: The sliding of a glacier over the ground on a layer of water.

Basalt: A dark, dense volcanic rock, about 50 percent of which is silica.

Base level: The level below which a stream cannot erode.

Basin: A hollow or depression in Earth's surface with no outlet for water.

Bay: A body of water in a curved inlet between headlands.

Beach: A deposit of loose material on shores that is moved by waves, tides, and, sometimes, winds.

Beach drift: The downwind movement of sand along a beach as a result of the zigzag pattern created by swash and backwash.

Bed load: The coarse sediment rolled along the bottom of a river or stream.

Bedrock: The general term for the solid rock that underlies the soil.

Berm: A distinct mound of sand or gravel running parallel to the shoreline that divides the foreshore zone from the backshore zone of a beach.

Blowout: A depression or low spot made in sand or light soil by strong wind.

Bottomset bed: A fine, horizontal layer of clay and silt deposited beyond the edge of a delta.

Breccia: A coarse-grained rock composed of angular, broken rock fragments held together by a mineral cement.

Butte: A flat-topped hill with steep sides that is smaller in area than a mesa.

C

Caldera: Large, usually circular, steep-walled basin at the summit of a volcano.

Canyon: A narrow, deep, rocky, and steep-walled valley carved by a swift-moving river.

Cap rock: Erosion-resistant rock that overlies other layers of less-resistant rock.

Cave: A naturally formed cavity or hollow beneath the surface of Earth that is beyond the zone of light and is large enough to be entered by humans.

Cavern: A large chamber within a cave.

Cave system: A series of caves connected by passages.

Channel: The depression where a stream flows or may flow.

Chemical weathering: The process by which chemical reactions alter the chemical makeup of rocks and minerals.

Cirque: A bowl-shaped depression carved out of a mountain by an alpine glacier.

Cliff: A high, steep face of rock.

Coast: A strip of land that extends landward from the coastline to the first major change in terrain features.

Coastal plain: A low, generally broad plain that lies between an oceanic shore and a higher landform such as a plateau or a mountain range.

Coastline: The boundary between the coast and the shore.

Comet: An icy extraterrestrial object that glows when it approaches the Sun, producing a long, wispy tail that points away from the Sun.

Compression: The reduction in the mass or volume of something by applying pressure.

Continental drift: The hypothesis proposed by Alfred Wegener that the continents are not stationary, but have moved across the surface of Earth over time.

Continental glacier: A glacier that forms over large areas of continents close to the poles.

Continental margin: The submerged outer edge of a continent, composed of the continental shelf and the continental slope.

Continental rise: The gently sloping, smooth-surfaced, thick accumulation of sediment at the base of certain continental slopes.

Continental shelf: The gently sloping region of the continental margin that extends seaward from the shoreline to the continental shelf break.

Continental shelf break: The outer edge of the continental shelf at which there is a sharp drop-off to the steeper continental slope.

Continental slope: The steeply sloping region of the continental margin that extends from the continental shelf break downward to the ocean basin.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Coral polyp: A small, invertebrate marine animal with tentacles that lives within a hard, cuplike skeleton that it secretes around itself.

Coral reef: A wave-resistant limestone structure produced by living organisms, found principally in shallow, tropical marine waters.

Cordillera: A complex group of mountain ranges, systems, and chains.

Creep: The extremely slow, almost continuous movement of soil and other material downslope.

Crest: The highest point or level; summit.

Crevasse: A deep, nearly vertical crack that develops in the upper portion of glacier ice.

Crust: The thin, solid outermost layer of Earth.

Curtain: A thin, wavy or folded sheetlike mineral deposit that hangs from the ceiling of a cave.

Cut bank: A steep, bare slope formed on the outside of a meander.

D

Debris avalanche: The extremely rapid downward movement of rocks, soil, mud, and other debris mixed with air and water.

Debris flow: A mixture of water and clay, silt, sand, and rock fragments that flows rapidly down steep slopes.

Deflation: The lowering of the land surface due to the removal of fine-grained particles by the wind.

Delta: A body of sediment deposited at the mouth of a river or stream where it enters an ocean or lake.

Desert pavement: Surface of flat desert lands covered with a layer of closely packed coarse pebbles and gravel.

Dip: The measured angle from the horizontal plane (Earth's surface) to a fault plane or bed of rock.

Dissolved load: Dissolved substances, the result of the chemical weathering of rock, that are carried along in a river or stream.

Distributaries: The channels that branch off of the main river in a delta, carrying water and sediment to the delta's edges.

Dune: A mound or ridge of loose, wind-blown sand.

E

Earthflow: The downward movement of water-saturated, clay-rich soil on a moderate slope.

Ecosystem: A system formed by the interaction of a community of plants, animals, and microorganisms with their environment.

Ejecta blanket: The circular layer of rock and dust lying immediately around a meteorite crater.

Emergent coast: A coast in which land formerly under water has gradually risen above sea level through geologic uplift of the land or has been exposed because of a drop in sea level.

Eolian: Formed or deposited by the action of the wind.

Erg: A vast area deeply covered with sand and topped with dunes.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Erratic: A large boulder that a glacier deposits on a surface made of different rock.

Esker: A long, snakelike ridge of sediment deposited by a stream that ran under or within a glacier.

F

Fall: A sudden, steep drop of rock fragments or debris.

Fall line: The imaginary line that marks the sharp upward slope of land along a coastal plain's inland edge where waterfalls and rapids occur as rivers cross the zone from harder to softer rocks.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Fault creep: The slow, continuous movement of crustal blocks along a fault.

Fault line: The line on Earth's surface defining a fault; also known as a fault trace.

Fault plane: The area where crustal blocks meet and move along a fault from the fault line down into the crust.

Fault scarp: A steep-sided ledge or cliff generated as a result of fault movement.

Fault system: A network of connected faults.

Flash flood: A flood that occurs after a period of heavy rain, usually within six hours of the rain event.

Firn: The granular ice formed by the recrystallization of snow; also known as névé.

Fjord: A deep glacial trough submerged with seawater.

Floodplain: An area of nearly flat land bordering a stream or river that is naturally subject to periodic flooding.

Flow: A type of mass wasting that occurs when a loose mixture of debris, water, and air moves down a slope in a fluidlike manner.

Flowstone: The general term for a sheetlike mineral deposit on a wall or floor of a cave.

Fold: A bend or warp in a layered rock.

Foothill: A high hill at the base of a mountain.

Footwall: The crustal block that lies beneath an inclined fault plane.

Fore reef: The seaward edge of a reef that is fairly steep and slopes down to deeper water.

Foreset bed: An inclined layer of sand and gravel deposited along the edge of a delta.

Foreshore zone: The area of a beach between the ordinary low tide mark and the high tide mark.

Fracture zone: The area where faults occur at right angles to a main feature, such as a mid-ocean ridge.

Fringing reef: A coral reef formed close to a shoreline.

Fumarole: A small hole or vent in Earth's surface through which volcanic gases escape from underground.

G

Geyser: A hot spring that periodically erupts through an opening in Earth's surface, spewing hot water and steam.

Geyserite: A white or grayish silica-based deposit formed around hot springs.

Glacial drift: A general term for all material transported and deposited directly by or from glacial ice.

Glacial polish: The smooth and shiny surfaces produced on rocks underneath a glacier by material carried in the base of that glacier.

Glacial surge: The rapid forward movement of a glacier.

Glacial trough: A U-shaped valley carved out of a V-shaped stream valley by a valley glacier.

Glaciation: The transformation of the landscape through the action of glaciers.

Glacier: A large body of ice that formed on land by the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity.

Graben: A block of Earth's crust dropped downward between faults.

Graded stream: A stream that is maintaining a balance between the processes of erosion and deposition.

Granular flow: A flow that contains up to 20 percent water.

Gravity: The physical force of attraction between any two objects in the universe.

Ground moraine: A continuous layer of till deposited beneath a steadily retreating glacier.

Groundwater: Freshwater lying within the uppermost parts of Earth's crust, filling the pore spaces in soil and fractured rock.

Gully: A channel cut into Earth's surface by running water, especially after a heavy rain.

Guyot: An undersea, flat-topped seamount.

H

Hanging valley: A shallow glacial trough that leads into the side of a larger, main glacial trough.

Hanging wall: The crustal block that lies above an inclined fault plane.

Headland: An elevated area of hard rock that projects out into an ocean or other large body of water.

Hill: A highland that rises up to 1,000 feet (305 meters) above its surroundings, has a rounded top, and is less rugged in outline than a mountain.

Horn: A high mountain peak that forms when the walls of three or more glacial cirques intersect.

Horst: A block of Earth's crust forced upward between faults.

Hot spot: An area beneath Earth's crust where magma currents rise.

Hot spring: A pool of hot water that has seeped through an opening in Earth's surface.

I

Igneous rock: Rock formed by the cooling and hardening of magma, molten rock that is underground (called lava once it reaches Earth's surface).

Internal flow: The movement of ice inside a glacier through the deformation and realignment of ice crystals; also known as creep.

Invertebrates: Animals without backbones.

K

Kame: A steep-sided, conical mound or hill formed of glacial drift that is created when sediment is washed into a depression on the top surface of

a glacier and is then deposited on the ground below when the glacier melts away.

Karst topography: A landscape characterized by the presence of sinkholes, caves, springs, and losing streams.

Kettle: A shallow, bowl-shaped depression formed when a large block of glacial ice breaks away from the main glacier and is buried beneath glacial till, then melts. If the depression fills with water, it is known as a kettle lake.

L

Lagoon: A quiet, shallow stretch of water separated from the open sea by an offshore reef or other type of landform.

Lahar: A mudflow composed of volcanic ash, rocks, and water produced by a volcanic eruption.

Landslide: A general term used to describe all relatively rapid forms of mass wasting.

Lateral moraine: A moraine deposited along the side of a valley glacier.

Lava: Magma that has reached Earth's surface.

Lava dome: Mass of lava, created by many individual flows, that forms in the crater of a volcano after a major eruption.

Leeward: On or toward the side facing away from the wind.

Levee (natural): A low ridge or mound along a stream bank, formed by deposits left when floodwater slows down on leaving the channel.

Limestone: A sedimentary rock composed primarily of the mineral calcite (calcium carbonate).

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Longshore current: An ocean current that flows close and almost parallel to the shoreline and is caused by the angled rush of waves toward the shore.

Longshore drift: The movement of sand and other material along a shoreline in the longshore current.

Losing stream: A stream on Earth's surface that is diverted underground through a sinkhole or a cave.

M

Magma: Molten rock containing particles of mineral grains and dissolved gas that forms deep within Earth.

Magma chamber: A reservoir or cavity beneath Earth's surface containing magma that feeds a volcano.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Mass wasting: The spontaneous movement of material down a slope in response to gravity.

Meander: A bend or loop in a stream's course.

Mechanical weathering: The process by which a rock or mineral is broken down into smaller fragments without altering its chemical makeup.

Medial moraine: A moraine formed when two adjacent glaciers flow into each other and their lateral moraines are caught in the middle of the joined glacier.

Meltwater: The water from melted snow or ice.

Mesa: A flat-topped hill or mountain with steep sides that is smaller in area than a plateau.

Metamorphic rock: Rock whose texture or composition has been changed by extreme heat and pressure.

Meteor: A glowing fragment of extraterrestrial material passing through Earth's atmosphere.

Meteorite: A fragment of extraterrestrial material that strikes the surface of Earth.

Meteorite crater: A crater or depression in the surface of a celestial body caused by the impact of a meteorite; also known as an impact crater.

Meteoroid: A small, solid body floating in space.

Mid-ocean ridge: A long, continuous volcanic mountain range found on the basins of all oceans.

Moraine: The general term for a ridge or mound of till deposited by a glacier.

Mountain: A landmass that rises 1,000 feet (305 meters) or more above its surroundings and has steep sides meeting in a summit that is much narrower in width than the base of the landmass.

Mudflow: A mixture primarily of the smallest silt and clay particles and water that has the consistency of newly mixed concrete and flows quickly down slopes.

Mud pot: A hot spring that contains thick, muddy clay.

O

Oasis: A fertile area in a desert or other dry region where groundwater reaches the surface through springs or wells.

Ocean basin: That part of Earth's surface that extends seaward from a continental margin.

Oxbow lake: A crescent-shaped body of water formed from a single loop that was cut off from a meandering stream.

P

Paleomagnetism: The study of changes in the intensity and direction of Earth's magnetic field through time.

Passive continental margin: A continental margin that has a broad continental shelf, a gentle continental slope, and a pronounced continental rise; it is marked by a lack of earthquake and volcanic activity.

Peneplain: A broad, low, almost featureless surface allegedly created by long-continued erosion.

Photosynthesis: The process by which plants use energy from sunlight to change water and carbon dioxide into sugars and starches.

Piedmont glacier: A valley glacier that flows out of a mountainous area onto a gentle slope or plain and spreads out over the surrounding terrain.

Pinnacle: A tall, slender tower or spire of rock.

Plateau: A relatively level, large expanse of land that rises some 1,500 feet (457 meters) or more above its surroundings and has at least one steep side.

Plates: Large sections of Earth's lithosphere separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Playa: A shallow, short-lived lake that forms where water drains into a basin and quickly evaporates, leaving a flat surface of clay, silt, and minerals.

Point bar: The low, crescent-shaped deposit of sediment on the inside of a meander.

Pyroclastic material: Rock fragments, crystals, ash, pumice, and glass shards formed by a volcanic explosion or ejection from a volcanic vent.

R

Rapids: The section of a stream where water flows fast over hard rocks.

Reef crest: The high point of a coral reef that is almost always exposed at low tide.

Regolith: The layer of loose, uncemented rocks and rock fragments of various size that lies beneath the soil and above the bedrock.

Rhyolite: A fine-grained type of volcanic rock that has a high silica content.

Rift valley: The deep central crevice in a mid-ocean ridge; also, a valley or trough formed between two normal faults.

Ring of Fire: The name given to the geographically active belt around the Pacific Ocean that is home to more than 75 percent of the planet's volcanoes.

River: A large stream.

Rock flour: Fine-grained rock material produced when a glacier abrades or scrapes rock beneath it.

S

Saltation: The jumping movement of sand caused by the wind.

Sea arch: An arch created by the erosion of weak rock in a sea cliff through wave action.

Seafloor spreading: The process by which new oceanic crust is formed by the upwelling of magma at mid-ocean ridges, resulting in the continuous lateral movement of existing oceanic crust.

Seamount: An isolated volcanic mountain that often rises 3,280 feet (1,000 meters) or more above the surrounding ocean floor.

Sea stack: An isolated column of rock, the eroded remnant of a sea arch, located in the ocean a short distance from the shoreline.

Sediment: Rock debris such as gravel, sand, silt, and clay.

Sedimentary rock: Rock that is formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Shear stress: The force of gravity acting on an object on a slope, pulling it downward in a direction parallel to the slope.

Shock wave: Wave of increased temperature and pressure formed by the sudden compression of the medium through which the wave moves.

Shore: The strip of ground bordering a body of water that is alternately covered or exposed by waves or tides.

Shoreline: The fluctuating line between water and the shore.

Silica: An oxide (a compound of an element and oxygen) found in magma that, when cooled, crystallizes to become the mineral quartz, which is one of the most common compounds found in Earth's crust.

Silt: Fine earthy particles smaller than sand carried by moving water and deposited as a sediment.

Sinkhole: A bowl-like depression that develops on Earth's surface above a cave ceiling that has collapsed or on an area where the underlying sedimentary rock has been eroded away.

Slide: The movement of a mass of rocks or debris down a slope.

Slip face: The steeply sloped side of a dune that faces away from the wind.

Slope failure: A type of mass wasting that occurs when debris moves downward as the result of a sudden failure on a steep slope or cliff.

Slump: The downward movement of blocks of material on a curved surface.

Slurry flow: A flow that contains between 20 and 40 percent water.

Snow line: The elevation above which snow can form and remain all year.

Solifluction: A form of mass wasting that occurs in relatively cold regions in which waterlogged soil flows very slowly down a slope.

Speleothem: A mineral deposit formed in a cave.

Spit: A long, narrow deposit of sand or gravel that projects from land into open water.

Stalactite: An icicle-shaped mineral deposit hanging from the roof of a cave.

Stalagmite: A cone-shaped mineral deposit projecting upward from the floor of a cave.

Strain: The change in a rock's shape or volume (or both) in response to stress.

Strata: The layers in a series of sedimentary rocks.

Stream: Any body of running water that moves downslope under the influence of gravity in a narrow and defined channel on Earth's surface.

Stress: The force acting on an object (per unit of area).

Striations: The long, parallel scratches and grooves produced in rocks underneath a glacier as it moves over them.

Strike: The compass direction of a fault line.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Submarine canyon: A steep-walled, V-shaped canyon that is cut into the rocks and sediments of the continental slope and, sometimes, the outer continental shelf.

Submergent coast: A coast in which formerly dry land has been gradually flooded, either by land sinking or by sea level rising.

Surface creep: The rolling and pushing of sand and slightly larger particles by the wind.

Suspended load: The fine-grained sediment that is suspended in the flow of water in a river or stream.

Swash: The rush of water up the shore after the breaking of a wave.

Symbiosis: The close, long-term association between two organisms of different species, which may or may not be beneficial for both organisms.

Syncline: A downward-curving (concave) fold in rock that resembles a trough.

T

Talus: A sloping pile of rock fragments lying at the base of the cliff or steep slope from which they have broken off; also known as scree.

Tarn: A small lake that fills the central depression in a cirque.

Terminal moraine: A moraine found near the terminus of a glacier; also known as an end moraine.

Terminus: The leading edge of a glacier; also known as the glacier snout.

Terrace: The exposed portion of a former floodplain that stands like a flat bench above the outer edges of the new floodplain.

Tide: The periodic rising and falling of water in oceans and other large bodies of water that results from the gravitational attraction of the Moon and the Sun upon Earth.

Till: A random mixture of finely crushed rock, sand, pebbles, and boulders deposited by a glacier.

Tombolo: A mound of sand or other beach material that rises above the water to connect an offshore island to the shore or to another island.

Topset bed: A horizontal layer of coarse sand and gravel deposited on top of a delta.

Travertine: A dense, white deposit formed from calcium carbonate that creates rock formations around hot springs.

Trench: A long, deep, narrow depression on the ocean basin with relatively steep sides.

Turbidity current: A turbulent mixture of water and sediment that flows down a continental slope under the influence of gravity.

U

Uplift: In geology, the slow upward movement of large parts of stable areas of Earth's crust.

U-shaped valley: A valley created by glacial erosion that has a profile suggesting the form of the letter "U," characterized by steep sides that may curve inwards at their base and a broad, nearly flat floor.

V

Valley glacier: An alpine glacier flowing downward through a preexisting stream valley.

Ventifact: A stone or bedrock surface that has been shaped or eroded by the wind.

Viscosity: The measure of a fluid's resistance to flow.

Volcano: A vent or hole in Earth's surface through which magma, hot gases, ash, and rock fragments escape from deep inside the planet; the term is also used to describe the cone of erupted material that builds up around that opening.

V-shaped valley: A narrow valley created by the downcutting action of a stream that has a profile suggesting the form of the letter "V," characterized by steeply sloping sides.

W

Waterfall: An often steep drop in a stream bed causing the water in a stream channel to fall vertically or nearly vertically.

Wave crest: The highest part of a wave.

Wave-cut notch: An indentation produced by wave erosion at the base of a sea cliff.

Wave-cut platform: A horizontal bench of rock formed beneath the waves at the base of a sea cliff as it retreats because of wave erosion.

Wave height: The vertical distance between the wave crest and the wave trough.

Wavelength: The horizontal distance between two wave crests or troughs.

Wave trough: The lowest part of a wave form between two crests.

Weathering: The process by which rocks and minerals are broken down at or near Earth's surface.

Windward: On or toward the side facing into the wind.

Y

Yardang: Wind-sculpted, streamlined ridge that lies parallel to the prevailing winds.

Yazoo stream: A small stream that enters a floodplain and flows alongside a larger stream or river for quite a distance before eventually flowing into the larger waterway.

Z

Zooxanthellae: Microscopic algae that live symbiotically within the cells of some marine invertebrates, especially coral.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

Basin

Throughout Earth's 4.5-billion-year history, the heat at its core has rearranged the surface over and over. The crust, the surface layer of the planet, has been compressed, pulled apart, raised, and lowered. The force of these various movements has fractured the crust, breaking it into sections. The sections have slammed into each other, slid under each other, or scraped by each other. As a result, great mountain ranges have been raised and great valleys and trenches have been lowered.

Not all landforms created by the constant movement of the crust are as dramatic as these. Some are merely bumps and dips in a landscape that rises and falls. Basins are such landforms. Created by heat forces beneath the surface and weathering forces above it, basins are part of distinctive landscapes found worldwide.

The shape of the land

A simple definition of a basin is a hollow or depression in Earth's surface with no outlet for water. This means that any water that originates in or flows into a basin does not escape it. A basin can be approximately circular, resembling a bowl, or it can be oval-shaped. It can be a small structure, measuring only a few miles in diameter. Often, it is much larger. A basin is usually surrounded mostly by higher land. Depending on where it is located, a basin may sometimes include desert areas, which are arid or dry regions receiving less than 10 inches (25 centimeters) of rain per year.

Given its shape and the fact that it has no surface outlet, a basin collects what flows into it. This is especially true of the products of erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. When water that falls as rain or snow washes over the surface of the higher land surrounding a basin, it strips away sediment—gravel, clay, sand, silt, various salts, and other rock particles.

As this water then flows into the basin, it carries along this sediment. Collecting in low-lying areas of the basin, the water either quickly evaporates, sinks into the ground, or forms lakes and marshes. The bottoms of these water-filled areas are lined with this sediment. Often, these lakes eventually evaporate. What is left behind is a dry, flat, salt-encrusted, cracked surface known as a playa (pronounced PLY-uh).

Over thousands to millions of years, sediment may collect in a basin to a depth of 1 mile (1.6 kilometers) or more. Because of this, basins are also often known as sedimentary basins.

Forces and changes: Construction and destruction

Basins are created in one of two ways. In both, land downwarps or sinks. This lowering of the land surface is brought about by the movement of the sections of the crust, known as plates, and by the way rock deforms or changes shape in response to that movement.

The scientific theory explaining the movement and interaction of the plates is known as plate tectonics. (A theory is a principle supported by extensive scientific evidence and testing.) Geologists developed this theory in the early 1960s. A revolutionary idea, it transformed our understanding of Earth. It helped explain how landforms and other geologic features are created and how Earth's surface changes over time.

Although Earth appears to be made up of solid rock, it is actually made up of three distinct layers: the crust, the mantle, and the core. Each layer has its own unique properties and composition.

A layered planet

As mentioned earlier, the crust is the thin shell of rock that covers Earth. It is separated into two types: continental crust (which underlies the continents) and oceanic crust (which underlies the oceans). It varies in thickness from 3 to 31 miles (5 to 50 kilometers). The crust is thickest below land and thinnest below the oceans.

The layer below the crust is the mantle, which extends down approximately 1,800 miles (2,900 kilometers) below the surface of the planet. The mantle is denser than the crust because it contains more of the elements iron and magnesium. It is separated into two layers: The uppermost part of the mantle is solid and, along with the overlying crust, forms the lithosphere (pronounced LITH-uh-sfeer). Measuring about 60 miles (100 kilometers) thick, the lithosphere is brittle. It is the lithosphere that has broken into the thick, moving slabs of rock known as tectonic plates.

OPPOSITE *Titcomb Basin, Wyoming. A basin is an area of relatively flat-lying ground surrounded by higher terrain.* **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

The part of the mantle immediately beneath the lithosphere is known as the asthenosphere (pronounced as-THEN-uh-sfeer). The greater the depth beneath Earth's surface, the greater the temperature and pressure. As rock is heated, it becomes pliable or what geologists call "plastic." Rock in the asthenosphere is hot enough to fold, stretch, compress, and flow very slowly without fracturing. It is puttylike in its consistency. The rigid tectonic plates "float" on the more dense, flowing asthenosphere.

At the center of the planet lies the core, composed of a liquid outer layer and a solid inner layer. Unlike the rocky layers above it, the core is made up of the metallic elements iron and nickel. It is almost five times as dense as rock on Earth's surface. Temperatures in the core are estimated to exceed 9,900°F (5,482°C), creating extreme heat energy.

What makes the plates move

The heat energy generated at Earth's core moves the tectonic plates across the planet's surface. This energy is carried to the area beneath the plates by convection currents, which act similar to the currents produced in a pot of boiling liquid on a hot stove. When a liquid in a pot begins to boil, it turns over and over. The liquid heated at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense (lighter). Once at the surface, the heated liquid cools and becomes dense once more. It then sinks back down to the bottom to become reheated. This continuous motion of heated material rising, cooling, and sinking forms the circular currents known as convection currents.

Like an enormous stove or furnace, the core heats the mantle rock that immediately surrounds it. Expanding and becoming less dense, the heated rock slowly rises through cooler, denser mantle rock above it. When it reaches the lithosphere, the heated rock moves along the base of the lithosphere, exerting dragging forces on the tectonic plates. This causes the plates to move. In the process, the heated rock begins to lose heat. Cooling and becoming denser, the rock then sinks back toward the core, where it will be heated once more. Scientists estimate that it takes 200 million years for heated mantle rock to make the circular trip from the core to the lithosphere and back again.

Tectonic plates are in constant contact with each other, fitting together like pieces in a giant jigsaw puzzle. No single plate can move without affecting one or more other plates. Generally, a plate inches its way across the surface of Earth at a rate no faster than human fingernails grow, which is roughly 2 inches (5 centimeters) per year. As it moves, a plate can transform or slide along another, converge or move into another, or diverge or move away from another. The boundaries where plates meet and interact are known as plate margins.

Words to Know

Anticline: An upward-curving (convex) fold in rock that resembles an arch.

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid outermost layer of Earth.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Fault plane: The area where crustal blocks meet and move along a fault from the fault line down into the crust.

Fold: A bend or warp in a layered rock.

Graben: A block of Earth's crust dropped downward between faults.

Horst: A block of Earth's crust forced upward between faults.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Plates: Large sections of Earth's lithosphere separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Playa: A shallow, short-lived lake that forms where water drains into a basin and quickly evaporates, leaving a flat surface of clay, silt, and minerals.

Strain: The change in a rock's shape or volume (or both) in response to stress.

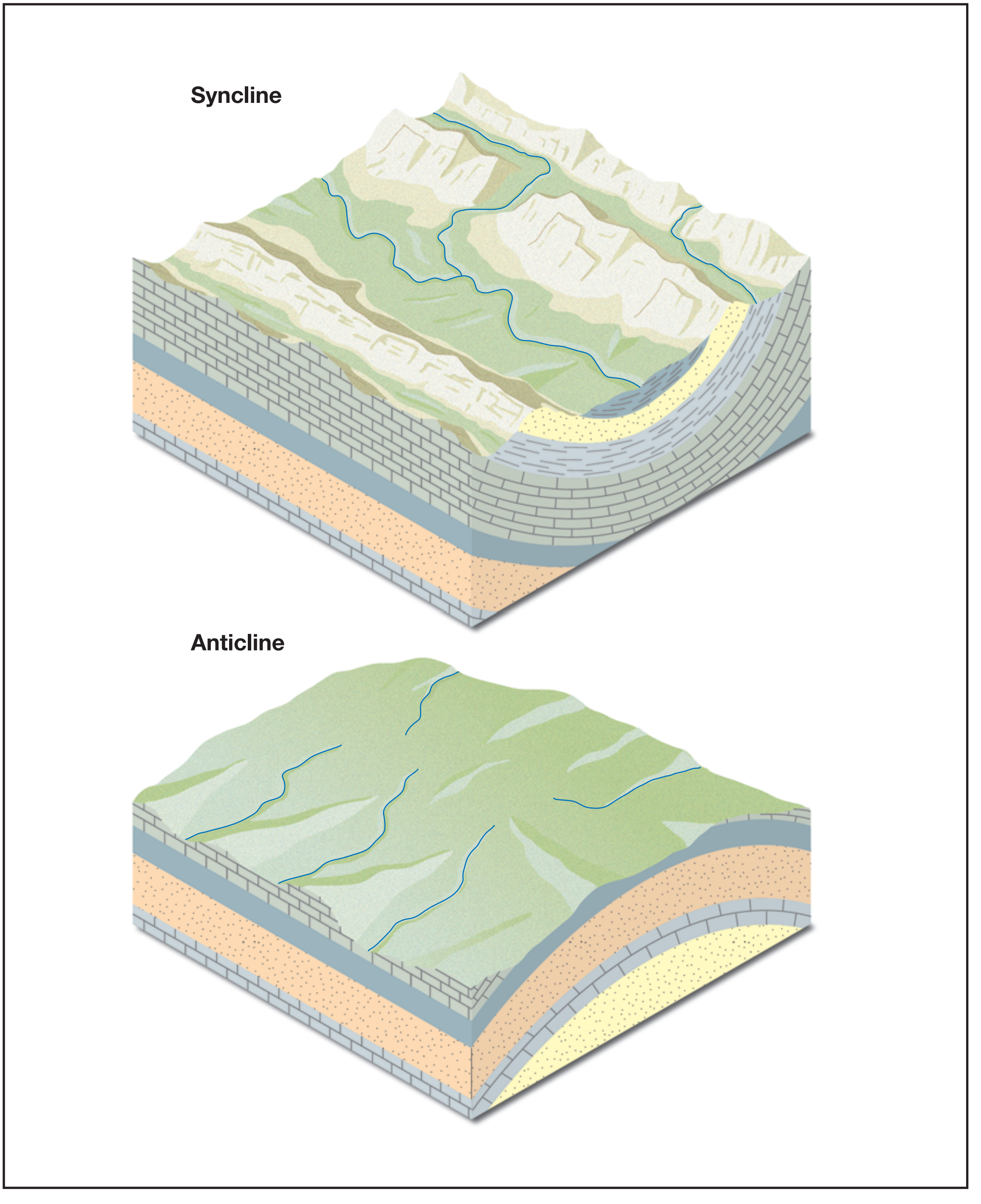
Stress: The force acting on an object (per unit of area).

Syncline: A downward-curving (concave) fold in rock that resembles a trough.

Rocks under stress and strain

The movement of a tectonic plate can create stress (force acting on an object) anywhere within the plate. In response to stress, rock will change its shape or volume or both. This change is known as strain. There are three main types of stress that cause rock to change: Tension pulls rock, causing it to stretch. The ends of the rock become thicker while the middle becomes thinner. Compression squeezes rock, causing it to become denser and take up less space (more matter in a smaller volume). Shearing pushes rock in two opposite directions. This usually results in a simple bend or break.

When a rock is subjected to stress, it will deform. How it deforms depends on temperature and pressure. At higher temperatures and pressures, rock will soften and bend. At lower temperatures and pressures, however, rock will break or fracture instead of bending. A bend or warp in layered rock is called a fold. A fracture in rock along which there has been



Folds are formed by tectonic forces that act to compress Earth's crust. A downward-curving fold that resembles a trough is called a syncline. An upward-curving fold that resembles an arch is called an anticline.

no movement is called a joint; a fracture along which there has been some type of movement is called a fault. Basins form because of folding and faulting. (Basinlike formations, such as cirques and kettles, may be formed by glacial action. For more information on glaciers and the landforms they create, see the **Glacial landforms and features** chapter.)

Basins created by folding

Tectonic forces that act to compress Earth's crust form folds. A fold may be a broad, gentle warping over many hundreds of miles or a small flex over just a few inches. An upward-curving fold that resembles an arch is called an anticline (pronounced AN-ti-kline). A downward-curving fold that resembles a trough is called a syncline (pronounced SIN-kline). Anticlines and synclines often occur together in sets, similar to the up-and-down folds created in a carpet when its ends are pushed together.

A basin created by folding is a large, synclinelike fold in which all sides dip toward the center. Basins formed in this manner are subject to the dueling forces of plate tectonics and erosion. Once formed, the basin will fill with sediment carried down into it by water that washes over its sides.

Basins created by faulting

There are different types of faults, created by different kinds of stress. The area where blocks of rock meet and move along a fault from the surface down into the crust is known as the fault plane. Faults are categorized by the angle of the fault plane in relation to the surface and the relative movement of the rocks on either side of the fault. (For more information on fault formation, see the **Fault** chapter.)

A basin created by faulting forms along normal faults, which usually have a fault plane angle of 60 degrees. These types of faults arise when tensional forces act on brittle rock to stretch or pull it apart. The block of rock above the fault plane (the one that seems to be "resting" on the fault) drops down relative to the block on the other side. In a landscape, normal faults often occur in series of parallel pairs. Depending on the direction of the fault planes of the faults, the block between a pair of faults will either rise or drop down when movement occurs between the faults. If the fault planes are angled downward away from each other (such as / \), the block between them rises. This uplifted block is called a horst (from the German word meaning high perch). If the fault planes are angled downward toward each other (such as \ /), the block between them drops. This down-dropped block is called a graben (pronounced GRAH-bin; from the German word meaning trench).

Basins develop from grabens where there is no surface outlet. In such a case, sediment from the sides rimming the graben is carried downward

The Great Basin stretches through more than 200,000 square miles in Nevada and Utah. One-fifth of the American West drains into the Great Basin—and stays in the Great Basin; none of its rivers empty into the sea. **PHOTOGRAPH REPRODUCED BY PERMISSION OF GETTY IMAGES, INC.**

by water. As the sediment collects, it often does so mainly near the outer edges of the graben. Building up, the sediment softens the angle, giving the newly formed basin its characteristic bowl-like shape.

Spotlight on famous forms

Great Artesian Basin, Australia

The Great Artesian Basin is one of the largest artesian groundwater basins in the world. (Artesian water is underground water that is confined under pressure. When it is tapped, such as through a well, it flows to the surface without pumping due to this pressure.) The basin covers approximately 670,000 square miles (1,735,300 square kilometers) between the Eastern Highlands and the Western Plateau in east-central Australia.

Three large depressions—the Carpentaria Basin, the Eromanga Basin, and the Surat Basin—form the Great Artesian Basin. Some 200 million years ago, tectonic activity raised the edges of these basins. Water subsequently eroded the edges, carrying sand, gravel, clays, and clayey sands into the basins. This sediment was laid down in alternating layers, which measure from 330 to more than 9,840 feet (100 to more than 3,000 meters) thick. The sandy layers are not as dense as the layers formed by the various clays. Water is thus able to flow into the spaces between the sediments forming the sandy layers. This led to the accumulation of the vast groundwater found in the Great Artesian Basin.

The saucer-shaped basin is mostly arid. Water from rainfall mainly on the Eastern Highlands soaks through the rock and flows toward the center of the basin. The oldest waters in the basin are over 2 million years old. Thousands of wells tap into the underground water, which ranges in temperature from 86°F to over 212°F (30°C to over 100°C). Because the water has a high salt content, it cannot be used to irrigate farmland.

Great Basin, Nevada and Utah

The Great Basin, located mainly in Nevada and Utah, is the northern part of the larger Basin and Range province. Parallel mountain ranges and the valleys between them characterize this province. It is an area that is being pulled apart by tectonic forces. The surface of the Great Basin is broken into blocks, separated by normal faults. The basin is not one basin, but many separated by mountain ranges created by the faults. Both the mountains and the basins tend to be about 25 to 50 miles (40 to 80 kilometers) long and about 15 to 20 miles (24 to 32 kilometers) wide.

The Great Basin has drainage unlike other areas in the United States. None of its rivers empty in the sea. One-fifth of the American West, roughly 200,000 square miles (518,000 square kilometers), drains into the Great Basin. Mostly an arid region, the basin features many playas that remain after water has evaporated. Water that does not stand and evaporate in the basin sinks into the ground to become groundwater (water that fills the pore spaces and openings in rocks underneath Earth's surface).

In Utah, a large portion of the Great Basin is called the Bonneville Basin. At one time, the area lay beneath ancient Lake Bonneville. In the present day, the Great Salt Lake (one-tenth the size of Bonneville Lake) covers the lowest part of the Bonneville Basin and of the Great Basin. The surface of the Great Salt Lake is about 4,200 feet (1,280 meters) above sea level.

Witwatersrand Basin, South Africa

Gold was discovered in the Witwatersrand (pronounced VIT-vah-turz-rahnd) Basin in South Africa in 1886. Since then, more than 40 percent of all the gold ever mined on Earth has come from the area. The total amount of gold extracted has been valued at U.S. $500 billion.

Located between the Vaal River and the city of Johannesburg, the basin covers an area approximately 217 miles (350 kilometers) long by 124 miles (200 kilometers) wide. Scientists believe the basin was originally a

Death Valley or Death Basin?

The hottest place on the North American continent is Death Valley, located in eastern California. Temperatures in the summer exceed 120°F (49°C). Rainfall is scant: no more than 2 inches (5 centimeters) falls per year. Death Valley also contains the lowest point in the Western Hemisphere, Badwater, a salty pool whose surface is 282 feet (86 meters) below sea level. Nearly 550 square miles (1,425 kilometers) of the entire area lie below sea level.

But Death Valley is not a valley. Technically, it is a desert basin, part of the Basin and Range province. It is a 156-mile-long (251-kilometer-long) trough that lies near the Nevada border between two fault-block mountain ranges: the Panamint Mountains on the west and the Amargosa Range on the east. The deep Death Valley basin is filled with sediment eroded from the surrounding mountains. Most of the little water that drains into Death Valley quickly evaporates, leaving playas. What water remains forms salt ponds and marshes.

Despite the harsh environmental conditions in Death Valley, plant and animal species thrive there. Many of these are found nowhere else on the planet.

lake that began to fill with sediment possibly from mountains to the north and southwest almost 3 billion years ago. Along with sand and silt, the sediment contained gold particles. Today, the gold lies within thin layers of rock, called reefs, that wrap around the edge of the basin and extend to depths of 16,400 feet (5,000 meters) or more.

In the center of the basin lies the Vredefort Dome, which is the remnant of the world's oldest and largest preserved meteorite crater. Scientists believe an asteroid slammed into the area some 2 billion years ago. Its impact crater is estimated to have been as large as the basin itself.

For More Information

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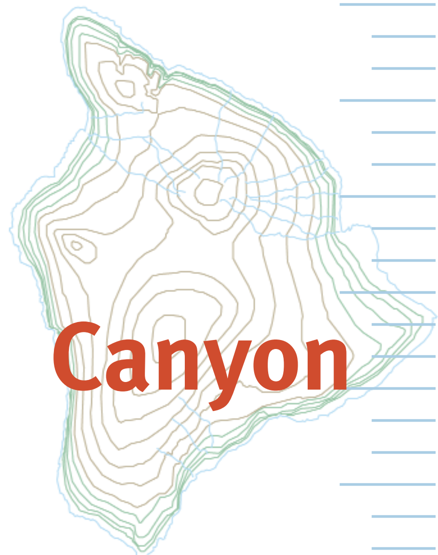

Canyon

Canyons exist below the rim of the land, below the horizon. These ragged scars on the face of the planet descend hundreds to thousands of feet below their surrounding landscape, giving it depth. Their widths may stretch for miles or mere feet. Sunlight may fill them or may never reach their darkened bottom regions. Winding through many is water, possibly the most powerful force on the planet.

Sudden, tremendous events in Earth's history did not produce these landforms. Instead, it was mainly the slow, orderly process of erosion, the wearing away of the planet's surface through the action of wind and water. While wind has played a part in their formation, its effect has been subtle. The true creator of a canyon is water, primarily in the form of a river. Over millions of years, water has scoured and cut away layer upon layer of rock, lowering a canyon's floor and widening its walls. Although perhaps much more slowly, canyons created millions of years ago continue to be shaped in the present day. The erosive power of water is unrelenting.

The shape of the land

A canyon may be defined as a narrow, deep, rocky, and steep-walled valley carved by a swift-moving river. Its depth may be considerably greater than its width. Some sources use the words gorge, ravine, and chasm interchangeably with canyon. Others say they are all variations of steep-sided valleys normally with a stream or river flowing through them. A few make the distinction that canyons are usually found in arid (dry) regions characterized by plateaus, which are relatively level, large expanses of land that rise some 1,500 feet (457 meters) or more above their surroundings and have at least one steep side.

Canyons are incredibly diverse in their forms. The walls of some canyons are V-shaped and ragged; the walls of others are steeper and almost

smooth. Some canyons have been carved through sandstone and limestone and other types of sedimentary rock (rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals). Others have been carved through multiple layers of igneous (pronounced IG-nee-us) rock, which is formed by the cooling and hardening of magma, melted rock material from within Earth, and metamorphic (pronounced meh-tah-MORE-fik) rock, whose texture or composition has been changed by extreme heat and pressure. Some canyons are dry; others are filled with rushing rivers. Some cover vast spaces; others are so narrow a person can barely squeeze through the walls.

Two main types of canyons are plateau canyons and slot canyons. The general processes responsible for their creation are uplift (the slow upward movement of large parts of stable areas of Earth's crust) and erosion. The main differences between the two types of canyons are the amount and flow of water that erodes and creates them and their relationship to their surrounding landscape.

As their name suggests, plateau canyons, such as the Grand Canyon in Arizona and the Black Canyon in Colorado, form on plateaus. They have at their floors a rushing river that continuously erodes and shapes them. If the rock forming their walls is hard and somewhat resistant to erosion, those walls may be high and steep. If their walls are made of rock that is softer and more vulnerable to erosion, those walls are likely to be less steep, V-shaped, and prone to landslides and slumps (a slump is the downward movement of blocks of material on a curved surface).

By contrast, slot canyons may be easily missed by a casual observer on a plateau. They do not open widely to the sky; their form and beauty often lie hidden beneath the ground. On the surface, the opening to a slot canyon may appear as a slash, a narrow crevice sliced through the ground. Some slot canyons measure less than 3 feet (1 meter) across at their opening. Yet beneath, from their rim to their floor, the distance may be 100 feet (30.5 meters) or more. Most often, these deep canyons are dark. At times, light from the Sun may filter down, illuminating the sculpted sandstone walls to display their palette of colors.

Slot canyons are cut and scoured by rushing water in the form of flash floods. A flash flood is a flood that occurs after a period of heavy rain, usually within six hours of the rain event. In arid environments where there is little soil to absorb the rain, water quickly runs downhill, gathering

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OPPOSITE *Inner gorge of the Grand Canyon, located in northwestern Arizona. Carved by the power of the Colorado River, the canyon stretches for 277 miles.* PHOTOGRAPH REPRODUCED BY PERMISSION OF HENRY HOLT AND COMPANY.

Words to Know

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid, outermost layer of Earth.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Flash flood: A flood that occurs after a period of heavy rain, usually within six hours of the rain event.

Igneous rock: Rock formed by the cooling and hardening of magma, molten rock that is underground (called lava once it reaches Earth's surface).

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Metamorphic rock: Rock whose texture or composition has been changed by extreme heat and pressure.

Plateau: A relatively level, large expanse of land that rises some 1,500 feet (457 meters) or more above its surroundings and has at least one steep side.

Plates: Large sections of Earth's lithosphere separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Sedimentary rock: Rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Slump: The downward movement of blocks of material on a curved surface.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Uplift: In geology, the slow upward movement of large parts of stable areas of Earth's crust.

volume and speed as it goes. When it runs over the canyon, it descends in a wall of water that blasts through the canyon, eroding the walls and floor. As quickly as the water appears, it disappears, leaving the canyon dry and slightly changed until the next flood.

Forces and changes: Construction and destruction

Water is a natural force of erosion everywhere on Earth. Surging over a landscape, water will pick up and transport as much material from the surface as it can carry. Aided by gravity and steep slopes, rushing water can carry increasingly larger and heavier objects, including boulders as large as cars. If a river and its surroundings have been elevated from their original position by natural forces within the planet, that river will seek to return to its natural level as quickly as possible. Finding the least resistant path, a river will cut through rock layers. Lowering its floor little by little, the river will take millions of years to carve through the surrounding rock before it reaches the level it seeks. In the process, it creates a canyon.

Uplift and plate tectonics

The formation of a plateau canyon is the direct result of the uplift of the region it occupies. Without regional uplift and the subsequent erosion by a river, there would be no canyons, deep gorges, or other associated landforms. Uplift, however, does not make a canyon. Rather, uplift creates conditions for a river to erode the landscape into the unique and beautiful shape of a canyon.

Uplift occurs because of the tremendous heat forces contained beneath Earth's crust, the rocky outer layer that forms the planet's surface. Deep underground, at Earth's core, temperatures exceed 9,900°F (5,482°C). The planet's interior would melt if the heat energy created by such high temperatures were not released. This is achieved through convection currents, which carry the heat to the surface of the planet.

Convection currents form when rock surrounding the core heats up. Much like a gas or liquid that is heated, this rock expands and becomes less dense (or lighter). It then slowly rises above cooler, denser rock that surrounds it in the mantle, the thick layer of rock that lies between the planet's core and crust. It continues to rise until it reaches the lithosphere (pronounced LITH-uh-sfeer), the rigid uppermost section of the mantle combined with the crust. As the heated rock moves along the bottom of the lithosphere, it loses its heat. As it cools, the rock becomes denser (or heavier) and sinks back toward the core, only to be heated once again. This continuous motion of heated material rising, cooling, and sinking within Earth's mantle forms circular currents called convection currents.

The slowly moving convection currents are able to release their heat energy near the surface of the planet because both Earth's interior and its surface are in motion. Earth's lithosphere is not solid, but is broken into many large slabs or plates that "float" on the asthenosphere (pronounced as-THEN-uh-sfeer), the region of the mantle below the lithosphere that is composed of rocks that are soft like putty. These plates are in constant contact with each other, fitting together like a jigsaw puzzle. When one plate moves, it causes other plates to move. The movement of the plates toward or away from each other is in response to the pressure exerted by the convection currents. The scientific theory explaining the plates and their movements and interactions is known as plate tectonics.

The plates interact with each other in one of three ways: they converge (move toward each other), they diverge (move away from each other), or they transform (slide past each other). The boundaries where plates meet and interact are known as plate margins. At convergent plate

The Painted Wall of the Black Canyon

The Black Canyon in Colorado has been carved by the erosive action of the Gunnison River over the last two million years. The river runs sharply through the canyon, dropping an average of 95 feet per mile (18 meters per kilometer), one of the greatest rates of fall for a river in North America. Aided by the power of this drop, the river has slowly worked its way through the sturdy rock, forming the narrow and steep-sided canyon.

The walls of the Black Canyon are dark gray and composed of schist (pronounced shist) and gneiss (pronounced nice). Both of these are coarse-grained types of metamorphic rock, or rock that was once buried deep within Earth where intense heat and pressure changed its texture and composition. The walls of the canyon are composed of some of the oldest exposed rock in the world. Some of these rocks are nearly two billion years old.

One wall along the canyon appears like marble, with alternating layers of dark and light rock streaking across its surface. This wall, known as Painted Wall, is the highest rock wall in Colorado. From its rim to the river below is a drop of 1,800 feet (550 meters). The light bands in the wall are pinkish and are igneous rock. Igneous rock has been formed by the cooling and hardening of magma, molten rock that is underground (called lava once it reaches Earth's surface). Shortly after the base rock in this wall formed, molten material was forced under great pressure into its cracks and joints, creating the now-famous Painted Wall.

margins, the two plates will either crumple up and compress, forming complex mountain ranges, or one plate will slide beneath the other. This latter process is known as subduction, and the region where it occurs is known as a subduction zone.

When a tectonic plate subducts or sinks beneath another, the leading edge of the subducting plate is pushed farther and farther beneath the surface. When it reaches about 70 miles (112 kilometers) into the mantle, high temperature and pressure melt the rock at the edge of the plate, forming thick, flowing magma. Since it is less dense than the rock that typically surrounds it deep underground, magma tends to rise toward Earth's surface, forcing its way through weakened layers of rock. Most often, magma collects in underground reservoirs called magma chambers, where it remains until it is ejected onto the planet's surface through vents called volcanoes. (For further information, see the **Volcano** chapter.)

Sometimes the magma plume rises beneath a large, stable landmass and does not break through any cracks or vents. Instead, the pressure

The Gunnison River flowing through the Black Canyon, Colorado. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

exerted by the magma forces the land to rise upward in one piece. Geologists believe this uplifting process formed the Colorado Plateau about 5 million years ago. Sprawling across southeastern Utah, northern Arizona, northwestern New Mexico, and western Colorado, the Colorado Plateau covers a land area of 130,000 square miles (336,700 square kilometers). This arid region, which was originally close to sea level, was slowly uplifted 4,000 to 6,000 feet (1,220 to 1,830 meters). Once the plateau was raised, the rivers contained on it began to carve thousands of miles of deep, narrow canyons into the plateau's multi-layered rock. Today, even as the Colorado Plateau continues slowly rising, erosion is wearing it down.

The erosive power of water: Rivers and flash floods

The rivers that created the canyons on the Colorado Plateau and elsewhere did so because rivers have a natural tendency to reach a base level. This refers to the point at which the river reaches the elevation of the large body of water, such a lake or ocean, into which it drains. Aided by

The Literary Landscape

"Another half mile and I come to a 'dripping spring.' This is a seep high on the canyon wall, two hundred feet above my head, where ground water breaks out between beds of sandstone and slides over the contours of the cliff, nourishing the typical delicate greenery of moss, fern, columbine, and monkeyflower. Below the garden the cliff curves deeply inward, forming an overhang that would shelter a house; at this point the water is released from the draw of surface tension and falls free through the air in a misty, wavy spray down to the canyon floor where I stand, as in a fine shower, filling my canteen and soaking myself and drinking all at the same time."

—Edward Abbey, *Desert Solitaire*, 1968.

gravity, a river will downcut or erode its channel deeper and deeper in order to reach the level of its final destination as quickly as possible. The larger the difference in height between the river and its destination, the greater the erosive or cutting force of the river.

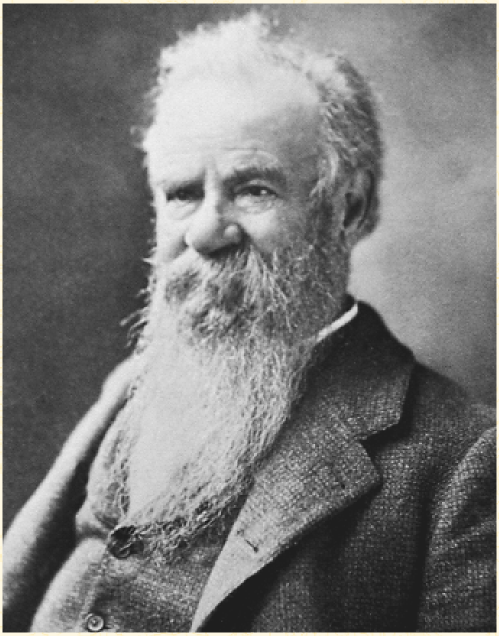
Rivers erode because they have the ability to pick up sediments (loose rock fragments) and transport them to a new location. The size of the material that can be transported depends on the velocity, or speed, of the river. A fast-moving river carries more sediment and larger material than a slow-moving one. As it is carried along, the sediment acts as an abrasive, scouring and eating away at the banks and bed of the river. The river then picks up this newly eroded material, which, in turn, helps the river cut even deeper into its channel.

If a river cuts through resistant rock, such as granite, its channel and the canyon it creates will be narrow and deep. If it cuts through weaker material, such as clay or sandstone, its channel and its accompanying canyon will be wide. When cutting through soft rock, a river can undercut its banks, removing a soft layer of material while a harder layer remains above, forming an overhang. The overhang continues to grow as material beneath it is eroded away by the river until the overhang can no longer be supported and collapses into the river. Repeated undercutting can lead to landslides and slumps, creating a V-shaped canyon.

The walls of V-shaped canyons, especially those located in arid environments, are further eroded by rain and ice. In areas where there is little plant cover, dry soil and rock fragments are carried away easily as rain washes over the canyon walls into the river below. When water seeps into cracks between the rocks of the canyon walls and freezes in colder weather, it expands, widening the cracks and pushing the rocks apart. Eventually, the rocks lose their hold and plummet down the canyon wall. On the way down, they often hit and loosen other rocks, creating a rock fall that significantly alters the shape of the canyon.

Flash floods erode rocks in similar fashion. On the Colorado Plateau, where slot canyons are primarily found, the dry soil cannot fully absorb

In Bryce Canyon, erosion has shaped colorful layers of limestone, sandstone, and mudstone into thousands of spires, fins, pinnacles, and mazes that are collectively called hoodoos. **PHOTOGRAPH REPRODUCED BY PERMISSION OF CORBIS CORPORATION.**



Into Canyon Country: An Epic American Adventure

By the latter part of the nineteenth century, the canyons of the Green and Colorado rivers were among the few remaining unexplored areas on the North American continent. Legends told of a region of giant waterfalls, vicious whirlpools and rapids, and enormous rock cliffs that offered no escape or refuge from the punishment of the rivers. In 1869, a party of nine men led by John Wesley Powell (1834–1902) ventured into this unknown and seemingly terrifying landscape to survey, map, and study the geology of the plateau and canyon country.

Powell, who had served as a major in the Union Army during the American Civil War (1861–1865) and who had lost an arm at the battle of Shiloh, had a lifelong interest in natural history. Drawn by the glamour and mystery of the American West, he set out to explore not only how the region looked but also how its canyons, plateaus, and mountains had been formed.

On May 24, 1869, Powell and his men set off on a river descent of nearly nine hundred miles with no real idea of what terrors and adventures lay before them. Their small vessels plunged through turbulent rapids, foaming waterfalls, and towering canyon walls. Two boats were lost, one member of the team deserted early, and three other members were killed by Native Americans as they gave up on the river journey and attempted to climb out of the Grand Canyon. Despite these hardships, Powell and his remaining men explored the entire reach of the Colorado River, including the Grand Canyon. They were on the river for ninety-two days.

After this epic journey, Powell undertook additional Western adventures, exploring the plateaus of Utah, the Colorado Plateau, and Zion and Bryce canyons. Through his expeditions, he developed the geological idea that the vast processes of uplift and erosion were responsible for the topography or physical features of the canyon and plateau country. In 1895 he published these findings and ideas in *Canyons of the Colorado*.

John Wesley Powell. **COURTESY OF THE LIBRARY OF CONGRESS.**

the amount of water deposited by sudden, violent storms. Rushing across the sloping landscape in a torrent, the flash flood picks up stones and other debris. Finding cracks in the sandstone on the plateau floor, the debris-laden flood acts like an abrasive, scouring away the relatively soft rock grain by grain. Over millions of years, flash floods and wind have dug deeper and deeper into the sandstone, sculpting the floors and spiraling walls of these unique underground canyons.

Spotlight on famous forms

Antelope Canyon, Arizona

Discovered in 1931 by a twelve-year-old girl, Antelope Canyon (also known as Corkscrew Canyon) lies just outside Page, Arizona, on land owned by the Navajo Nation. Over hundreds of thousands of years, infrequent but often violent water flows have carved the delicate curves and hollows of this slot canyon from hairline cracks in the sandstone. Noted for its photographic beauty, the canyon changes color from violet to red to orange to yellow as light from the Sun filters in from above, illuminating its sculpted sandy walls.

The canyon, a series of passageways of varying widths and heights, is divided into an upper and lower section. The entire canyon measures 5 miles (8 kilometers) in length, and in places it is no more than a few feet wide. Walls of the canyon often rise to a height of 120 feet (36.5 meters).

In August 1997, a severe thunderstorm hit the plateau area around Page, Arizona, dropping a vast amount of water in a short period of time. Since the dry soil in the area could not absorb that amount of water, a flash flood quickly developed and raced toward the normally dry canyon, which was 2,000 feet (610 meters) below the height of the plateau. A group of twelve tourists were trapped in the lower section of the canyon as an 11-foot (3.3-meter) wall of water, carrying tons of mud and debris, washed over them with a force that stripped off their clothes. Only one person survived the deluge.

Colca Canyon, Peru

Colca Canyon (Cañon del Colca) in Peru is one of the deepest canyons in the world. At more than 11,330 feet (3,400 meters), it descends to a depth almost twice that of Arizona's Grand Canyon. The canyon developed from a fault that has been eroded for millions of years by the Colca River, which runs more than 124 miles (200 kilometers) along the Peruvian coast. Looming high in the background of the canyon are snow-capped volcanoes that stand more than 16,400 feet (5,000 meters) in height.

The Inca, the native people who flourished in the area from the twelfth century to the mid-sixteenth century, had carved vaults into the

Upper Antelope Canyon, a slot canyon near the town of Page, Arizona. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

canyon walls in which they stored grain. The Inca word for these sealed vaults, *colcas*, gives the canyon its present name. Other Incan artifacts in the canyon include ancient tombs perched high on the vertical canyon walls and terraces, flat and relatively narrow strips of ground constructed on the sloping sides of the canyon in order to grow crops.

Colca Canyon, in Peru, is one of the deepest canyons in the world at a depth of more than 11,330 feet—more than twice as deep as the Grand Canyon. Unlike the Grand Canyon, parts of Colca Canyon are habitable, with terraced fields supporting agriculture and human life. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Grand Canyon, Arizona

The Grand Canyon, perhaps the world's most famous canyon, lies at the northwestern edge of Arizona near its borders with Utah and Nevada. Carved by the power of the Colorado River, the canyon stretches for 277 miles (446 kilometers). It begins at Lees Ferry and ends at Grand Wash Cliffs. The Colorado River itself is much longer than the canyon, flowing 1,450 miles (2,333 kilometers) from the Rocky Mountains in Colorado to the Gulf of California in Mexico.

The canyon's depth and width vary. The maximum depth in the canyon is roughly 6,000 feet (1,829 kilometers). Along its South Rim, the average depth from the rim to the river at its bottom is about 5,000 feet (1,524 meters). At its narrowest part, the Grand Canyon is less

Canyon de Chelly and the Anasazi

Canyon de Chelly (pronounced CAN-yon de SHAY; Spanish corruption of Navajo word "Tsegi," meaning rock canyon) is a long three-armed canyon located in northeast Arizona. Carved by running streams, the canyon's red sandstone walls are almost vertical, with some rising 800 feet (244 meters). This makes access to the canyon floor difficult. For this reason, the canyon has served as a protective home for more than two thousand years for many ancient and modern Native American tribes.

From about 350 to 1300, the canyon served as a home for the Anasazi. These people, thought to be the ancestors of the modern Pueblo, constructed spectacular dwellings both on the canyon floor and high up the walls on ledges between the sandstone layers. Several hundred different ruins are located in the canyon, ranging from individual small grain storage bins to large housing complexes, including a three-story tower house. On the rock walls throughout the canyon are numerous petroglyphs (rock carvings) and pictographs (rock paintings) dating from this period.

Perhaps because of drought, perhaps because of other, mysterious reasons, the Anasazi abandoned their cliff dwellings after about 1300 and scattered throughout the American Southwest. In the years after, various Native American tribes inhabited the canyon, including the Navajo, who continue to live and farm on the canyon floor.

than 1 mile (1.6 kilometers) across. At its widest, it is 18 miles (29 kilometers). On average, the width of the canyon from rim to rim is 10 miles (16 kilometers).

While the Colorado River was the main source behind its creation, present-day precipitation continues to shape it. The area of the canyon that receives the most precipitation, either in the form of snow or rain, is the South Rim, which receives 15 inches (38 centimeters) of precipitation each year. By contrast, the bottom of the canyon receives only 8 inches (20 centimeters).

What makes the Grand Canyon unique are the different rock layers that form its varying slopes and cliffs. Although found elsewhere around the world, the layers are not found in such great variety and with such clear exposure. The canyon is a mere five to six million years old, but the rocks exposed in its walls reveal a more complex history. While rocks at its rim are about 250 million years old, those near the bottom of the canyon are almost 2 billion years old.

Anasazi cliff dwellings, Arizona. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Hells Canyon, Idaho and Oregon

The deepest river canyon in North America is Hells Canyon, which straddles the border between Idaho and Oregon. Created by the Snake River, Hells Canyon extends for 110 miles (177 kilometers) along the river's length. In places, the canyon measures over 8,000 feet (2,438 meters) deep. Along a 40-mile (64-kilometer) section of its length, the canyon averages 5,500 feet (1,676 meters) in depth. In Idaho, the highest point along the canyon is the summit of He Devil Peak at 9,393 feet (2,863 meters). In Oregon, the highest point is Hat Point at 6,982 feet (2,128 meters). On average, the canyon is about 10 miles (16 kilometers) wide.

Geologists estimate the canyon was carved by river erosion over nearly six million years; most of this erosion probably took place during the last two million years when melting glaciers, large amounts of rainfall, and spillovers of large lakes increased the power of the river. The erosional activity of the Snake River is still at work today.

Hells Canyon, located along the border of Idaho and Oregon, is the deepest canyon in North America. Carved by the Snake River, the canyon measures more than 8,000 feet in depth at some places. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Yarlung Zangbo (Tsangpo) Grand Canyon, Tibet

The Yarlung Zangbo River, the highest river above sea level in the world, flows from Tibet through northeast India (where it is known as the Brahmaputra) before joining with the Ganges River in Bangladesh. In Tibet, the river runs across the Tibetan Plateau, the world's highest region with an average elevation exceeding 16,400 feet (5,000 meters). Over millions of years, the river has cut through the weakest part of the plateau, forming the Yarlung Zangbo Grand Canyon. In 1994, Chinese scientists declared the canyon to be the deepest in the world.

The canyon reportedly measures 1,627 feet (496 meters) in length and has an average depth of 16,400 feet (5,000 meters). In places, the canyon drops down to 17,658 feet (5,382 meters). Because of the depth of the canyon, it hosts a range of climates and ecosystems, from glacier environments to tropical rain forests. Very little other information about the canyon is available to the world. Since the region is very remote, and since foreigners are forbidden in many parts of the area, Western scientists have yet to conduct studies of the canyon.

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Cave

They are beautiful and sometimes otherworldly. Existing beneath the surface of the planet, caves have attracted humans for hundreds of thousands of years. Considered by some cultures as sacred, caves have been used in rituals and ceremonies. They have served both as shelter and burial tombs. The human remains and artifacts found in them have aided archaeologists in learning about early humans. Pictographs (rock paintings) in caves, some estimated to be more than 30,000 years old, attest to the creativity of early humans and their relationship to the natural world.

The shape of the land

The scientific study of caves is called speleology (pronounced spee-lee-AH-luh-jee; from the Greek words *spelaion*, meaning "cave," and *logos*, meaning "study of"). A cave is generally defined as a naturally formed cavity or hollow beneath the surface of Earth that is beyond the zone of light and is large enough to be entered by humans. Some sources use the word cavern interchangeably with cave. Technically, a cavern is a large chamber within a cave. A series of caves connected by passages is a cave system.

Individual caverns and cave systems may be immense. In the Chiquibul (pronounced chee-ke-BOOL) Cave System in Belize and Guatemala, the Belize Chamber measures nearly 1,600 feet (490 meters) long by 600 feet (180 meters) wide. It is the largest cavern in the Western Hemisphere. The largest recorded cave system in the world is Mammoth Cave System. It extends for more than 345 miles (555 kilometers) in south-central Kentucky.

There are different types of caves, formed in different areas by different geologic processes, that do not meet the general definition of a cave.

Sea caves, like the one seen here along the coast of Lake Huron, Michigan, are formed by the pounding of waves along the cliffs and ledges of a coast. **PHOTOGRAPH REPRODUCED BY PERMISSION OF FIELD MARK PUBLICATIONS.**

Glacier caves are formed inside glaciers by meltwater (water from melted ice or snow) that runs through cracks in the ice, producing tunnels and cavities. Sea caves are formed in cliffs and ledges along the shores of oceans and other large bodies of water where the constant pounding of waves wears away rock. Lava tube caves are formed when the outer surface of a lava flow begins to cool and harden while lava inside remains hot. Once the stream of molten lava inside drains out, a tube or tunnel remains. Kazumura Cave in Hawaii, measuring approximately 38 miles (61 kilometers) in length, is the longest lava tube cave in the world.

The most common, largest, and most spectacular caves, however, are solution caves. These caves are formed through the chemical interaction of air, water, soil, and rock. They usually form in areas where the dominant rock is limestone, a type of sedimentary rock (rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals). Many solution caves feature streams and lakes and unusual mineral formations. These formations are known as speleothems (pronounced SPEE-lee-oh-thems; from the Greek words *spelaion,* meaning "cave," and *thema,* meaning "deposit"). Because of the way they form, speleothems are also commonly known as dripstone.

The primary speleothems are stalactites, stalagmites, columns, curtains, and flowstones. A stalactite (pronounced sta-LACK-tite) is an icicle-shaped formation that hangs from the ceiling of a cave. A similarly shaped deposit, though often not as pointy, that projects upward from the floor of a cave is a stalagmite (pronounced sta-LAG-mite). Stalagmites generally form underneath stalactites. The two deposits often grow until they join, forming a stout, singular deposit known as a column. A curtain (sometimes called drapery) is a mineral deposit that forms a thin, wavy or folded sheet that hangs from the ceiling of a cave. Any mineral deposit that forms sheets on a wall or floor of a cave is known by the general term flowstone. Although normally whitish or off-white in color, speleothems may contain traces of different minerals that add shades of brown, orange, yellow, red, pink, green, black, and other colors.

Cave ceilings often collapse. As they do, the rock or ground above them also collapses. If the cave is located near Earth's surface, a bowl-like depression known as a sinkhole can develop on the surface. Sinkholes may also form above areas where limestone or other sedimentary rock has been eroded away (erosion is the gradual wearing away of Earth surfaces through the action of wind and water). Sinkholes may range in diameter from a few feet to a few thousand feet.

A landscape dominated by sinkholes on the surface and extensive cave systems underneath is known as karst topography or karst terrain. Karst (*Kras* in Serbo-Croatian) is the name of a limestone plateau in the Dinaric Alps in northwest Slovenia that is marked by such geological formations. It was the first area to be studied based on these formations. Karst topography also features losing streams, which are streams on Earth's surface that are diverted underground through sinkholes or caves, and springs, which are areas where water from underground flows out almost continuously through an opening at Earth's surface.

Words to Know

Cave: A naturally formed cavity or hollow beneath the surface of Earth that is beyond the zone of light and is large enough to be entered by humans.

Cavern: A large chamber within a cave.

Cave system: A series of caves connected by passages.

Curtain: A thin, wavy or folded sheetlike mineral deposit that hangs from the ceiling of a cave.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Flowstone: The general term for a sheetlike mineral deposit on a wall or floor of a cave.

Groundwater: Freshwater lying within the uppermost parts of Earth's crust, filling the pore spaces in soil and fractured rock.

Karst topography: A landscape characterized by the presence of sinkholes, caves, springs, and losing streams.

Limestone: A sedimentary rock composed primarily of the mineral calcite (calcium carbonate).

Losing stream: A stream on Earth's surface that is diverted underground through a sinkhole or a cave.

Sedimentary rock: Rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Sinkhole: A bowl-like depression that develops on Earth's surface above a cave ceiling that has collapsed or on an area where the underlying sedimentary rock has been eroded away.

Speleothem: A mineral deposit formed in a cave.

Stalactite: An icicle-shaped mineral deposit hanging from the roof of a cave.

Stalagmite: A cone-shaped mineral deposit projecting upward from the floor of a cave.

As karst topography continues to develop, a variety of landforms may arise on the surface. This is especially true in tropical or humid climate areas. Caves that grow ever larger soon start to collapse. Sinkholes in the area enlarge and merge. Sections of the ground remain elevated as streams and other running water erode the limestone rock mass around them ever deeper. These sections may form hills, known as cone karst, separated by the sinkholes. Eventually, steep limestone landforms called karst towers may remain standing hundreds of feet above the surrounding landscape. With nearly vertical walls, the towers are often bare of vegetation. The world's most impressive karst towers are perhaps those found in the Guangxi (pronounced GWAN-shee) Province in southern China.

Forces and changes: Construction and destruction

Caves are found almost everywhere around the planet. More than 17,000 have been identified in the United States, underlying 20 percent of the country's land surface. They are found in 48 of the 50 states (only Louisiana and Rhode Island lack caves). While the processes that form

A Sinking State

The entire state of Florida lies on limestone. Much of this underlying rock is weathered, featuring cavities exceeding 100 feet (30 meters) in height and width. Although many are buried beneath sediments, sinkholes dot the land surface. This is especially true in central Florida, an area prone to sinkhole formation. The water table in this area is often only 5 to 10 feet (1.5 to 3 meters) below the surface of the ground.

The largest sinkhole to have formed in Florida in recorded history appeared suddenly in May 1981 in the city of Winter Park. In the span of one day, a hole measuring 350 feet (107 meters) wide and 110 feet (34 meters) deep opened up. The Winter Park sinkhole, as it became known afterward, swallowed a house, five cars from a nearby parking lot, and part of a city swimming pool. The city later stabilized and sealed the sinkhole, converting it into an urban lake.

lava tube caves, glacier caves, sea caves, and other caves are obvious, those that form solution caves—the most common caves of all—are not. Solution caves are not formed by volcanic activity or by the abrasive forces of water or wind. The primary force behind their formation is chemical weathering, which alters the internal structure of minerals by removing or adding elements.

It begins in the sky

The formation of a solution cave begins in Earth's atmosphere. As precipitation (mainly rain) falls to the planet's surface, the water (H_2O) reacts with carbon dioxide (CO_2) in the atmosphere to form weak carbonic acid (H_2CO_3). This is the same acid found in soda pop that produces its "fizz." Once this water and carbonic acid solution reaches Earth's surface and begins to percolate down through the soil, it reacts with carbon dioxide given off by decaying plants and animal matter to form even more carbonic acid solution.

The main mineral in limestone is calcite (calcium carbonate). Most seashells are made of this mineral. Limestone is almost insoluble (unable to be dissolved) in water. Carbonic acid, however, dissolves calcite from limestone. Over hundreds of thousands to millions of years, as carbonic acid moves downward through cracks and fractures in limestone, it dissolves the rock and forms crevices. Over time, these crevices widen to become passages and caverns.

This activity occurs in an area beneath Earth's surface where freshwater fills all pore spaces and microscopic openings in rocks and sediment. These openings include the spaces between grains of sand as well as cracks

Karst topography, like that seen here along the Li River, in China, is dominated by sinkholes on the surface and extensive cave systems underneath. **PHOTOGRAPH REPRODUCED BY PERMISSION OF FIELD MARK PUBLICATIONS.**

and fractures in rocks. As rain or melted snow seeps through the ground, some of it clings to particles of soil or to roots of plants. The remaining water moves deeper, drawn downward by gravity, until it reaches a layer of rock or sediment, such as clay, through which it cannot easily pass. It then fills the empty spaces and cracks above that layer. This water is known as groundwater, and the area where it fills all the spaces and pores underground is the zone of saturation. The top surface of this zone is called the water table. Above it, the pores and spaces in rock hold mainly air, along with some water. This is called the zone of aeration.

Caves initially form just below the water table. Filled with water, the cavities and fractures in the limestone are enlarged by the continuous movement of water and carbonic acid through them. Air enters a cave only when the water table is lowered through some geologic event, such as erosion of the land surface above or uplift of the rock beneath the cave. When this occurs, the cave stops enlarging and water begins to drain out of the cave down through cracks and other passages in the surrounding limestone. Areas of the cave may continue to lie below the water table and, therefore, are still water-filled. An underground stream, whose water source lies farther away, may still flow through the cave.

The Largest Enclosed Space on Earth

The largest cavern in the world is the Sarawak Chamber of the Good Luck Cave in Sarawak, Malaysia. It measures approximately 1,970 feet (600 meters) in length, 1,310 feet (400 meters) in width, and 330 feet (100 meters) in height. It has a total area of 1,751,300 square feet (162,700 square meters). The cavern is large enough to hold eight Boeing 747 aircraft lined up nose to tail.

By comparison, the largest cavern in the United States is the Big Room in the Carlsbad Caverns cave system in New Mexico. Covering an area of 357,472 square feet (33,210 square meters), it is just over one-fifth the size of the Sarawak Chamber.

Drip by drip

The air-filled sections of the cave provide the perfect environment for the development of speleothems. Even though the water table may have dropped, water weaving its way downward from Earth's surface still enters a cave through cracks and crevices in its ceiling and walls. When this water and carbonic acid solution enters the cave, some of the carbon dioxide in the solution escapes into the air (much like a soda pop that loses carbon dioxide and goes "flat" when left uncovered). This changes the chemical structure of the solution, and it can no longer hold the dissolved calcite. The calcite is then deposited in crystallized form as a speleothem. Its shape depends on where and how quickly water enters the cave. Though growth rates of speleothems vary from cave to cave, it may take 120 years or longer for 1 cubic inch (16.4 cubic centimeters) of calcite to be deposited on a cave formation.

Water slowly dripping from a small opening in the ceiling of the cave initially forms a soda straw. This tubelike formation develops when each drop evaporates, leaving behind a small amount of calcite around its border. As more drops fall, more calcite is deposited and the tube grows downward. Even though they are quite fragile and have the diameter of a drop of water, soda straws may grow to 3 feet (1 meter) or more in length. If the tube becomes blocked and more drops begin to fall, then a stalactite forms around the soda straw. If drops of water increase even further from the ceiling, they may fall off a stalactite before evaporating and form a stalagmite. Because the drops spread when they hit the floor or ledge of a cave, a stalagmite is often wider than the stalactite under which it often grows. An extremely rapid drip from a ceiling may form a pool of water on the floor of a cave. As the water evaporates along the edges of the pool, calcite may form terraces.

Fragile Features

Caves are environments that contain not only fantastic mineral formations but rare and unusual animals. These include blind fish, colorless spiders, and many other troglobites (pronounced TROG-lah-bites), animals that live in caves and cannot survive outside of them. Troglobites have evolved over millions of years, becoming adapted to the absolute blackness and meager food offerings of cave life. Caves are also home to animals that venture out periodically in search of food. Beetles, crickets, frogs, salamanders, and others are of this type. Finally, caves serve as temporary homes to animals that move freely in and out of them. Bats, bears, moths, and skunks are examples of these.

For many people, cave exploration is a fascinating and fun activity. Spelunking (pronounced spi-LUNG-king) is the term given to such exploration. Spelunking societies, organizations, and groups exist across the country, helping people explore the more than 100 caves that are open to the public for study and enjoyment.

Although caves are carved out of rock, they are fragile. Vandalism, property development, and air and water pollution have all had a devastating effect on caves and cave life. Even oil left on a speleothem by the accidental touch of a human hand can alter its formation, eventually destroying it. Of the more than 130 species that inhabit the Mammoth Cave System in Kentucky, dozens are considered threatened or endangered. For the continued study and exploration of caves and the life they harbor, great care must be taken.

If water drips from various points in a crack in a cave ceiling, stalactites may grow in a row. Eventually, they may grow together, forming a continuous sheet. A flowing sheet may also develop if water seeps slowly along the length of a thin slit in the ceiling. When a crack appears in a cave wall, a film of the water may flow down the wall and over ledges, forming sheets of flowstone.

The multitude of speleothems that develop in caves vary widely. In fact, no two caves are ever alike. The air temperature of the cave, the amount and chemical composition of the water entering it, and the size of the joints and cracks in its ceiling and walls are just a few of the factors that determine a cave's particular appearance.

Most caves are constantly changing. Some are still enlarging, with new passages being formed below the water table (in a cave system, the oldest caves and passages are closest to Earth's surface). Many caves are still wet, with calcite being deposited on various formations. Other caves and cave systems, however, are dry and are no longer enlarging or growing speleothems. Eventually, in a dry cave, the thin ceiling may lose support and collapse, exposing the cave to the surface through a sinkhole.

Spotlight on famous forms

Lechuguilla Cave, New Mexico

The deepest limestone cave in the United States is Lechuguilla (pronounced lech-uh-GEE-yah) Cave. Part of the Carlsbad Caverns cave system in southeast New Mexico, it extends to a depth of 1,571 feet (479 meters). The cave was discovered by a group of cavers in 1986. Scientists estimate that the cave has existed beneath Earth's surface for at least 2 million years.

The cave is notable not only for its size, but for its fantastic array of rare speleothems. Unlike other solution caves, Lechuguilla was not formed by carbonic acid. Rather, rising hydrogen sulfide from nearby oil fields reacted with groundwater to form sulfuric acid. This acid dissolved the limestone and created a cave filled with lemon-yellow sulfur formations. Among those is a 24-foot (7.3-meter) soda straw, the longest in the world.

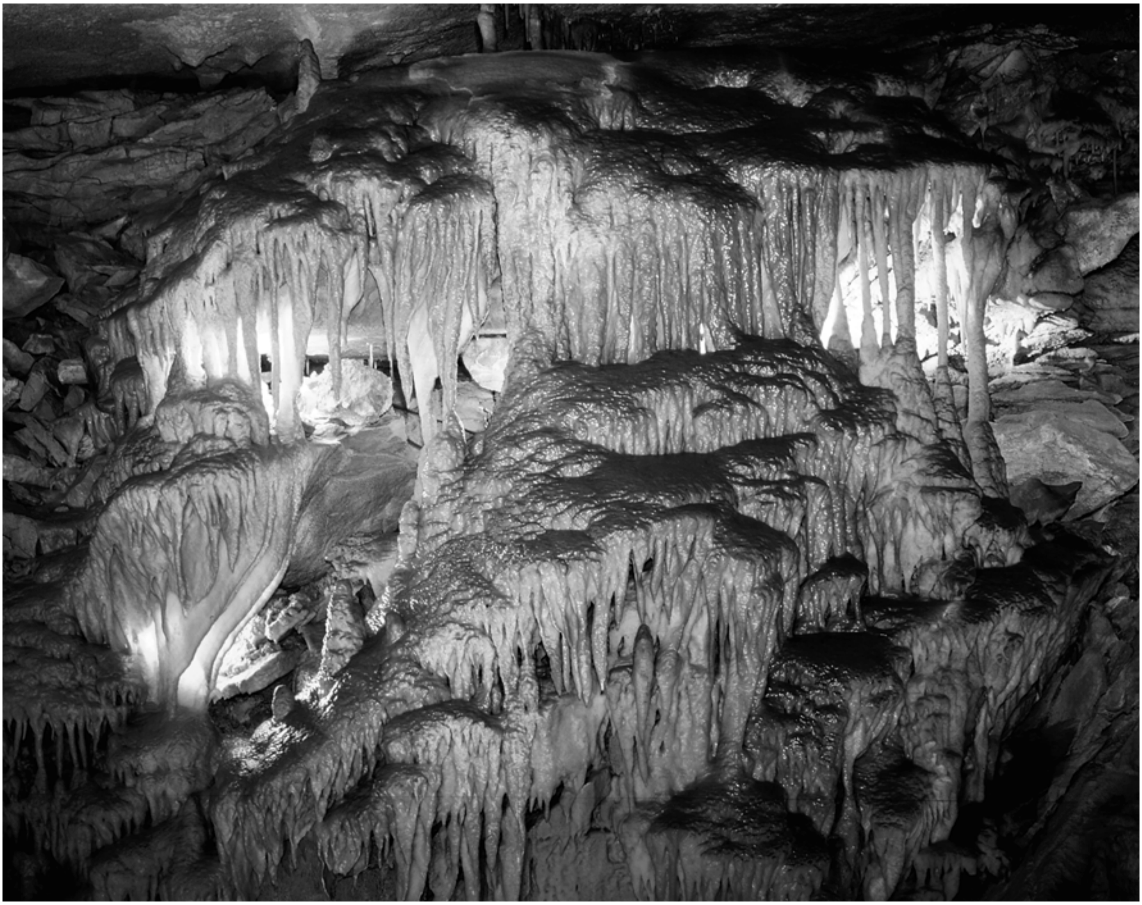
In addition to unusual speleothems, Lechuguilla contains rare bacteria that feed on the sulfur, iron, and manganese minerals present in the cave. Scientists believe these bacteria may have played a part in the formation of the cave and its speleothems. They also believe the sulfur-laden environment of Lechuguilla may be similar to that on the surface of Mars, so they have studied the cave's bacteria to determine how life may exist on that planet.

Mammoth Cave System, Kentucky

The Mammoth Cave System, properly known as the Mammoth Cave-Flint Ridge System, is the largest cave system in the world. Lying beneath the surface in south-central Kentucky, the system extends for more than 345 miles (555 kilometers) and to a depth of 379 feet (116 meters). Geologists believe there may be an additional 600 miles (965 kilometers) of undiscovered passageways connected to the system.

Scientists estimate the system began to form in the limestone rocks underlying the area some 30 million years ago. Archaeologists have found evidence that early Native Americans inhabited the cave system as many as 4,000 years ago.

The land surface above Mammoth Cave System is marked by sinkholes and losing streams. Underneath this karst topography lie tunnels, passages, caverns, and almost every type of speleothem. Underground rivers flow through some of the system's deepest caverns. Mammoth Dome



Stalactites hanging from the roof of the Drapery Room, part of the Mammoth Cave System. The system extends for more than 345 miles and is the largest cave system in the world. **PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.**

is a cavity in the system that measures 192 feet (59 meters) in height. Another extraordinary feature is Frozen Niagara, a mass of flowstone 75 feet (23 meters) tall and 4 feet (1.2 meters) wide.

Voronya Cave, Republic of Georgia

On January 6, 2001, a team of Ukrainian and Russian cavers exploring a cave in the Abkhazia region of the Republic of Georgia reached a depth of 5,610 feet (1,710 meters). This event confirmed Voronya Cave (also known as Krubera Cave) as the world's deepest cave. The previous record holder had been Lamprechtsofen-Vogelshacht Cave in Austria, which measures 5,355 feet (1,632 meters) in depth.

Voronya Cave was so-named because of the large number of crows that gather around its entrance (*voron* is Russian for "crow"). Discovered in the late 1960s, the cave is located in a valley in the western Caucasus Mountains. Meandering downward through dense limestone, the cave features one entrance that leads to three branches. When first explored in the 1980s, the cave was thought to end in a narrow passage 1,110 feet (3,335 meters) beneath the surface. In 1999, an expedition found new passages that led to deeper pits.

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Coast and shore

Coasts mark the area where dry land meets oceans or other large bodies of water. They are one of the most active environments found on Earth. The coastal landscape is ever-changing. It reflects the conflicting processes of erosion (the gradual wearing away of Earth surfaces through the action of wind and water) and deposition (the accumulation and building up of natural materials). It is a landscape that is affected by the interactions of Earth, the Moon, and the Sun.

Coasts are among the most beautiful and inspiring landscapes on the planet, whether they are scenes of torrential storms or serene calm. Throughout recorded history, humans have sought to live on or near coasts. Although coasts account for only 10 percent of Earth's land surface, they serve as home to two-thirds of the world's human population.

The shape of the land

Coast and shore, coastline and shoreline, are commonly used in place of each other. Technically, they are different areas along a coastal landscape. The line that marks the boundary between water and land is the shoreline. It constantly fluctuates because of the regular action of waves and tides. The shore is that strip of ground bordering a body of water that is alternately covered or exposed by waves or tides. The boundaries of the shore are marked by the shoreline at its farthest seaward (low tide) and farthest landward (high tide).

Tide is the periodic rising and falling of water in oceans and other large bodies of water in response to the gravitational attraction of the Moon and the Sun upon Earth. Although the Sun is larger than the Moon, the Moon is closer to Earth and, therefore, its gravitational force is approximately 2.2 times greater. The gravitational pull of the Moon creates two types of tides: high and low. A tidal bulge occurs in the oceans on

The California coast is known as an emergent coast, an area that was formerly under water and has gradually risen above sea level either through geologic uplift of the land or a drop in sea level. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

the side of Earth nearest the Moon; at the same time, a second tidal bulge occurs on the opposite side of Earth. This second bulge forms because the force of the Moon's gravity pulls the solid body of Earth slightly away from the water on Earth's far side. These bulges are high tides. The areas between the tidal bulges experience low tide.

As Earth rotates, the tides move over its surface. It takes approximately 24 hours and 50 minutes for a given point on Earth to make a complete cycle relative to the Moon, and two lunar tidal cycles occur during this time. Thus, the average time between high tides is 12 hours and 25 minutes. This is a generalized explanation of tides. They do not move evenly and predictably over Earth's surface. Variations in the depth of the oceans and the distribution of landmasses combine with other factors to produce highly complex tidal behavior.

The coast and coastline begin where the shore ends at its high tide mark (farthest landward). The line between the coast and the shore at high tide is the coastline. The coast extends landward from the coastline to the first major change in terrain features, which may be miles inland. This could be a highland or a forest or some other type of terrain. Sometimes, the change between the coast and the adjacent terrain is not so distinct.

Words to Know

Backshore zone: The area of a beach normally affected by waves only during a storm at high tide.

Backwash: The return flow of water to the ocean following the swash of a wave.

Bar: A ridge or mound of sand or gravel that lies partially or completely underwater a short distance from and parallel to a beach; also commonly known as a sand bar.

Barrier island: A bar that has been built up so that it rises above the normal high tide level.

Bay: A body of water in a curved inlet between headlands.

Beach: A deposit of loose material on shores that is moved by waves, tides, and, sometimes, winds.

Beach drift: The downwind movement of sand along a beach as a result of the zigzag pattern created by swash and backwash.

Berm: A distinct mound of sand or gravel running parallel to the shoreline that divides the foreshore zone from the backshore zone of a beach.

Cliff: A high, steep face of rock.

Coast: A strip of land that extends landward from the coastline to the first major change in terrain features.

Coastline: The boundary between the coast and the shore.

Emergent coast: A coast in which land formerly under water has gradually risen above sea level through geologic uplift of the land or has been exposed because of a drop in sea level.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Foreshore zone: The area of a beach between the ordinary low tide mark and the high tide mark.

Headland: An elevated area of hard rock that projects out into an ocean or other large body of water.

Longshore current: An ocean current that flows close and almost parallel to the shoreline and is caused by the angled rush of waves toward the shore.

Longshore drift: The movement of sand and other material along a shoreline in the longshore current.

Sea arch: An arch created by the erosion of weak rock in a sea cliff through wave action.

Sea stack: An isolated column of rock, the eroded remnant of a sea arch, located in the ocean a short distance from the shoreline.

Shore: The strip of ground bordering a body of water that is alternately covered or exposed by waves or tides.

Shoreline: The fluctuating line between water and the shore.

Spit: A long, narrow deposit of sand or gravel that projects from land into open water.

Submergent coast: A coast in which formerly dry land has been gradually flooded, either by land sinking or by sea level rising.

Swash: The rush of water up the shore after the breaking of a wave.

Tide: The periodic rising and falling of water in oceans and other large bodies of water that results from the gravitational attraction of the Moon and the Sun upon Earth.

Tombolo: A mound of sand or other beach material that rises above the water to connect an offshore island to the shore or to another island.

Wave crest: The highest part of a wave.

Wave-cut notch: An indentation produced by wave erosion at the base of a sea cliff.

Wave-cut platform: A horizontal bench of rock formed beneath the waves at the base of a sea cliff as it retreats because of wave erosion.

Wave height: The vertical distance between the wave crest and the wave trough.

Wavelength: The horizontal distance between two wave crests or troughs.

Wave trough: The lowest part of a wave form between two crests.

The Literary Landscape

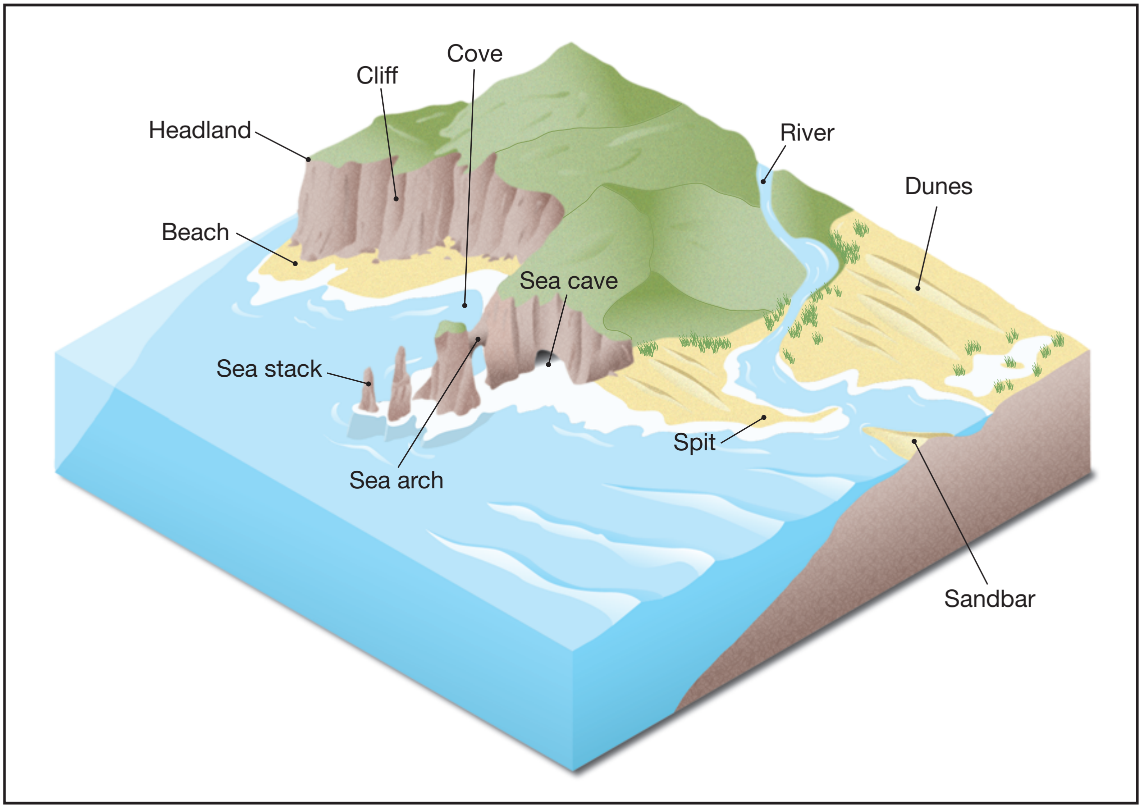
"At the foot of this cliff a great ocean beach runs north and south unbroken, mile lengthening into mile. Solitary and elemental, unsullied and remote, visited and possessed by the outer sea, these sands might be the end or the beginning of a world. Age by age, the sea here gives battle to the land; age by age, the earth struggles for her own, calling to her defense her energies and her creations, bidding her plants steal down upon the beach, and holding the frontier sands in a net of grass and roots which the storms wash free."

—Henry Beston, *The Outermost House: A Year of Life on the Great Beach of Cape Cod,* 1928.

Coasts are generally classified into two types: emergent and submergent. Emergent coasts are those in which land formerly under water has gradually risen above sea level through geologic uplift of the land or has been exposed because of a drop in sea level. Currently, sea level around the world is rising by an average of 0.1 inch (0.25 centimeter) per year because glaciers and ice sheets are melting due to global warming (an increase in the world's temperatures thought to be caused, in part, by the burning of fossil fuels and the depletion of the ozone layer). So an emergent coast in the present-day is one that is rising on average more than 0.1 inch (0.25 centimeter) per year. Coasts along Scandinavia, New England, California, and Hawaii are examples of emergent coasts. Submergent coasts are those in which formerly dry land has been gradually flooded, either by land sinking or by sea level rising. Coasts along the southeast Atlantic and the Gulf of Mexico are examples of submergent coasts.

Coastal landscapes may be broadly divided into rocky cliffs and sandy beaches and dunes. All coasts experience a combination of erosion and deposition to varying degrees. Emergent coasts are typically dominated by cliffs or high, steep faces of rock. Because the land is rising in these areas, its landforms are subject to erosion. As waves break against a cliff, certain features are formed, depending on the hardness of the rock. Initially, wave action may cut an indentation, called a wave-cut notch, at the base of the cliff. When the notch becomes larger, rock in the cliff face above the notch loses support and falls into the water where it is broken up by the action of the waves. This process continues and the cliff slowly retreats inland. As it does so, a horizontal bench of rock remains beneath the waves at high tide where the cliff once stood. This feature is called a wave-cut platform. Over time, as the land continues to rise, this platform may be elevated and a new cliff face formed.

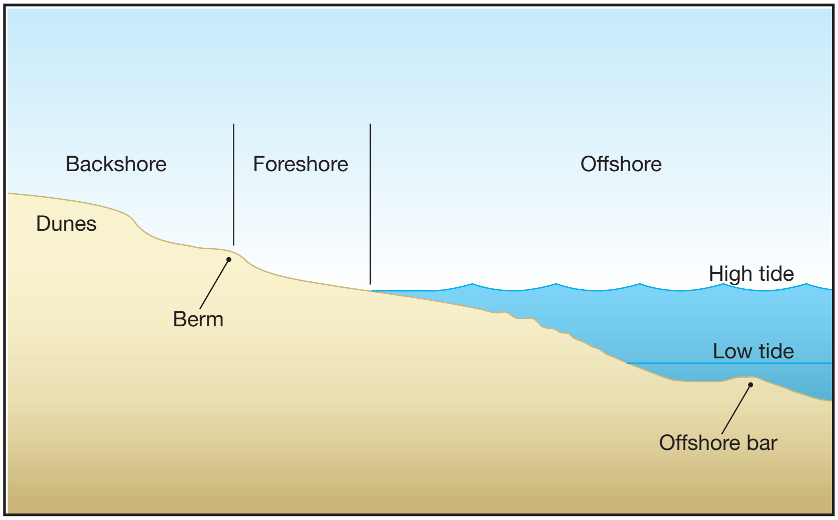
In areas where cliff rock is alternately hard and soft, headlands and bays may form. A headland is an elevated area of hard rock that projects out into an ocean or other large body of water. When soft rock is eroded away between headlands, a curved inlet that holds a body of water known as a bay forms. Because of its location, a headland receives the brunt of



Coastal features and landforms of both emergent and submergent coasts.

wave attack (wave energy is spread out and weaker in bays). Erosion by water and wind may create distinct features such as sea caves, sea arches, and sea stacks in a headland. Sea caves arise when waves hollow out weak areas of rock in headlands. Waves may then erode the cave through the headland, or caves on either side of the headland may meet. In either case, a sea arch is formed. Erosion of the arch continues until its top portion collapses, leaving a column of hard rock known as a sea stack standing detached from the sea cliff. Continual wave erosion eventually reduces the stack into a stump.

Beaches occur when sand, gravel, and other loose material are deposited by waves along a shore. A beach extends landward from the shoreline at low tide to the shoreline at high tide during storms, when waves are at their highest. In general, a beach is a sandy shore. Beaches are commonly divided into two zones: the foreshore zone and the backshore zone. The foreshore zone is the area between the ordinary low tide mark and the ordinary high tide mark. The backshore zone is the area normally affected by waves only during a storm at high tide. Behind the backshore zone may be cliffs, vegetation, or dunes created by winds moving



Common elements of beach topography.

sand from the beach. Commonly separating the two zones is a distinct mound of sand or gravel, called a berm, that runs parallel to the shoreline. It is created by the action of waves and tides.

Wave activity keeps sand and other loose material in constant motion. As a consequence, it can create other features along the shore, such as spits, bars, barrier islands, and tombolos. A spit is a long, narrow deposit of sand or gravel that projects from land into open water. Spits normally form at the mouth of a bay and curve inward. If a spit extends across the entire mouth of a bay, it is called a baymouth bar or bay barrier. A bar, commonly known as a sand bar, is a ridge or mound of sand or gravel that lies partially or completely underwater a short distance from and parallel to a beach. If more sand is deposited on the bar so that it rises above the normal high tide level, the bar becomes a barrier island. Barrier islands range in length from 1.8 to 62 miles (3 to 100 kilometers) and in width from 0.6 to 1.8 miles (1 to 3 kilometers). Separated from the shore by a shallow body of water known as a lagoon, a barrier island often helps protect the shore from the full force of waves. The East Coast of the United States from Massachusetts to Florida is noted for its system of barrier islands. A mound of sand or other beach material that rises above the water to connect an offshore island to the shore or to another island is called a tombolo (pronounced TOM-beh-low).

Forces and changes: Construction and destruction

Coasts and shores are constantly changing. The shoreline moves with the waves and the tides. Rock is eroded away, and gravel and sand are deposited onshore, only to be swept back offshore. Storms batter coasts, and tides flood areas on a daily basis. The premiere forces that shape the coastal landscape, however, are waves.

Breaking waves exert great force. A 10-foot (3-meter) wave can produce a force of 30 pounds per square inch (2.1 kilograms per square centimeter). In addition to the pressure exerted by their impact, waves erode by scouring rock cliffs and other coastal features with rock fragments they carry.

Waves

Most waves get energy and motion from the wind. Wind blowing over the surface of an ocean or other large water body creates friction along that surface, producing tiny ripples. Further pushed by the wind, these ripples combine and increase in size. The size of waves depends on the strength of the winds, the length of the time the winds blow, and the distance of open water across which the winds blow. Large waves may be created by strong winds blowing for long periods of time across large areas of water.

The highest part of a wave is called the wave crest. The lowest part of a wave between two crests is the wave trough. The vertical distance between the wave crest and the wave trough is the wave height. The horizontal distance between two wave crests or troughs is the wavelength. As a wave travels across an ocean or other body of water, the water particles in the wave move in circular patterns, in loops. These loops extend down underneath the surface of the water only one-half the distance of the wavelength. Water beneath that is not disturbed by wave motion. As the wave form advances across the surface, its energy moves forward, not the water itself. The water particles in the loops essentially return to their original position after the wave has passed.

As a wave enters shallow water near a shoreline, the lower loops in the wave begin to drag on the bottom. This causes the wave to slow down. As it does so, its wavelength decreases and its height increases. When the wave can no longer support its height, the wave breaks. Most of the energy it has carried across the ocean is then transferred into the churning, turbulent water known as surf. The powerful surf either crashes into a cliff or runs up a beach. The water moving up the beach is known as swash; the return flow toward the ocean is called the backwash. The speed of the swash is greater than that of the backwash.

Angled waves and drifting sand

Most of the sand and other sediments making up a beach come from weathered and eroded rock from the mainland that is deposited by rivers at the coast. Material eroded from cliffs at the head of a beach itself may

Bay of Fundy

Lying between New Brunswick and Nova Scotia, Canada, is an inlet of the Atlantic Ocean known as the Bay of Fundy. Measuring about 50 miles (80 kilometers) wide where its mouth meets the Atlantic, the somewhat funnel-shaped bay extends about 170 miles (270 kilometers) to the northeast. At its head it splits into two narrow bays, Chignecto Bay and Minas Basin.

The bay is famous for its tidal range. High and low tide alternate in the bay every 6 hours and 13 minutes. With each tide, 24 cubic miles (100 cubic kilometers) of water flushes through the Bay of Fundy, an amount equal to the daily discharge of all the world's rivers. The average range between high tide and low tide of oceans around the world is 3 feet (1 meter). In the Bay of Fundy, the average is 30 feet (10 meters). In Minas Basin, the difference between high tide and low tide can be as much as 52.5 feet (16 meters).

The reason tides rise and fall to such a great extent in the Bay of Fundy is primarily because of its shape. It tapers significantly at its head, and water flowing into the bay rises in response to this constriction. Also, water flows through the entire bay at the same rate that it enters the bay's mouth from the Atlantic Ocean.

Sandstone erosion of rocks along the coast of the Bay of Fundy. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

form the beach. Beach sand may also contain fragments of smoothed and rounded shells of marine creatures, such as clams. Tropical beaches often consist entirely of shell and coral fragments. Beaches in areas of volcanic activity, such as Hawaii, can be black since the sand is created by the erosion of volcanic rock. Because sand is in constant motion, beaches are often referred to as "rivers of sand." Depending on the action of waves, sand on a beach may travel along the shore hundreds of feet a day.

When waves approach a shoreline, they rarely do so parallel or straight on. Most often, they do so at a slight angle. After a wave breaks, the swash runs up the shore at that slight angle. Because of gravity, however, the backwash runs straight back to the water directly, without any angle. As a result, the water moves the sand along the beach downwind in a zigzag pattern. This movement is known as beach drift. In addition to beach drift, sand and other sediment is transported downwind along the beach in the longshore current, a current formed by the angled rush of waves that runs close to and almost parallel to the shoreline. The movement of material in this current is known as longshore drift. Over long periods of time, beach drift and longshore drift may combine to transport sand and other material great distances, eventually forming coastal features such as spits.

Beaches are not fixed features; they are dynamic environments. They expand and contract depending on wave conditions. In winter and during storms, when wind and wave action are more powerful and frequent, erosion often reduces the size of beaches. In summer and during calm weather, gentle waves deposit sand, creating wider beaches. All sandy landforms along a coast—spits, bars, barrier islands, tombolos—are subject to the erosional or depositional action of waves.

Although they do not change as quickly, rocky coasts will eventually change. An irregular coastline of headlands and bays will be straightened by erosion. Wave action will cut away at headlands, quickly break up rock debris and other material, then deposit it along the shoreline of the bay.

Spotlight on famous forms

Cape Cod, Massachusetts

On the East Coast of the United States, just south of Boston, Massachusetts, a large peninsula resembling a flexed arm extends 60 miles (96.5 kilometers) into the Atlantic Ocean (a peninsula is a piece of land that projects from a mainland into a body of water). Considered a premiere vacation resort, Cape Cod features the longest uninterrupted sandy shore in New England.

Cape Cod was formed more than 15,000 years ago by glaciers that covered the area, deposited sediment, then retreated. Ever since, waves

Although glaciers originally shaped the unusual landscape of Cape Cod some 15,000 years ago, waves and nearshore currents continue to sculpt the 40-mile coastline. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

and currents near the shore have shaped and reshaped the peninsula. They continue to do so in the present, transporting sand along the shore to create a variety of coastal landforms, including chains of barrier islands, curved spits, and dunes. Cape Cod's wide sandy beaches are maintained by material that is eroded from cliffs that border the beaches.

During calm summer months, the amount of beach material that is eroded is equal to the amount that is deposited. In winter months, dominated by severe storms from the northeast, erosion takes over. Prevailing waves drag away sand and other material. Overall, land is lost. On average, the cliffs retreat by 3 feet (1 meter) every year. Structures such as walls and jetties built to protect housing and other development from erosion actually increased its rate. To protect this delicate environment from further development, over 43,600 acres (17,440 hectares) along the outer portion of Cape Cod were designated a national seashore in 1961.

Oregon coast

The coast of Oregon along the Pacific Ocean is noted for sheer cliffs, jagged sea stacks and arches, wave-battered headlands, and long sandy beaches. It is a battleground where land and ocean meet. Wind-driven waves that have traveled 6,000 miles (9,654 kilometers) from Japan—the longest stretch of open ocean in the Northern Hemisphere—crash into the coast unhindered by barrier islands or other features.

This emergent coast has been sculpted by pounding waves that create some of the most violent surf anywhere. The erosive process of the surf takes many years to produce noticeable results, but its force is relentless. Due to erosion, the rocky coast has retreated inland. Evidence of this are the numerous sea stacks jutting from the ocean along much of the coast.

Many of the sea stacks have been given names: Cathedral Rock, Elephant Rock, Face Rock, and the Cat and Kittens. Among the famous sea stacks lining the coast is Haystack Rock, which lies offshore near the town of Cannon Beach. One of the largest free-standing rocks in the world, it towers 235 feet (72 meters) above sea level. It is composed of basalt, a dark, dense volcanic rock. Some 10,000 years ago, Haystack Rock was once part of Tillamook Head (pronounced TIL-ah-muhk), a headland that rises to a height of more than 1,000 feet (305 meters) above sea level.

White Cliffs of Dover, England

Celebrated in literature, song, and film, the White Cliffs of Dover have been an important part of England's natural and social history. Located on the southeast coast of England facing the English Channel, the more than 300-foot-high (91-meter-high) cliffs have provided a natural barrier to foreign invaders throughout history. For English aircrews that flew bombing missions over Europe during World War II (1939–45), the cliffs were the first part of England they saw upon their return. They represented safety.

The cliffs are composed of chalk, which is a particular type of limestone that forms a brilliant white rock formation. Limestone is a sedimentary rock, or rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals. Chalk is formed mainly from coccoliths (pronounced COKE-ah-liths), the fossilized remains of tiny, single-celled marine organisms. The coccoliths that form the cliffs were first laid down more than 100 million years ago over a large area of shallow sea, eventually piling into layers.

Powerful waves have shaped and reshaped the dramatic cliffs, jagged sea stacks, and sandy beaches of the Oregon coast. **PHOTOGRAPH REPRODUCED BY PERMISSION OF MS. CINDY CLENDENON.**

The 300-foot White Cliffs of Dover, on the coast of England, are composed of chalk. The soft rock has formed from the fossilized remains of tiny marine organisms called coccoliths. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Before the last ice age some 10,000 years ago, England and France were linked by a chalk landmass. Over time, as sea levels rose, tidal movements eroded the mass, creating the English Channel. Layers of chalk still lie under the seabed of the channel, which has an average depth of 360 feet (110 meters). White cliffs along the French coast match the White Cliffs of Dover. Chalk is a soft rock, and the cliffs naturally erode as waves cut into lower levels while rain seeps into and weakens upper levels. On average, the cliffs are receding at a rate of 0.5 inch (1.3 centimeter) a year.

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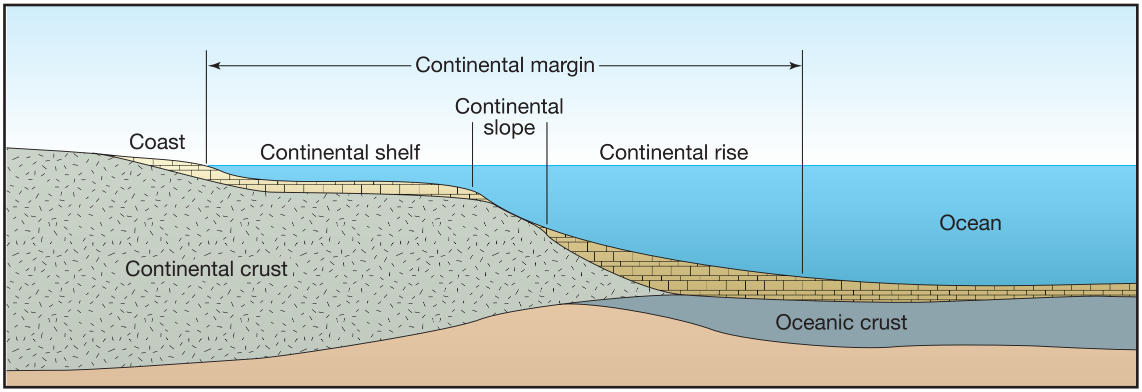
Continental margin

They are the drowned edges of continents. Covered by the oceans, continental margins are part of the same crust (thin, solid outermost layer of Earth) that forms the continents. They are covered in sediments that have been eroded from dry land. (Erosion is the gradual wearing away of Earth surfaces through the action of wind and water.) Lying between the deep ocean basins and the above-water land areas, continental margins account for 11 percent of Earth's surface.

The shape of the land

The continental margin is the submerged outer edge of a continent. It is generally divided into two sections: the continental shelf and the continental slope. The continental shelf is the region that extends seaward from the shoreline to a sharp drop-off that marks the beginning of the continental slope. That drop-off is known as the continental shelf break. Continental shelves vary in width from 3 to 930 miles (5 to 1,500 kilometers). The average width worldwide is about 40 miles (64 kilometers). The widest shelves are in the Arctic Ocean off the northern coasts of Siberia and North America. Narrow shelves are found off the western coasts of North and South America. Continental shelves along the coasts of the United States cover an area of about 891,000 square miles (2,307,690 square kilometers).

Continental shelves are normally gently sloping, with an average seaward slope of about 0.1 degree. They tend to have the same topography or surface features that dominate the adjacent land. Whether a coastal area is mountainous, dominated by low hills, or flat, the continental shelf next to it will be similarly shaped. The average depth of the continental shelf at the shelf break is about 430 feet (131 meters) below the surface of the ocean.



Basic composition of continental margins, which include the continental shelf, continental slope, and continental rise.

In contrast to the continental shelf, the continental slope is generally narrow in width, ranging from 6.2 to 62 miles (10 to 100 kilometers). Relatively steeper than the shelf, the slope angles down to the ocean basin at an average of 4 degrees; in some areas, the angle may be as much as 25 degrees. The steepness of a slope often reflects the steepness of the nearby coastal area. Slopes along mountainous coasts are steeper than those along flat coasts. In general, the steepest slopes tend to be found in the Pacific Ocean and the least steep slopes in the Atlantic and Indian Oceans.

The continental slope marks the transition between continental crust and oceanic crust. Continental crust is composed mostly of granite, whereas oceanic crust is mostly basalt. (Although they differ in composition, both are types of igneous rock, which forms when magma cools and solidifies. Granite forms when magma with a high silica content cools slowly deep beneath Earth's surface; basalt forms when magma with a low silica content cools quickly outside of or very near Earth's surface.)

The most distinctive features of continental slopes are submarine canyons. Typically, these are steep-walled, V-shaped canyons that may be thousands of feet deep. The incline of a canyon is normally related to that of the slope: steep slopes have short, steep canyons, while broader slopes have longer, shallower canyons. The deepest of the submarine canyons easily rival the size of the Grand Canyon on the Colorado River in Arizona. Sometimes, submarine canyons begin at the outer edge of the continental shelf. Most often, they form down-current from major rivers that flow into an ocean. Geologists believe that some submarine canyons may have been carved during a time in Earth's past when sea levels were lower than at present, and rivers were able to flow out to the edge of the shelf. Other canyons may have formed when earthquakes created faults or cracks along slopes that were subsequently eroded into the canyons.

Words to Know

Accretionary wedge: A mass of sediment and oceanic rock that is transferred from an oceanic plate to the edge of the less dense plate under which it is subducting.

Active continental margin: A continental margin that has a very narrow, or even nonexistent, continental shelf and a narrow and steep continental slope that ends in a deep trench instead of a continental rise; it is marked by earthquake and volcanic activity.

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Continental drift: The hypothesis proposed by Alfred Wegener that the continents are not stationary, but have moved across the surface of Earth over time.

Continental margin: The submerged outer edge of a continent, composed of the continental shelf and the continental slope.

Continental rise: The gently sloping, smooth-surfaced, thick accumulation of sediment at the base of certain continental slopes.

Continental shelf: The gently sloping region of the continental margin that extends seaward from the shoreline to the continental shelf break.

Continental shelf break: The outer edge of the continental shelf at which there is a sharp drop-off to the steeper continental slope.

Continental slope: The steeply sloping region of the continental margin that extends from the continental shelf break downward to the ocean basin.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid outermost layer of Earth.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Passive continental margin: A continental margin that has a broad continental shelf, a gentle continental slope, and a pronounced continental rise; it is marked by a lack of earthquake and volcanic activity.

Plates: Large sections of Earth's lithosphere separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Seafloor spreading: The process by which new oceanic crust is formed by the upwelling of magma at mid-ocean ridges, resulting in the continuous lateral movement of existing oceanic crust.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Submarine canyon: A steep-walled, V-shaped canyon that is cut into the rocks and sediments of the continental slope and, sometimes, the outer continental shelf.

Trench: A long, deep, narrow depression on the ocean basin with relatively steep sides.

Turbidity current: A turbulent mixture of water and sediment that flows down a continental slope under the influence of gravity.

Geologists know that underwater currents called turbidity currents have eroded most submarine canyons. These turbulent mixtures of water and sediment develop near the continental shelf break when some event, such as an earthquake or a violent storm, triggers their formation. Denser (heavier) than the surrounding water, the currents are pulled downward by gravity. Flowing down the continental slope like an avalanche at up to 50 miles (80 kilometers) per hour, the sediment-laden currents surge through the canyons, scouring their sides. When the currents reach the ocean basin, they slow, and the sediment they carry falls to the bottom in a fanlike deposit, much like an alluvial fan that forms in a desert environment when water flows out of a canyon onto a plain or flat area. (For further information on alluvial fans, see the **Dune and other desert features** chapter.)

At the base of certain continental slopes is a gently sloping, smooth-surfaced, thick accumulation of sediment from land that had been transported to the shelf and then down the slope. This transition between the continental slope and the ocean basin is known as the continental rise. Some sources include the continental rise as being a major section of the continental margin, along with the shelf and slope. Since it does not occur on all continental margins around the planet, it is best considered a characteristic of the margin in certain areas. Continental rises are well-developed around Antarctica and in the Atlantic and Indian Oceans. They are hardly found in the Pacific. When they are present, continental rises vary in width from 62 to 620 miles (100 to 1,000 kilometers).

A continental margin that has a broad continental shelf, a gentle continental slope, and a pronounced continental rise is known as a passive continental margin. This type of margin experiences little, if any, volcanic or earthquake activity. The build-up of sediment is the primary activity affecting a passive margin. Because these margins are found along the east coasts of North and South America and the west coasts of Europe and Africa, they are also known as "Atlantic-type" margins. The continental margins along India and Antarctica are other examples of passive margins.

A continental margin that has a very narrow, or even nonexistent, continental shelf and a narrow and steep continental slope is known as an active continental margin. Instead of ending in a continental rise, the continental slope of this type of margin often plunges into a deep-ocean trench, which may be filled with sediment. Earthquake and volcanic activity are prominent here. Since active continental margins occur along many coasts of the Pacific Ocean, these types of margins are also known as "Pacific-type" margins.

A Burial and Dumping Ground

Continental shelves have not always been covered by water. During Earth's history, changes in sea level have alternately exposed, then covered portions of the shelves. Scientists estimate that during the last glacial period over 10,000 years ago, much of Earth's water was trapped in the polar ice sheets. The level of the oceans may have dropped as much as 350 feet (107 meters) below the current level. At times of low sea level, land plants and animals, including humans and their ancestors, lived on the shelves. Evidence of this lies in their remains that are often found there in the present day. Twelve-thousand-year-old bones of mastodons, extinct relatives of the elephant, have been recovered off the coast of the northeastern United States.

Because water above continental shelves is not that deep, sunlight is able to penetrate, helping plants grow. This, in turn, leads to a rich web of sea life. Most commercial fishing takes place in these waters. Extensive deposits of oil, natural gas, minerals, and other natural resources lie beneath continental shelves. The economic benefit of the fish and natural resources is important to many nations, which claim territorial ownership of the continental shelves adjacent to their land areas. Many political disagreements have arisen because of this. In spite of their desire to reap the benefits contained over and in the shelves, many nations illegally dump much of their waste in the ocean over these areas.

Forces and changes: Construction and destruction

The two types of continental margins, passive and active, tell about the geologic history of Earth and the activities that are continually affecting its surface. The continents are not stationary, but move about the planet's surface. That movement varies, but in general is extremely slow, only about 2 inches (5 centimeters) per year. Over millions of years, however, the continents have made their way along on an endless journey across the planet's surface, repeatedly crashing into or breaking away from one another.

The drifting continents

In 1915 German geophysicist Alfred Wegener (1880–1930) published a book in which he presented geological evidence that all the continents had once been joined together in a supercontinent he called Pangaea (pronounced pan-JEE-ah; from the Greek words meaning "all lands"). Wegener suggested that the Atlantic Ocean and the Indian Ocean formed when this supercontinent broke apart and the continents drifted away from each other. He called his hypothesis continental drift. (A hypothesis is an educated guess, while a theory is a principle supported by extensive scientific evidence and testing.)

Wegener formed his hypothesis after he had observed that the present-day continental margins along some of the continents seemed to fit together like pieces in a jigsaw puzzle: eastern South America with western Africa, eastern North America with western Europe, and India and Antarctica with eastern Africa. When the continents are linked, some of their geological features, such as mountain ranges and mineral deposits, also match. In addition, related species of land animals are often present on both side of the present-day oceans. Wegener argued further that if the continents had drifted, they would have passed through various climate zones. This explains how evidence of past glaciers could be found in the Sahara desert region and why fossil coral reefs appear north of the Arctic Circle.

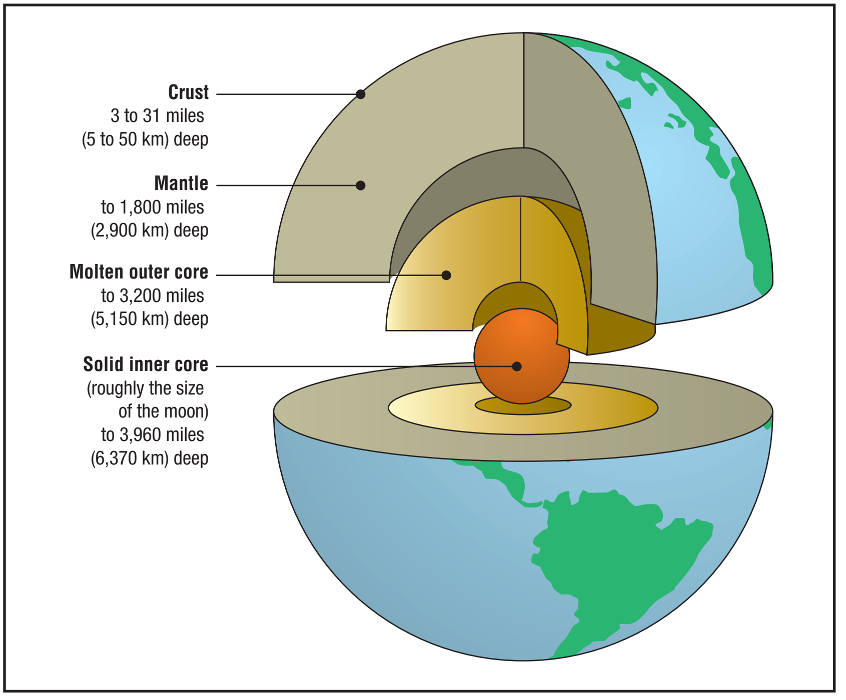
The theory of plate tectonics

What Wegener lacked, however, was a convincing explanation as to what moved the continents along the surface. Evidence to support his hypothesis did not come until the early 1960s when geologists developed the theory of plate tectonics (from the Greek word *tekton,* meaning "builder"). A revolutionary idea, it helps geologists and others understand how Earth has changed over long periods of time. Changes in the positions and features of the continents and oceans have had a profound effect on everything from global climate to the evolution of life.

Simply, the theory states that the surface of the planet is broken into sections—some large, some small—called tectonic plates. As these plates drift slowly over Earth, they slide past, collide with, and move away from each other. The boundaries where the plates meet and interact are called plate margins. What moves the plates along occurs within the planet.

Geologists divide Earth into three distinct layers: the crust, the mantle, and the core. Each layer has its own unique properties and composition. As already mentioned, the crust is the thin shell of rock that covers Earth. Two types of crust exist: continental crust, which underlies the continents, and oceanic crust, which underlies the oceans. Varying in thickness, the crust is thickest below land and thinnest below the oceans.

Underneath the crust is the mantle, which is separated into two layers: The uppermost part of the mantle is solid. Along with the overlying crust, it forms what is called the lithosphere (pronounced LITH-uh-sfeer). It is the brittle lithosphere that has broken into the tectonic plates. Under the lithosphere is the part of the mantle known as the asthenosphere (pronounced as-THEN-uh-sfeer). Beneath Earth's surface, temperature and pressure increase with increasing depths. Rock in the asthenosphere is hot



Cross-section of Earth's interior, with the solid inner core, molten outer core, mantle, and crust.

enough to fold, stretch, compress, and flow very slowly without fracturing. It is puttylike in its consistency, or what geologists call "plastic." The rigid tectonic plates "float" on the more dense, flowing asthenosphere.

The core, lying at the center of the planet, is divided into a liquid outer layer and a solid inner layer. Made up of the metallic elements iron and nickel, the core is almost five times as dense as rock on Earth's surface. Temperatures in the core are estimated to exceed 9,900°F (5,482°C), creating extreme heat energy.

Moving the plates

This heat energy moves the tectonic plates across the planet's surface. It is carried to the area beneath the plates by convection currents, which act similar to the currents produced in a pot of boiling liquid on a hot stove. When a liquid in a pot begins to boil, it turns over and over. Liquid heated at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense (lighter). Once at the surface, the heated material cools and becomes dense once more. It then sinks back down to the bottom to become reheated. This continuous motion of heated material rising, cooling, and sinking forms the circular convection currents.

Like a gigantic furnace, the core heats the mantle rock immediately above it. Expanding and becoming less dense, the heated rock slowly rises through cooler, denser mantle rock. When the heated rock reaches the lithosphere, it moves along its base, exerting dragging forces on the tectonic plates. This causes the plates to move. In the process, the heated rock begins to lose heat. Cooling and becoming denser, the rock then sinks back toward the core, where it will be heated once more. It takes an estimated 200 million years for heated mantle rock to make the circular trip from the core to the lithosphere and back again.

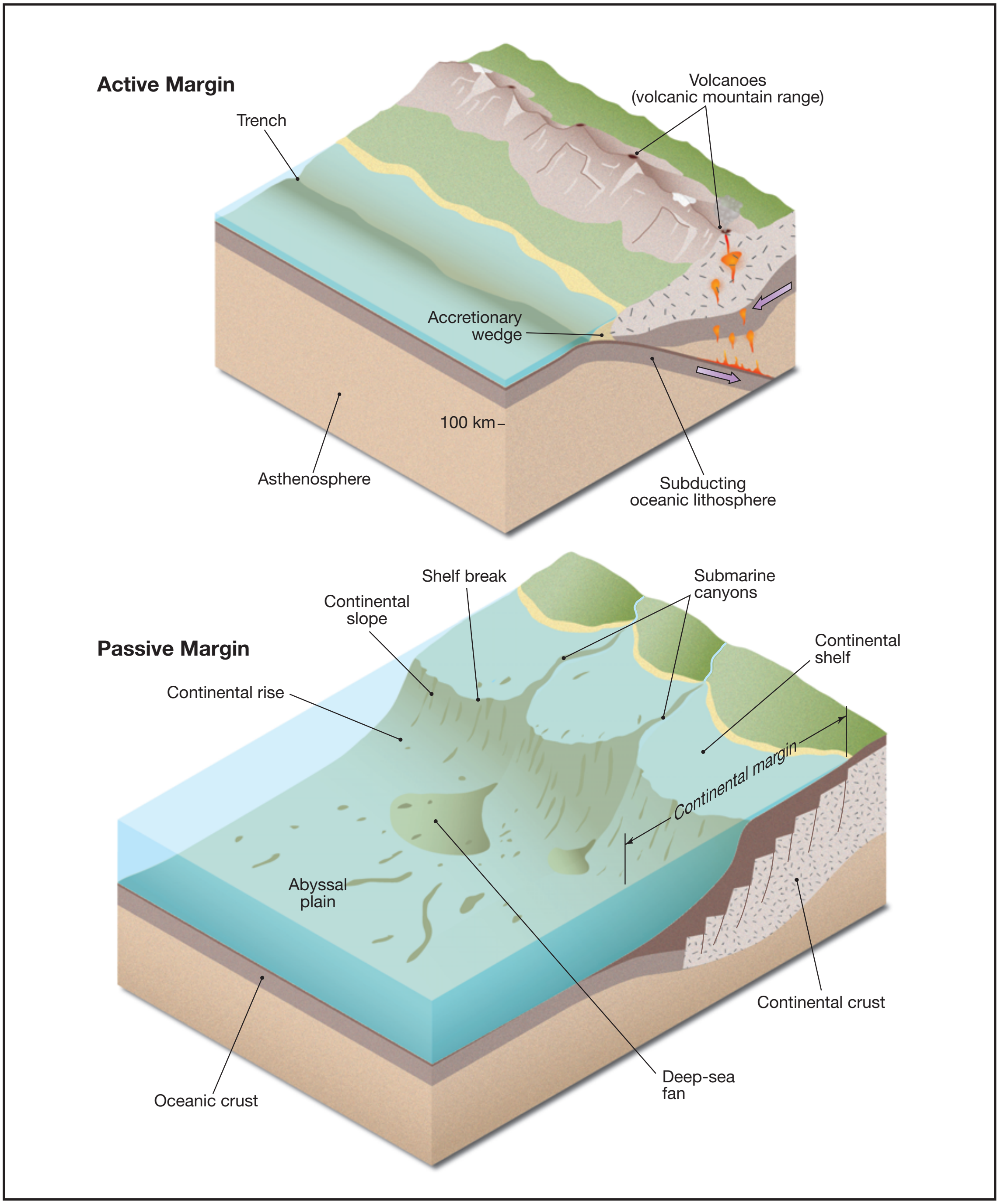
As the plates move, they interact in several different ways. Where they diverge, or move away from each other, new lithospheric rock is created as magma rises up through the crust at the plate boundary and gradually begins to cool. Many boundaries of diverging plates are on the floors of the oceans. They are known as mid-ocean ridges, and the process of new ocean crust forming at the ridges is known as seafloor spreading.

Where plates converge, or move into one another, either they crumple up and compress or one plate slides beneath the other. When two continental (land) plates converge, the crust bends and breaks from the collision, forming complex mountain ranges and very high plateaus. When a continental plate and an oceanic plate converge, the oceanic plate (which is thinner, yet denser) bends and plunges at an angle into the asthenosphere beneath the continental plate. As it does so, its leading edge begins to melt because of high temperature and pressure in the mantle. This forms thick, flowing magma (molten rock beneath the planet's surface). Less dense than the rock that surrounds it deep underground, the magma rises toward Earth's surface, forcing its way through weakened layers of rock. In most instances, the magma collects in underground reservoirs called magma chambers. It remains there until enough pressure builds up to eject it onto the planet's surface through vents called volcanoes. (For further information, see the **Volcano** chapter.) The process of one plate sinking beneath another is known as subduction, and the area where it occurs is known as a subduction zone.

At about 10 percent of the plate boundaries, the plates neither diverge nor converge; instead, they transform or slide past one another. On land, such a boundary is called a slip-strike boundary. A classic example of such a boundary is the San Andreas Fault system, an area of cracks in Earth's surface that occurs at the boundary between two tectonic plates, which extends down the coast of California.

Passive continental margins

The passive continental margins of eastern North America, eastern South America, western Africa, and western Europe began to form about 200 million years ago when Pangaea began to break up. The rift or crack that caused them to split, known as the Mid-Atlantic Ridge, now lies on



Two types of continental margins exist: active margins and passive margins. Active margins form primarily along the boundaries of plates that are actively converging. Passive margins currently exist in the middle of plates, not at plate boundaries.

the ocean floor. Tectonic activity continues along the rift, but seafloor spreading has moved the plates thousands of miles away from the Mid-Atlantic Ridge. Thus, the continental margins along these continents are considered tectonically quiet.

Although they are the "trailing edge" of the continents, passive continental margins currently exist in the middle of plates, not at plate boundaries. Erosion is the primary force acting on them, having continually deposited sediment from dry land since their formation. In places along passive margins in the Atlantic Ocean, the sediment measures more than 6 miles (10 kilometers) deep. Because they are built seaward by the sediment, passive margins may also be called "constructive" margins. They do not fill completely with sediment because the underlying crust subsides or sinks into the soft mantle, providing additional room for sediment to accumulate.

Active continental margins

Active continental margins form primarily along the boundaries of plates that are actively converging and where one plate is sinking beneath the other. Active margins mark the continents that border the Pacific Ocean where oceanic plates are subducting beneath continental plates. These areas are sites of tectonic activity, such as earthquakes and the formation of large volcanic mountains. Examples include the Andes Mountains along the western coast of South America. Coasts along active margins are typically lifted upward by the subduction of the oceanic plate, forming terraces and cliffs that are eroded by the ocean's waves. The seaside cliffs on the northwestern coast of North America are such an example.

The "leading edge" of a continental plate as it moves across Earth's surface, an active margin lacks a wide shelf. In fact, a shelf may not even exist. The margin's narrow slope may begin close to the coast, then angle steeply downward into a trench formed where the oceanic plate subducts beneath the continental plate. When the oceanic plate slips beneath the less dense plate, rock may be scraped from the oceanic plate. These scraps of oceanic crust accumulate with sediment to form what are called accretionary (pronounced ah-KREE-sha-nair-ee) wedges that build up on the landward side of the trench.

Spotlight on famous forms

Monterey Canyon, off the coast of California

The largest submarine canyon on the west coast of the United States lies in Monterey Bay just south of San Francisco, California. First discovered in 1857 and labeled a submarine gulch, Monterey Canyon rivals the Grand Canyon in size and complexity. Almost perfectly bisecting the floor of the bay, the canyon begins just off the shore in 30 feet (9 meters) of water. It then extends 60 miles (97 kilometers) out into the ocean, widening while dropping to a depth 2 miles (3 kilometers) beneath the surface.

The steep walls of the canyon are lined with cliffs, ridges, crevices, and sediment-covered shelves. The canyon contains several smaller side canyons. Where it meets the ocean floor, the canyon opens and the sediment that has washed down through it spills out into a fan. Over its life, the canyon has been filled and refilled with sediment that has helped scour and erode the canyon's walls.

Geologists believe the canyon formed 25 to 30 million years ago. The reason behind its formation is still debated. Some believe that the powerful outflow of an ancient river from the southern end of the present-day San Joaquin Valley carved the canyon when the river flowed through a gap in the mountains and into the bay. Since that time, the bay and the surrounding land has slowly moved northward along the San Andreas Fault to its present location. Other geologists believe an ancient earthquake opened a crack that was widened through the erosive force of turbidity currents to become the present-day canyon.

For More Information

Web Sites

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Coastal Processes and the Continental Margins. http://www.ocean.washington.edu/education/magic/Ipage/happened/2/coastal.htm (accessed on June 30, 2003).

"Ocean Regions: Ocean Floor-Continental Margin and Rise." *Office of Naval Research*. http://www.onr.navy.mil/focus/ocean/regions/oceanfloor2.htm (accessed on June 30, 2003).

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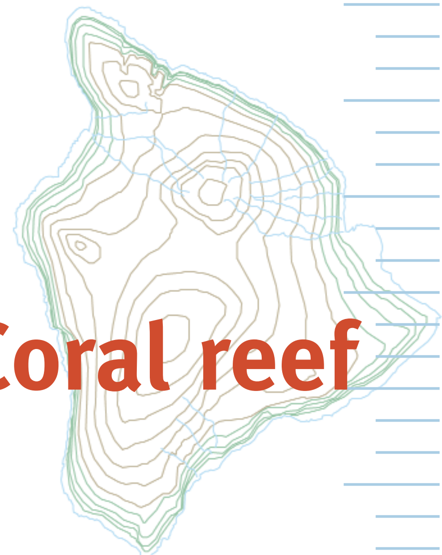


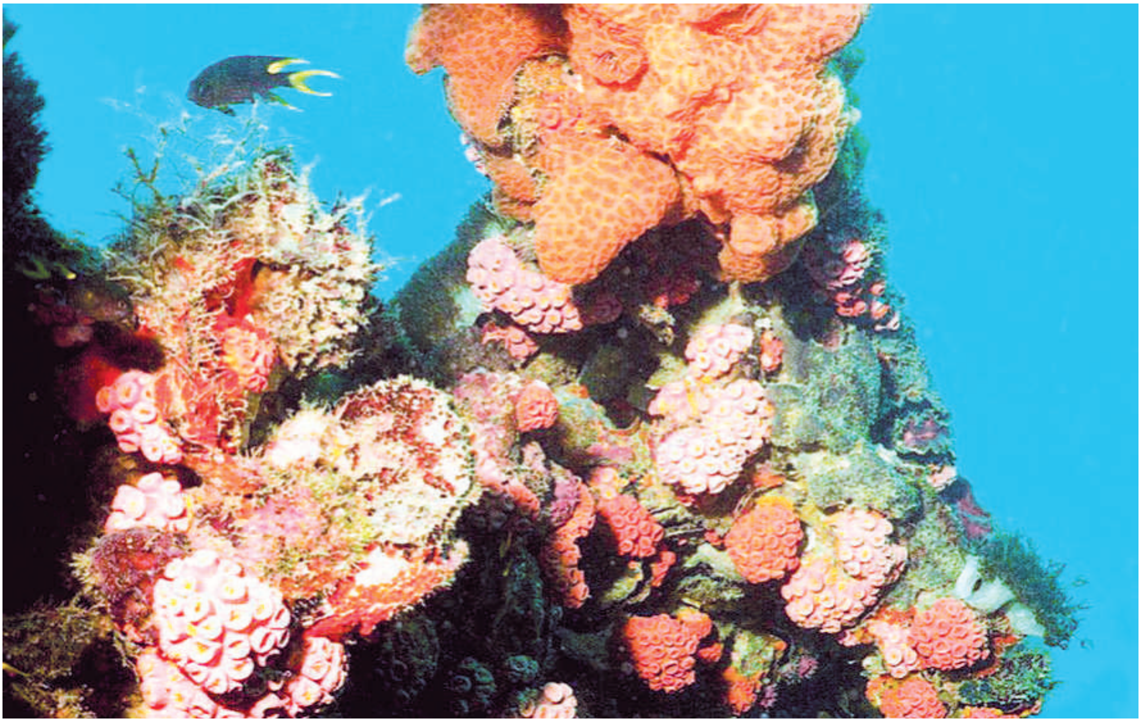
Coral reef

Coral reefs are not only spectacular marine environments, but they are one of the oldest ecosystems (community of plants and animals interacting with their environment) on Earth. They are created by colonies of organisms called coral polyps (pronounced PAH-lips). Among biological organisms, only humans have the ability to alter the surface of the planet more than these tiny marine creatures. Over thousands to millions of years, they may form massive structures of limestone that alter the shoreline of continents.

Although coral reefs cover 0.2 percent of the total area of the oceans, they are critically important for a diversity of marine species. They provide a habitat for at least 25 percent of all marine animals, including sponges, more than 4,000 different species of fish, anemones, sea stars, crabs and other crustaceans, and clams and other mollusks. Home to so many different species, coral reefs are often referred to as the "rainforests of the oceans." They also provide physical barriers to the force of strong waves, protecting beaches, lagoons, and other coastal features lying behind them. Yet they are highly vulnerable to pollution, an increase in water temperature, and damage from tourism and coastal development. By the early twenty-first century, these threats had already claimed more than one-quarter of the world's coral.

The shape of the land

A coral reef is a wave-resistant limestone structure produced by living organisms, found principally in shallow, tropical marine waters. Limestone is a type of rock composed primarily of the mineral calcite, which is a crystalline form of calcium carbonate ($CaCO_3$). Thousands of species inhabit coral reefs, but only a fraction produce the calcium carbonate that crystallizes into the limestone that forms the reef.



Coral reefs are one of the oldest ecosystems on the planet. They provide a habitat for more than 4,000 marine animals and are often referred to as the "rainforests of the oceans." PHOTOGRAPH REPRODUCED BY PERMISSION OF AP/WIDE WORLD PHOTOS.

Coral polyps are the most important reef-building organism. The species that secrete calcium carbonate are known as hard coral polyps or, simply, stony corals. In the western Pacific Ocean, more than three hundred species of stony corals exist. Coral polyps are invertebrates (pronounced in-VER-tuh-brets), or animals without backbones. They are related to anemones and jellyfish. In fact, a coral polyp looks similar to an anemone: it is a jellylike sac attached at one end to its skeleton. The open end, the mouth, is fringed with six stinging tentacles (or a multiple of six), which the polyp extends at night to feed. The size of coral polyps varies greatly, depending on the species. They may be as small as 0.04 inch (0.1 centimeter) in diameter or as large as 8 inches (20 centimeters) in diameter.

Worldwide, coral reefs cover an estimated 110,000 square miles (284,900 square kilometers). Many stony corals grow best in clear, salty water with a temperature between 70°F and 85°F (21°C and 29°C). Because of this, most reefs are found in the Pacific Ocean, the Caribbean Sea, the Red Sea, the Arabian Sea, and the Indian Ocean between the tropic of Cancer and the tropic of Capricorn, two parallel lines of latitude lying one-quarter of the way from the equator to the North and South Poles, respectively. Reefs are also found around

Words to Know

Atoll: A ring-shaped collection of coral reefs that nearly or entirely encloses a lagoon.

Back reef: The landward side of a reef between the reefcrest and the land.

Barrier reef: A long, narrow ridge of coral relatively near and parallel to a shoreline, separated from it by a lagoon.

Coral polyp: A small, invertebrate marine animal with tentacles that lives within a hard, cuplike skeleton that it secretes around itself.

Ecosystem: A system formed by the interaction of a community of plants, animals, and microorganisms with their environment.

Fore reef: The seaward edge of a reef that is fairly steep and slopes down to deeper water.

Fringing reef: A coral reef formed close to a shoreline.

Invertebrates: Animals without backbones.

Lagoon: A quiet, shallow stretch of water separated from the open sea by an offshore reef or other type of landform.

Limestone: A sedimentary rock composed primarily of the mineral calcite (calcium carbonate).

Photosynthesis: The process by which plants use energy from sunlight to change water and carbon dioxide into sugars and starches.

Reef crest: The high point of a coral reef that is almost always exposed at low tide.

Symbiosis: The close, long-term association between two organisms of different species, which may or may not be beneficial for both organisms.

Zooxanthellae: Microscopic algae that live symbiotically within the cells of some marine invertebrates, especially coral.

Florida and southern Japan because warm-water currents flow into these areas from the Tropics.

The shape of a coral reef depends on the species of coral building it. Different types of coral produce different shapes. Some are pointed and hard; others are round and soft. They may be robust or delicate. Various shapes in reefs include fingerlike branches, flat branches, knobs or wedges, boulders or balls, mushroom caps, and tablelike structures.

Most coral reefs are brightly colored, but that color does not come from the coral polyps themselves. In fact, the bodies of the tiny creatures are clear. The calcium carbonate they produce to form their external skeleton is white, much like the bones of a human skeleton. Reef colors come from the microscopic, single-celled algae called zooxanthellae (pronounced zoe-ah-zan-THEL-ee) that live in the tissue of the coral. Zooxanthellae and coral polyps have what is termed a symbiotic (pronounced sim-bee-AH-tik) relationship. Symbiosis is the close, long-term association between two organisms of different species, which may or may not be beneficial for both organisms. In the case of the zooxanthellae and coral polyps, the relationship benefits both. The algae provide the coral polyps with more than 90 percent of their nutrients, and the coral polyps provide the algae with essential minerals and a protected habitat. Their unique relationship allows coral reefs to exist and grow year after year.

Coral reefs are generally divided into three classes: fringing reefs, barrier reefs, and atolls (pronounced A-toles). The simplest and most common type of coral reef, fringing reefs, form close to the shoreline of islands and continents. A shallow lagoon, a quiet stretch of water separated from the open sea, may or may not lie between the shoreline and the fringing reef. Barrier reefs also form parallel to the shoreline of an island or a continent, but farther away than fringing reefs. In addition, they are larger and may stretch for great distances. Wide, deep lagoons often separate barrier reefs from the shoreline. Atolls are ring-shaped coral reefs that enclose or nearly enclose a deep lagoon. They are typically found around islands that have sunk beneath sea level in the deep ocean. These islands are often the tops of underwater volcanoes. On the lagoon side of atolls, sediment from broken coral may collect and partially fill the lagoon, allowing vegetation to grow. Eventually, the entire lagoon may be filled in, forming an island that may become inhabited. Atolls such as this are common in the Indian and Pacific oceans.

Forces and changes: Construction and destruction

Geologists have discovered that ancient corals existed on Earth as long ago as 400 million years. Present-day stony corals evolved over the last 25 million years. Most established coral reefs are between 5,000 and 10,000 years old. Although they are the largest structures of biological origin on the planet and represent thousands of years of history, coral reefs are extremely delicate. Their formation takes place only under certain conditions.

Corals reproduce two ways. They may do so sexually by releasing eggs and sperm. Once fertilized, the eggs produce multitudes of free-swimming larvae (pronounced LAR-vee; immature forms of the coral polyps) that ocean currents carry great distances. After settling on a suitable hard surface, the larvae secrete their own calcium carbonate cups and grow into mature corals, thus forming a new colony and a new reef. Corals may also reproduce asexually by budding or forming new coral polyps attached to themselves by thin sheets of tissue and skeletal material. Through budding, a single coral polyp can develop over time into a massive coral head.

The hard, cuplike skeleton that a coral secretes around itself from its lower portion consists of clusters of calcium carbonate, one of the most common minerals on Earth. In order to produce calcium carbonate, stony corals need the assistance of zooxanthellae, which live within cells in the lining of a coral polyp's gut. A polyp not only provides the zooxanthellae

Like other atolls, Kayangel atoll in the western Pacific Ocean is a ring-shaped coral reef that encloses a deep lagoon. Atolls are common in the Indian and Pacific oceans. PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS.

with a protected environment but with carbon dioxide and nutrients that the polyp gives off as waste products. In return, the zooxanthellae use the carbon dioxide to provide the coral polyp with nutrients, including glucose (sugar) and amino acids, through photosynthesis (pronounced foe-toe-SIN-thih-sis). Photosynthesis is the process by which plants use energy from sunlight to change water and carbon dioxide into sugars and starches. The polyp uses the compounds supplied by the zooxanthellae to create proteins, fats, carbohydrates, and calcium carbonate.

Sunlight and clear water

Since zooxanthellae need sunlight in order to photosynthesize, corals flourish in waters less than 230 feet (70 meters) deep. Maximum growth rates occur when the coral is in water less than 60 feet (18 meters) deep. Corals may grow at deeper depths, sometimes up to 300 feet (91 meters), but their ability to produce calcium carbonate is greatly reduced. As a result, they grow poorly. The growth rate of corals is also reduced if the water is murky and sunlight is not able to penetrate. Water temperature and the amount of salt in the water also affect growth rate. Corals may grow in water slightly below 70°F (21°C) and slightly above 85°F (29°C), but that growth is very slow. Stony corals also prefer waters where the salt concentration ranges between 32 and 42 parts per thousand. The concentration of oxygen in the water must also remain high.

When optimum conditions are present, corals may grow as much as 1.7 inches (4.5 centimeters) per year. Different species grow at different rates. In general, the larger the coral, the slower the growth. Very large corals may grow only 0.2 to 0.8 inch (0.5 to 2 centimeters) per year. Branching corals may grow much faster, up to 8 inches (20 centimeters) per year. Because of their fast growth rate and their treelike structure, branching corals are prone to damage from strong storm waves, which may break off their branching limbs. Large, dense corals are much more stable and less prone to damage from wave action.

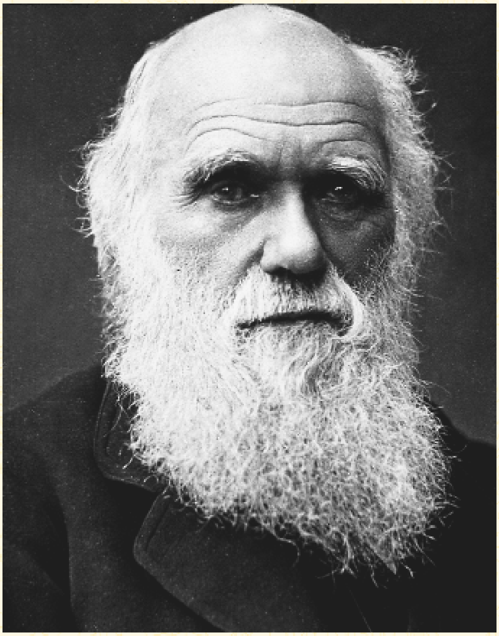
While a coral polyp is alive, it periodically rises up in its cuplike skeleton and secretes more calcium carbonate to form a new base or floor. In this way, the polyp enlarges its skeleton, creating chambers underneath its base. When a polyp dies, its skeleton remains, becoming the foundation on which a new polyp attaches and builds its skeleton. Coral reefs are composed of layer upon layer of polyp skeletons, sometimes numbering in the billions. Only the thin, top layer contains living coral polyps.

Other creatures add to the complex structure of a coral reef. A type of red algae known as coralline algae contribute to the framework of reefs by secreting their own encrusting skeleton that helps cement loose sediment on the reef. Other organisms that contribute reef sediments include sponges, clams, and snails. These marine creatures live in the holes and crevices of the reef. When they die, their remains provide a foundation for new coral polyps.

Reef structure and forms

Coral reefs remain underwater except when water levels periodically decrease, such as at low tides. At this time, only the highest part of the coral reef, the reef crest, is exposed, washed over by waves. Coral polyps that exist and grow on this section of a reef must be able to tolerate the Sun's heat and wave action. In order to do so, they generally grow in platelike, stubby branching or massive structures. The upper surface is often encrusted with coralline algae.

Corals that exist on the reef seaward from the reef crest are diverse and show the greatest range of forms. In areas where wave energy is still high, massive corals are predominant. As the reef angles deeper and deeper beneath the water's surface, delicate branching corals take over. The outermost seaward slope is called the fore reef. It may angle down to



Darwin and Atoll Formation

While traveling aboard the *H.M.S. Beagle* in the mid-1830s, English naturalist Charles Darwin (1809–1882) devised the modern theory of coral atoll formation. Although widely known for his theory of evolution by natural selection, Darwin made many contributions to the science of geology. His theory of coral reefs is his best-known.

Darwin proposed that fringing reefs, barrier reefs, and atolls represented a series through geologic time. He held that the transition from fringing reef to barrier reef to atoll could result from the upward growth of coral on the edge of a gradually sinking volcano. He believed that barrier reefs represented a middle stage between fringing reefs and atolls, and that the ringlike appearance of an atoll with a central lagoon resulted from the total submergence of the summit of a volcano.

In the 1950s, scientists from the U.S. Geological Survey, an earth science research and information agency, undertook extensive drilling programs on atolls in the Pacific Ocean. Hundreds of feet down, they encountered volcanic rock, proving Darwin's theory that atolls are perched over ancient submerged volcanoes.

Charles Darwin. **PHOTOGRAPH REPRODUCED BY PERMISSION OF GETTY IMAGES.**

the sea bottom by as much as 30 degrees. The fore reef consists of limestone boulders, coral branches, and smaller sediments. It may have deep channels cut into it, forming fingerlike structures that extend seaward from the reef. These help stabilize the reef and cut down the force of incoming strong waves.

The area lying landward of the reef crest is known as the back reef. Sand and other fine-grained sediment often inhibit reef growth in this area, so various other marine organisms dominate. However, scattered stubby, branching, or low knobby corals may develop in water as shallow as 3 feet (1 meter). Beyond the back reef, the water begins to deepen again, to as

Cold-water Corals

Most well-known corals exist in tropical coral reefs, but reef-forming corals also exist in deep, cold water. Known as *Lophelia,* these corals lack zooxanthellae, so they do not depend on sunlight for survival. Instead, they feed by capturing food particles with their tentacles from the surrounding water. They are found at depths ranging from 230 to 3,280 feet (70 to 1,000 meters). These types of corals grow slower than their warm-water relatives, averaging 0.04 inch (0.1 centimeter) per year.

The largest known *Lophelia* coral reef is found off central Norway at a depth of about 1,312 feet (400 meters). It measures almost 9 miles (14 kilometers) in length and 2 miles (3 kilometers) in width. It stands almost 98 feet (30 meters) in height.

Cold-water corals are found throughout the western Atlantic Ocean from Nova Scotia to Brazil. They are also found in the eastern Atlantic, the Mediterranean Sea, the Indian Ocean, and eastern Pacific Ocean. Like warm-water reefs, *Lophelia* coral reefs support very rich communities of fish, shrimps, and other invertebrates.

much as 100 feet (30 meters) or more, within the lagoon. Protected from the full force of waves, the lagoon floor is smooth and fine-grained.

While fringing and barrier reefs are common on the submerged portions of continents, atolls are not. Atolls formed in the deep ocean around submerged submarine volcanoes. They began to grow as a small fringing reef around the shoreline of a volcanic island. Once the volcano had become extinct, the sea floor beneath it may have begun to subside or sink under the weight of the volcano. As the island slowly submerged over millions of years, the corals continued to grow upward to the surface of the water, keeping pace with the rate the island was sinking. The sides of some atolls reach depths as great as 1,500 feet (457 meters). Eventually, as the island slipped beneath the ocean's surface, a ring of coral reefs remained, surrounding a central lagoon.

Some atolls formed when sea levels rose, submerging the tops of islands. The rise and fall of the sea level over the past few million years has been caused by changes in the volume of water tied up in land glaciers and ice sheets during the ice ages. When ice sheets grew in the Northern Hemisphere, the sea level dropped and coral reefs such as atolls were stranded above the waterline. Since present-day water levels have not risen to what they were before the last ice age, which ended approximately 10,000 years ago, the tops of many atolls have remained exposed.

Reef damage

While coral reefs may be damaged by natural forces such as storms and hurricanes, they suffer the severest damage from human activity. Reefs are often destroyed by collectors who use coral to create jewelry and by fisherman who use poison or dynamite to catch fish around coral reefs. Because corals need sunlight and sediment-free water to survive, water pollution poses a grave danger. Oil spills, the dumping of sewage wastes, and the runoff of soil and agricultural chemicals such as pesticides all threaten the delicately balanced ecosystem of coral reefs.

Global warming, an increase in the world's temperatures, is the biggest threat facing coral reefs. It is thought to be caused, in part, by the burning of fossil fuels and the depletion of the ozone layer, both brought about through human activities. Scientists believe a warming of water temperature, by even just a few degrees, can cause coral polyps to expel the zooxanthellae living inside them. This results in coral bleaching, which is the whitening of coral colonies due to the loss of the zooxanthellae. The end result is death of the coral. While pollution and changes in the salt content of the water can also bring about coral bleaching, warmer sea temperatures seem to be the biggest culprit. Natural occurrences, such as El Niño (the irregular periods during which the normally cold waters off the coast of Peru are made warmer by the arrival of warm waters from the equatorial region), have been blamed for some coral bleaching. However, these events are short-lived. Global warming is not.

Spotlight on famous forms

Great Barrier Reef, off the northeastern coast of Australia

The Great Barrier Reef, situated off Queensland state in Australia's northeast, is the largest structure on the planet created by living organisms. Approximately 1,250 miles (2,011 kilometers) in length, the coral reef consists of more than 2,800 individual detached reefs, separated by deep channels. It is separated from the Australian shoreline by a shallow lagoon that varies from 10 to 100 miles (16 to 161 kilometers) in width. At its widest, the reef measures 45 miles (72 kilometers) across. It covers roughly 80,000 square miles (207,200 square kilometers), an area approximately as large as the state of Kansas. The reef can be seen from space and was first mapped by *Apollo 7* astronauts in 1968.

Geological evidence shows the reef began growing more than 25 million years ago. Its age and size are due to the very stable geological setting of the area off the Australian continent and the favorable circulation of oceanic water. Winds in the area help stir the water, keeping it a relatively constant warm temperature regardless of depth.

The Great Barrier Reef covers roughly 80,000 square miles, an area approximately as large as the state of Kansas. It is the largest structure created by living organisms. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

The reef is home to millions of living creatures. More than 350 species of stony corals make up the reef. Countless other organisms inhabit the area, including more than 1,500 species of fish, 4,000 species of mollusks, 200 species of birds, as well as varieties of dolphins, whales, green turtles, and dugongs or "seacows."

The Great Barrier Reef is a major tourist destination, attracting more than 2 million tourists each year. To prevent the reef's destruction, the Australian government established the Great Barrier Marine Park in 1975. Encompassing most of the reef, the park is the world's largest protected marine area. Despite this protection, the reef is still endangered by rising sea temperatures and human activity. In 2003, the Australian government sought to ban commercial and recreational fishing from more than 30 percent of the reef.

Kiritimati, Pacific Ocean

With a total area of 222 square miles (575 square kilometers), Kiritimati is the largest coral atoll in the world. It encloses a large lagoon, which accounts for almost half of its area, and more than 100 lakes or ponds. Lying 145 miles (233 kilometers) north of the equator, it is part of the Republic of Kiribati, composed of 33 islands scattered across 2,400 miles (3,860 kilometers) of the Pacific Ocean. In the local language, "ti" is pronounced "s," so Kiritimati is pronounced ki-RIS-mas.

English explorer and navigator James Cook (1728–1779) landed on the atoll in 1777. Because the day of his arrival was Christmas Eve, Cook named the atoll Christmas Island (not to be confused with the Australian-administered Christmas Island that lies in the eastern Indian Ocean south of Java). More than a century later, England claimed the atoll as part of the Gilbert and Ellice Islands colony, extending its rule over it. In the late 1950s and early 1960s, England and the United States conducted nuclear tests on the atoll. In 1979, the Republic of Kiritabi was granted full independence.

Despite the fact that some areas of Kiritimati still remain barren as a result of nuclear tests, the atoll boasts much wildlife. It is particularly important as a seabird-nesting site: an estimated six million birds use or breed on the atoll. In 1975, Kiritimati was declared a wildlife sanctuary.

Maldives, Indian Ocean

The Maldives is an archipelago (pronounced ar-keh-PELL-ah-go; a group or chain of islands) of almost 1,200 coral islands in the Indian Ocean, located about 420 miles (675 kilometers) southwest of Sri Lanka. The archipelago is 511 miles (823 kilometers) long and 81 miles (130 kilometers) at its greatest width. The total area including land and sea is approximately 34,750 square miles (90,000 square kilometers). About 2 percent of this is land.

Many of the islands are small, level, and low-lying, often no more than 6.5 feet (2 meters) above sea level. Some are gradually washing away into the ocean, while others are in the process of formation and are constantly growing in size. The island of Malé, location of the capital city, is the most densely populated and developed. It is 1.2 miles (2 kilometers) long and just over 0.5 mile (0.8 kilometer) wide.

The islands are formed from the growth of coral over a long-submerged volcanic mountain range. A protective fringing coral reef surrounds each island, some of which have freshwater lagoons. These are true coral islands: there is no trace of yellow or black coloring in the sandy coral beaches, as there is on other beaches around the world. Because the soil on the islands is completely coral-based, it is poor in nutrients and thick jungles do not grow. The coconut palm is the most common tree, and it grows densely on many of the islands. There are no hills, mountains, or rivers on any of the islands.

The Maldives is an archipelago of almost 1,200 coral islands in the Indian Ocean. The islands are formed from the growth of coral over a long-submerged volcanic mountain range. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

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Delta

Deltas have long played an important role in human history. These fertile areas where rivers flow into large bodies of water have served as fishing, farming, and living sites. Of the great deltas around the world, perhaps none has had a greater role in civilization than the delta of Egypt's Nile River. Greek historian Herodotus (c. 484–c. 425 B.C.E.), considered by many as the "Father of History," studied this great geologic feature. He is credited with coining the term "delta" for this type of landform because its triangular shape reminded him of the Greek letter Δ (delta).

The shape of the land

A delta is a body of sediment deposited at the mouth of a river or stream where it enters an ocean or lake. Unlike other landforms affected by running water, a delta is not created primarily by water cutting into or eroding the landscape (erosion is the gradual wearing away of Earth surfaces through the action of wind and water). Water does not tear down a delta; instead, it builds up a delta.

A river creates a delta by laying down sediment or rock debris such as gravel, sand, silt, and clay that it has picked up and carried along its course. Alluvium (pronounced ah-LOO-vee-em) is the general term for sediment deposited by running water. A river's depth, its width, and its speed determine how much sediment it can carry. The Mississippi River flows at an average surface speed of about 2 miles (3 kilometers) per hour. Yet it drains between 1.2 and 1.8 million square miles (3.1 and 4.6 million square kilometers), which is more than 40 percent of the total area of the continental United States. Over the course of a year, it moves an average of 159 million tons (144 million metric tons) of sediment.

In general, deltas are similar in shape to another type of landform deposited by flowing water, alluvial (pronounced ah-LOO-vee-al) fans.

A river creates a delta, like that of the Colorado River, seen here, by laying down sediment or rock debris that it has picked up and carried along its course. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Found typically in desert and other arid (dry) environments, these fanlike deposits of sediment form where an intermittent, yet rapidly flowing canyon or mountain stream spills out onto a plain or relatively flat valley. An alluvial fan is a landform that forms on land. A delta is a landform that forms in water. (For further information on alluvial fans, see the **Dune and other desert features** chapter.)

Words to Know

Alluvial fan: A fanlike deposit of sediment that forms where an intermittent, yet rapidly flowing canyon or mountain stream spills out onto a plain or relatively flat valley.

Alluvium: A general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Bed load: The coarse sediment rolled along the bottom of a river or stream.

Bottomset bed: A fine, horizontal layer of clay and silt deposited beyond the edge of a delta.

Dissolved load: Dissolved substances, the result of the chemical weathering of rock, that are carried along in a river or stream.

Distributaries: The channels that branch off of the main river in a delta, carrying water and sediment to the delta's edges.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Foreset bed: An inclined layer of sand and gravel deposited along the edge of a delta.

Suspended load: The fine-grained sediment that is suspended in the flow of water in a river or stream.

Topset bed: A horizontal layer of coarse sand and gravel deposited on top of a delta.

A delta may be divided into three main zones: upper delta plain, lower delta plain, and subaqueous (pronounced sub-AY-kwee-us) delta plain. The upper delta plain is that part of the delta that is farthest inland. It lies above the high tide mark and is not affected by the action of waves or tides. (Tide is the periodic rising and falling of water in oceans and other large bodies of water in response to the gravitational attraction of the Moon and the Sun upon Earth.) The river or stream that forms the delta begins to divide in the upper delta plain into smaller channels called distributaries, which carry sediments toward the delta's edges. Immediately seaward of the upper delta plain is the lower delta plain. It occupies the area between high and low tides and, thus, periodically lies underwater. The landscape is affected by the action of distributaries, tides, and waves. Finally, the subaqueous delta plain is that part of the delta that lies below the low tide mark and, as a result, lies completely underwater.

The tug of war between land and water determines a delta's shape. It is a battle that pits the strength of a river's flow and the amount of sediment it carries against wave and tidal currents. Deltas build outward from a coast only if the slope from the shore is gentle and ocean currents are not strong enough to carry away the sediment deposited by the river. The three main varieties of deltas based on shape are the arcuate (pronounced AR-cue-et), the bird's foot, and the cuspate (pronounced KUSS-pate).

Arcuate deltas are the commonest form of delta. They are fan-shaped, with the wide portion of the fan farthest from the mainland. Crossed by many short, well-defined distributaries, these types of deltas are composed of relatively coarse sediments. Wave and river activity are fairly well balanced. The seaward edge of the delta is rather smooth because strong waves push the sediment back against that edge. The Nile Delta is an example of an arcuate delta.

Where the action of waves is weak and that of a river is strong, an irregular-shaped delta forms that extends out into the water well beyond the local shoreline. Resembling the spread claws of a bird's foot, this type of delta is called a bird's foot delta. Fine sediments and shifting distributaries mark this river-dominated delta. Bird's foot deltas are not common along ocean coasts because the action of ocean currents and waves is often as strong if not stronger than that of rivers. The Mississippi Delta, on the Gulf of Mexico, is a bird's foot delta.

Cuspate deltas form where a river drops sediment onto a straight shoreline with strong waves that hit head-on. The waves force the sediment to spread outwards in both directions from the river's mouth, making a pointed tooth shape with sides that curve inward. Few distributaries are found in cuspate deltas. The Tiber Delta in Italy is a classic example.

Forces and changes: Construction and destruction

Deltas are found throughout the world, except at the poles. Most of the world's great rivers—the Amazon, the Ganges-Brahmaputra, the Huang He, the Mississippi, the Nile—have built massive deltas. All have a few characteristics in common: they drain large land areas, they carry large quantities of sediment, and they empty at coasts that are geologically quiet (no earthquake or volcanic activity).

Deltas are geologically young landforms. Present-day deltas began forming no more than 7,000 years ago, when sea levels stopped rising after the last ice age ended. Over Earth's history, as sea levels have risen and fallen in response to glacial periods, deltas have formed and have been covered over. The current deltas of some rivers are built on the remains of numerous deltas stretching back millions of years. Yet their surface can change rapidly and significantly. The key to the creation of a delta, and its continual formation, is a river and the sediment it transports.

Running water

Water is a natural force of erosion everywhere on Earth. As it surges over a landscape, water picks up and transports as much material from the surface as it can carry. Gravity and steep slopes aid rushing water in carrying increasingly larger and heavier objects. Erosion by water begins as soon as raindrops hit the ground and loosen small particles. During heavy rains, sheets of water flow over the ground, loosening and picking up even

Largest Delta Areas

River	Location	Size of Delta Area
Ganges-Brahmaputra	Bangladesh/India	40,790 square miles (105,645 square kilometers)
Mekong	Southeast Asia	36,209 square miles (93,781 square kilometers)
Lena	Russia	16,820 square miles (43,563 square kilometers)
Huang He	China	14,005 square miles (36,272 square kilometers)
Mississippi	United States	13,000 square miles (33,670 square kilometers)
Indus	Pakistan	11,400 square miles (29,524 square kilometers)
Volga	Russia	10,511 square miles (27,224 square kilometers)
Niger	Western Africa	7,388 square miles (19,135 square kilometers)
Tigris-Euphrates	Southwest Asia	7,142 square miles (18,497 square kilometers)

more particles. This water quickly concentrates into channels, which then become streams that flow into rivers.

The amount and size of the material that a river can transport depends on the velocity, or speed, of the river. A fast-moving river carries more sediment and larger material than a slow-moving one. A river that is turbulent or agitated can also lift and carry more rocks and sediment than one that flows gently.

The sediment load in a river consists mainly of two parts. The first part is the coarse material that moves along the bed or bottom of the river. This is known as the bed load. As it is carried along, this coarse sediment acts as an abrasive, scouring and eating away at the banks and bed of the river. The river then picks up any newly loosened and eroded material. The second part is the fine-grained material that is suspended in the flow of water as the river moves downstream. This is the suspended load. Rivers also carry a dissolved load. These dissolved substances are the result of the chemical weathering of rock, which alters the internal structure of minerals by removing or adding elements.

A river will continue to carry its load as long as its velocity remains constant or increases (if it increases, it can carry an even larger load). Any change in the geography of the landscape that causes a river channel to bend or rise will slow the flow of water in a river. As soon as a river's speed decreases, it loses the ability to carry all of its load and a portion will be deposited, depending on how much the river slows down. Particles will be deposited by size with the largest settling out first.

Laying it down in a delta

When a river meets the standing water of an ocean at a coast, it quickly loses velocity and the heaviest particles drop out. The fine

The Greatest Sediment Load

The Huang He is the second longest river in China. It begins in the highlands of Tibet and flows eastward for 3,000 miles (4,830 kilometers) before it empties into Bohai Bay. Along its course, it drains more than 290,000 square miles (751,100 square kilometers) of land area. It is the muddiest river in the world, carrying more sediment than any other. Each year, it transports an estimated 1.6 billion tons (1.45 billion metric tons) of sediment. Because that sediment colors the water of the river yellow, the river is also known as the "Yellow River." Much of that sediment is deposited in a delta that has formed at the mouth of the Huang He. It increases in size by as much as 20 square miles (50 square kilometers) each year.

suspended load may be carried farther out into the water before it settles out and sinks to the bottom. Sediments deposited in a delta are laid down in layers known as beds. Bottomset beds are those nearly horizontal or flat layers of fine clay and silt that form underwater farthest from the mouth of the river. Closer to the mouth, yet still underwater, are foreset beds of sand and gravel that slope steeply down toward the bottomset beds at an angle up to 25 degrees. Thin, horizontal layers of coarser sand and gravel that are deposited on the surface of the delta are topset beds. As a delta increases in size and advances farther out into the water, the topset beds cover the foreset beds, which in turn cover the bottomset beds.

As more sediments are brought by the river to the delta, especially in times of flooding, the main river may become choked with sediment. When this occurs, the river branches into distributaries, finding the least resistant path to the shoreline. When sandy deposits block the distributaries, they then become inactive, and smaller, active distributaries branch off. As the process continues, distributaries constantly shift position across the surface of the delta.

A delta is often a patchwork of marshes, swamps, lakes, and tidal flats (muddy or marshy areas that are covered and uncovered by the rising and falling tides). During the normal flow of the main river in a delta, all the water is guided out to the ocean by the active distributaries. Sediment is deposited in these channels and immediately offshore to them. The areas between the channels receive no sediment. In times of flood, water flows out of the distributaries over the delta surface, depositing sediment. Coarse sandy particles are deposited first, producing low ridges or embankments along the banks of the distributaries. These are known as natural levees (pronounced LEH-veez).

The Ganges River Delta is the largest in the world, covering an area of roughly 40,790 square miles. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

When the balance between a river and ocean is shifted, the delta will either enlarge or decrease in size. If waves and currents are not strong enough to carry most of the sediments away, those sediments will collect over time to form landmasses laced with distributaries that extend a delta farther and farther out to sea. Floods and periods of heavy rain bring more sediment to a delta, building it up. Periods of drought, however, have the opposite effect. Human activity may also affect the size of a delta. If forests or similar types of land upstream are cleared, increased erosion may occur, sending more sediment downstream to build up a delta. If a dam is built on or water is otherwise diverted from a river, the velocity of the river and the amount of sediment it can carry will decrease. Consequently, the delta at its mouth will shrink.

Spotlight on famous forms

Ganges River Delta, Bangladesh and India

The combined Ganges and Brahmaputra Rivers have formed the largest delta in the world, the Ganges River Delta (sometimes called the Ganges-Brahmaputra Delta). Approximately 220 miles (345 kilometers) wide, the delta covers an area of roughly 40,790 square miles (105,645 square kilometers). Almost 1.1 billion tons (1 billion metric tons) of sediment is discharged from these rivers annually. This has produced the Bengal Fan, a deposit of sediment on the floor of the Bay of Bengal that stretches outward 1,865 miles (3,000 kilometers) in length and 620 miles (1,000 kilometers) in width. In places close to shore, the Bengal Fan measures up to 7.5 miles (12 kilometers) thick.

A glacier at about 22,100 feet (6,735 meters) in the Himalayan Mountains is the source of the Ganges River. The river flows southeast across India to combine with the Brahmaputra in Bangladesh. The Brahmaputra River has its source in Tibet along the northern slope of the Himalayan Mountains. From there, it flows across the Assam Valley of India into Bangladesh. The rising Himalayan Mountains provide much of the sediment load of these two rivers.

In Bangladesh, the rivers join to form the Padma, the main channel to the sea. The united rivers branch into many distributaries, forming the vast and fertile Ganges River Delta. The delta region covers roughly 25 percent of India's total territory. The delta's southern portion is covered largely with a swamp forest roughly 6,525 square miles (16,900 square kilometers) in area. Known as the Sunderbans, it is home to the endangered Royal Bengal tiger.

Mississippi Delta, Louisiana

The waters of almost half a continent flow through the Mississippi River. About 159 million tons (144 million metric tons) of sediment—70 percent of which consists of clay, silt, and fine sand—are carried by the river annually. Where it empties into the Gulf of Mexico in southern Louisiana, the river slows and drops its sediment load, forming the Mississippi Delta. The giant bird's foot delta, featuring a large middle toe, marks the seaward growth of land into the gulf.

The delta, the most fertile area of Louisiana, covers about 13,000 square miles (33,670 square kilometers), roughly 25 percent of the state's land area. It measures about 12 miles (19 kilometers) long and 30 miles (48 kilometers) wide. In the delta, the Mississippi River breaks into a number of distributaries, the most important of which are the Atchafalaya (pronounced uh-cha-fuh-LIE-uh) River and the Bayou Lafourche (pronounced BYE-oo luh-FOOSH). The main river continues southeast through the delta to enter the gulf through several mouths, including Southeast Pass, South Pass, and Pass à Loutre.

Geologists believe the present delta has been built outward into the gulf over the last 600 years. The river has built its unique shape because it carries so much sediment and the Gulf of Mexico has such a limited tidal range. One result of this is that the river's distributaries travel very long distances to reach the gulf. Over time, the river switches its route to the

The Mississippi River Delta is formed where the river empties into the Gulf of Mexico in southern Louisiana. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

sea, taking a shorter and more energy-efficient route. The Mississippi River has done this at least five times in the last 5,000 years.

Okavango Delta, Botswana

The Okavango (pronounced oh-kah-VANG-go) Delta is the world's largest inland delta. Instead of flowing into an ocean or a large lake, the Okavango River spreads over 6,000 square miles (15,540 square kilometers) of the Kalahari Desert in a maze of intricate waterways and reed-lined channels. This creates a diverse ecosystem that supports the greatest concentration of birds, animals, and fish in Africa.

Rain falling on the highlands in central Angola forms the Cubango River. It flows through Namibia as the Kuvango River before finally entering Botswana as the Okavango River. Each year, some 2.9 trillion gallons (11 trillion liters) of water carrying more than 2 million tons (1.8 million metric tons) of sediment enter the delta, which occupies a depression that contained a large prehistoric lake.

A notable feature about the Okavando Delta is the seasonal flooding that begins in mid-summer in the northern section and ends about six

The Okavango Delta spreads over 6,000 miles of the Kalahari Desert in Botswana, Africa. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

months later in the southern section. As a result, water rises in the north as it recedes in the south during summer, and rises in the south as it drops in the north during winter. Despite this latter drop, the north remains wet all year. The nature of the annual floods is gentle. Plains and islands disappear under water, then reappear in an ever-changing landscape.

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Dune and other desert features

Desert environments have fascinated humans throughout the ages. Covering approximately one-third of Earth's land surface, these arid (dry) landscapes receive less than 10 inches (25 centimeters) of rain per year and support only limited plant and animal life. Deserts may be hot, located primarily between the tropic of Cancer and the tropic of Capricorn, two parallel lines of latitude lying one-quarter of the way from the equator to the North and South Poles, respectively. Deserts may also be cold, located in polar regions where the mean temperature during the warmest month is less than 50°F (10°C). Most deserts on the planet lie within the Tropics (also called the Torrid Zone).

What differentiates deserts from other ecosystems (communities of plants and animals interacting with their environment) around the world is not only extreme climate but the landforms scattered across their surfaces. For many people, these fantastic forms define the desert landscape. Miles upon miles of rolling dunes, like waves on a sea suddenly stopped, dominate popular images of deserts in books and motion pictures. Yet, only one-fifth of all desert surfaces are covered with sand. Alluvial fans, arroyos, blowouts, desert pavement, oases, playas, yardangs: These are but a few of the many features that combine to create the spare desert landscape.

The shape of the land

Although dunes, wind-blown piles of sand, make up only 20 percent of the total desert landscape, these landforms may cover thousands of square miles and reach heights of up to 1,640 feet (500 meters). Dunes occur in many shapes, but common to all dunes is the contrast between the gentle slope of the windward side (the side facing into the wind) and the steep slope of the leeward side (the side facing away from the wind). The leeward side is known as the slip face of the dune. Geologists,

Sand dunes in the Gobi Desert, the coldest and northernmost desert in the world. The Gobi covers half a million square miles and is located on a plateau that is 3,000 to 5,000 feet above sea level in the heart of Asia. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

scientists who study the origin, history, and structure of Earth, have classified the most common dune forms into five types: barchan, parabolic, linear, transverse, and star.

Dune types

A barchan (pronounced bar-KAN) dune, sometimes known as a crescentic dune, is a crescent or U-shaped dune that has its "horns" or tips pointing downwind or away from the wind. Barchans arise where sand supply is limited, where the ground is hard, and where wind direction is fairly constant. They form around shrubs or larger rocks, which act as anchors to hold the main part of the dune in place while the tips migrate with the wind. Barchan dunes occur widely in deserts around Earth.

A parabolic dune is similar in shape to a barchan, but its tips point into the wind. Its formation is also influenced by the presence of some type of obstruction, such as a plant or a rock. Just the opposite of a barchan, a parabolic is anchored at its tips by the obstruction, which acts to block the wind, while its main body migrates with the wind, forming a depression between the tips. Because of this formation, parabolic dunes are also known as blowout dunes.

Words to Know

Abrasion: The erosion or wearing away of bedrock by continuous friction caused by sand or rock fragments in water, wind, and ice.

Atmospheric pressure: The pressure exerted by the weight of air over a given area of Earth's surface.

Bajada: Several alluvial fans that have joined together.

Basin: A hollow or depression in Earth's surface with no outlet for water.

Compression: The reduction in the mass or volume of something by applying pressure.

Crest: The highest point or level; summit.

Deflation: The lowering of the land surface due to the removal of fine-grained particles by the wind.

Ecosystem: A system formed by the interaction of a community of plants, animals, and microorganisms with their environment.

Eolian: Formed or deposited by the action of the wind.

Erg: A vast area deeply covered with sand and topped with dunes.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Gully: A channel cut into Earth's surface by running water, especially after a heavy rain.

Leeward: On or toward the side facing away from the wind.

Saltation: The jumping movement of sand caused by the wind.

Silt: Fine earthy particles smaller than sand carried by moving water and deposited as a sediment.

Slip face: The steeply sloped side of a dune that faces away from the wind.

Surface creep: The rolling and pushing of sand and slightly larger particles by the wind.

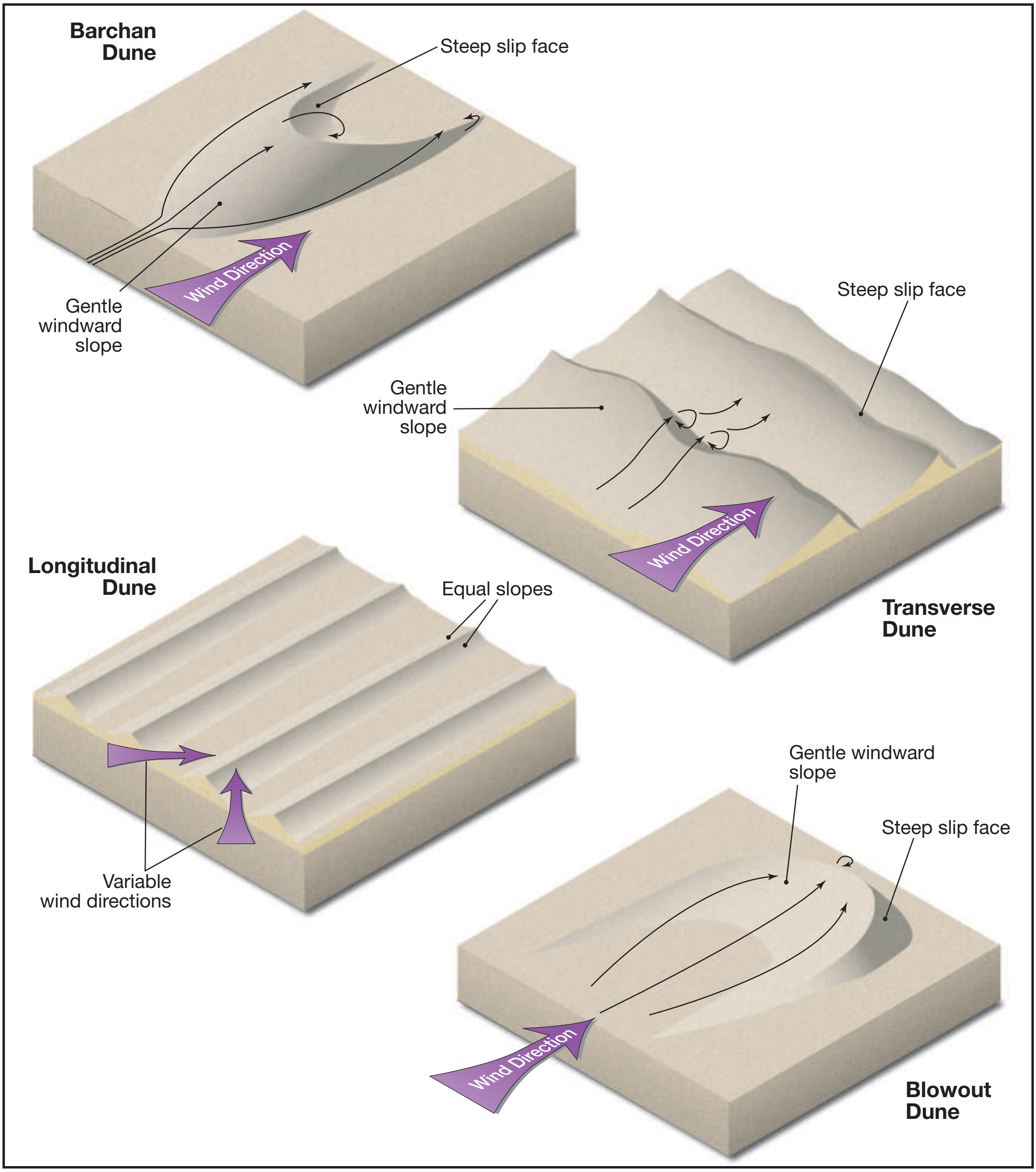
Ventifact: A stone or bedrock surface that has been shaped or eroded by the wind.

Windward: On or toward the side facing into the wind.

A linear, or longitudinal, dune is one that forms where sand is abundant and cross winds converge, often along seacoasts where the winds from the sea and winds from the land meet and push the sand into long lines. These high, parallel dunes can be quite large: Scientists have recorded linear dunes reaching 655 feet (200 meters) in height and 62 miles (103 kilometers) in length. The crests or summits of linear dunes are often straight or slightly wavy.

A transverse dune also forms where sand supply is great. This dune is a ridge of sand that forms perpendicular to the direction of the wind. The slip face of a transverse dune is often very steep. A group of transverse dunes resembles sand ripples on a large scale.

A star dune forms where there is plentiful sand and many dominant winds come from various directions. As its name implies, a star dune resembles a star with its many arms pointing out in different directions. The crests on the arms slope upward, meeting to form a point in the mid-



Four of the most common dune forms: barchan, transverse, longitudinal (or linear), and blowout (or parabolic).

dle of the dune similar to that of a pyramid. The largest and highest dunes are star dunes.

All the five major dunes can be further categorized into simple, compound, and complex types. When they occur in their original states, all dunes are simple. When a smaller dune forms on top of a larger dune of a similar type and orientation to the wind, the entire structure is known as a compound dune. When a smaller dune forms on top of a larger dune of a different type, it is known as a complex dune.

Alluvial fan

Water may be scarce in a desert environment, but when it does appear, such as in a brief and violent rainstorm, it can change the landscape quickly and dramatically. Precipitation that falls in higher elevations in deserts flows rapidly down to flat areas through canyons, valleys, and other narrow, confined channels. Because most desert soil lacks plants and their root systems to help hold the soil together, the flowing water easily picks up any loose material in its path. The faster the water flows, the larger the pieces of material it is able to pick up and carry along.

When the rushing water finally reaches a plain or flat area, it loses power since gravity is no longer helping it flow down a steep slope. As it slows, the water is unable to carry the sediment—gravel, clay, sand, and silt—it picked up on its way downhill. Large rocks and other heavy material are deposited first at the base of the canyon, followed by other material in decreasing size. No longer confined to a narrow channel, the water spreads out the farther it moves away from the base of the canyon. The finest material it carried is deposited at the outer edge. When the water evaporates, the sediments remain behind. Over time, as more water flows onto the plain, more sediment is deposited, and a wide, fan-shaped pile known as an alluvial (pronounced ah-LOO-vee-al) fan forms. When two or more alluvial fans merge on a plain to create a broad, sloping surface, they form a bajada (pronounced ba-HA-da; Spanish for slope).

Arroyo

An arroyo (pronounced ah-ROY-oh) is another desert landform sculpted by the action of water. Sudden heavy downpours cut channels in the desert floor, often in canyons or other low-lying areas. These fast-moving but short-lived streams create deeper channels or gullies with steep sides and an almost flat bed or bottom. Just as quickly as the water appears, it disappears in the normally dry desert environment. What remains is an arroyo, a dry watercourse with a floor that is often gravel-strewn.

Blowout

Following water, wind is a major cause of erosion (the gradual wearing away of Earth's surfaces through the action of wind and water) in the desert. Without plants and their anchoring roots, loose desert soil is moved easily by near-constant blowing winds. Blowouts, also known as deflation basins or hollows, are depressions made in sand or light soil by

Furnace Greek Formation, Death Valley National Park, California, which consists primarily of alluvial fan and playa deposits. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

strong wind action. These low spots may range in size from several feet to several miles in diameter. Blowouts can form around desert plants with hardy roots or around rock structures, leaving them perched atop a column as more and more sand or soil is blown away.

Desert pavement

The strength of the wind determines the amount and type of material it removes from the desert floor. As the wind increases in strength, it is able to move and transport more and larger particles. Initially, very fine particles are moved by the wind. As more and more of these types of particles are removed, the surface of the land lowers in elevation. This action, known as deflation, continues until what remains on the desert floor is a layer of closely packed pebbles and rocks too heavy for the wind to move. Settled and wind-polished, the entire surface is called desert pavement or reg. The older the pavement, the smoother and flatter it appears, like a highly worn cobblestone street. Younger pavement areas are coarser, less eroded by the action of the wind.

Oasis

Beneath Earth's surface, water fills the pore spaces and openings between rocks. This water that seeped through the soil, drawn downward by gravity, is known as groundwater. At a certain level below ground, all openings between the rocks are completely filled with groundwater. The upper surface of this area is called the water table, and it is found everywhere beneath Earth's surface. Even beneath desert regions, there is water.

Groundwater hardly ever reaches the desert surface, but when it does, it can transform the stark landscape into a fertile haven thriving with many species of plants and animals that otherwise would not exist in that hot, dry space. This green area, existing like an island in a sand sea, is an oasis (pronounced oh-AY-sis; plural form is oases). Many oases are artificial ecosystems, created by people living in the desert using large pipes to tap into the groundwater to bring it to the surface. A few, though, are the result of natural forces. These oases are centered on springs that have been exposed because of blowouts and other erosive actions by the wind that have lowered the land surface.

Playa

Permanent water bodies are rare in deserts. When precipitation does occur in a desert, it often runs down steep hills to form temporary surging streams in low-lying areas before evaporating or sinking into the ground. When the water falls on fairly flat areas, it may collect in a basin or other slightly depressed area, forming a small lake that may last for a while before the water evaporates or is absorbed. What remains after the water is gone are the sediments it collected as it flowed along the desert surface. Those sediments, mostly clay, silt, and various salts, form a level, broad, cracked surface called a playa (pronounced PLY-uh; Spanish for beach). When water is still present, these bodies are called playa lakes.

Although they are very rare, permanent desert lakes do exist. Two examples are the Great Salt Lake of Utah and the Dead Sea of Israel and Jordan. The Great Salt Lake is all that remains of ancient Lake Bonneville, which was ten times the size of the Great Salt Lake, while the Dead Sea was once part of the Mediterranean Sea.

Yardang

Among the most striking desert landforms created by the action of the wind are yardangs (from the Turkic word *yar,* meaning "steep slope"). A yardang is a wind-sculpted, streamlined ridge that can stretch for over one mile in length and 100 feet (30 meters) in height. It forms when strong winds blowing primarily in one direction remove all sand in an area down to the bedrock (solid rock beneath the sand). If the bedrock is slightly soft or porous, winds will erode the bedrock, sandblasting hollows out of the soft parts of its surface. Over a vast amount of time, winds cut away enough material to leave a sleek-shaped ridge, similar in shape to the bottom of an overturned boat, that runs parallel to the wind.

Forces and changes: Construction and destruction

The desert landscape is shaped primarily by two forces: wind and water. Through three main actions, wind sculpts the face of the desert landscape. It is the more prevalent force, but water is the more powerful. Though its appearance is limited, water is the primary agent of erosion in the desert.

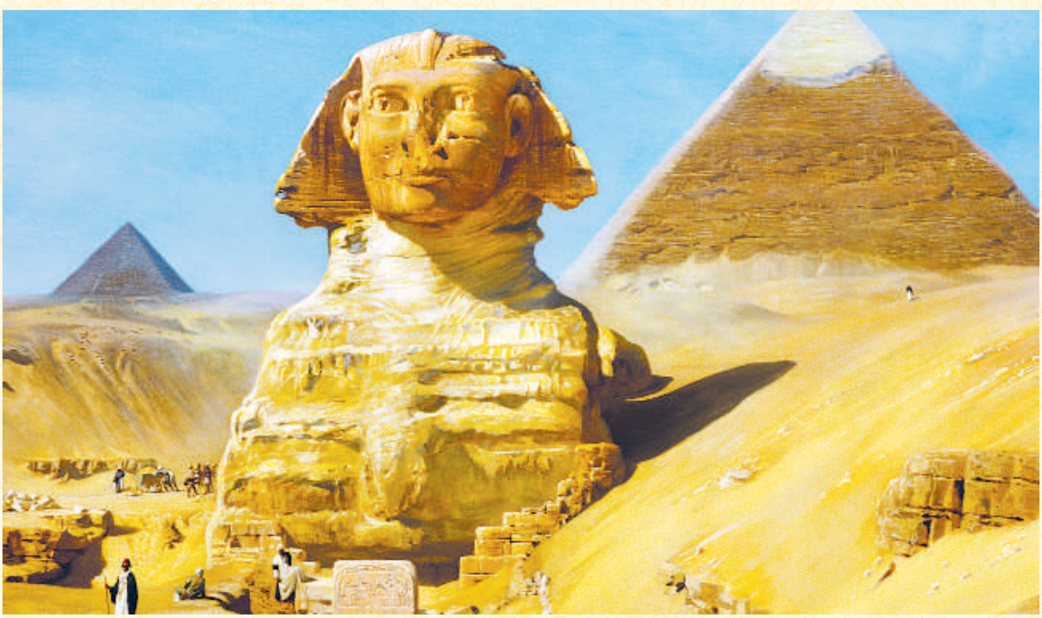
To understand the actions of wind and water in forming desert landforms, it is necessary to understand first how circulating air patterns in Earth's atmosphere create conditions that bring about desert environments. As mentioned earlier, the majority of the planet's deserts are located in two horizontal belts near the equator, where the Sun is closest to Earth. In this region, the Sun heats the air, causing it to rise. As the air rises, low air pressure develops beneath it. As the air rises even higher in the atmosphere, it cools, and moisture in the cooling air begins to condense and fall as rain (this explains why most rainforests are also found near the equator). When the cool air reaches the top of the troposphere, the lowest 10 miles (16 kilometers) of Earth's atmosphere, it can rise no further and begins to move toward the poles, cooling even more as it travels northward and southward.

At about 30° latitude north and south of the equator, the cool, dry air descends to Earth's surface. In the process, the air becomes strongly heated

Was the Sphinx Originally a Landform?

In 2001 Farouk El-Baz, Boston University professor and director of the university's Center for Remote Sensing, published a paper in which he suggested that the pyramids and the Great Sphinx located on Egypt's Giza Plateau were based on natural landforms found in the eastern Sahara Desert. El-Baz pointed out that the landscape of the Nile River valley features cone-shaped hills that have lasted many years because their shape forces the strong winds in the area upward, preventing the wind from eroding them or wearing them down. The pyramid builders, El-Baz believes, would have looked to these landforms in their quest to build lasting structures.

Extending his theory even further, El-Baz asserted that the Great Sphinx, the enormous sculpture with the head of a man and the body of a reclining lion, might even have been carved by ancient Egyptians in 2500 B.C.E. from an existing desert landform. He cited the works of early twentieth-century explorers and geologists that described wind-eroded yardangs in northwestern China and southwestern Egypt as "sphinx-like" or "lionlike." El-Baz believes the head of the sphinx was an existing yardang (a wind-sculpted ridge) the Egyptians reshaped. They then formed the body, which sits in a hollow or depression, by digging out the naturally occurring limestone on the plateau around it.



Great Sphinx, Egypt. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

The Literary Landscape

"What land can equal the desert with its wide plains, its grim mountains, and its expanding canopy of sky! You shall never see elsewhere as here the dome, the pinnacle, the minaret fretted with golden fire at sunrise and sunset; you shall never see elsewhere as here the sunset valleys swimming in a pink and lilac haze, the great mesas and plateaus fading into blue distance, the gorges and canyons banked full of purple shadow. Never again shall you see such light and air and color."

—John C. Van Dyke, *The Desert*, 1901.

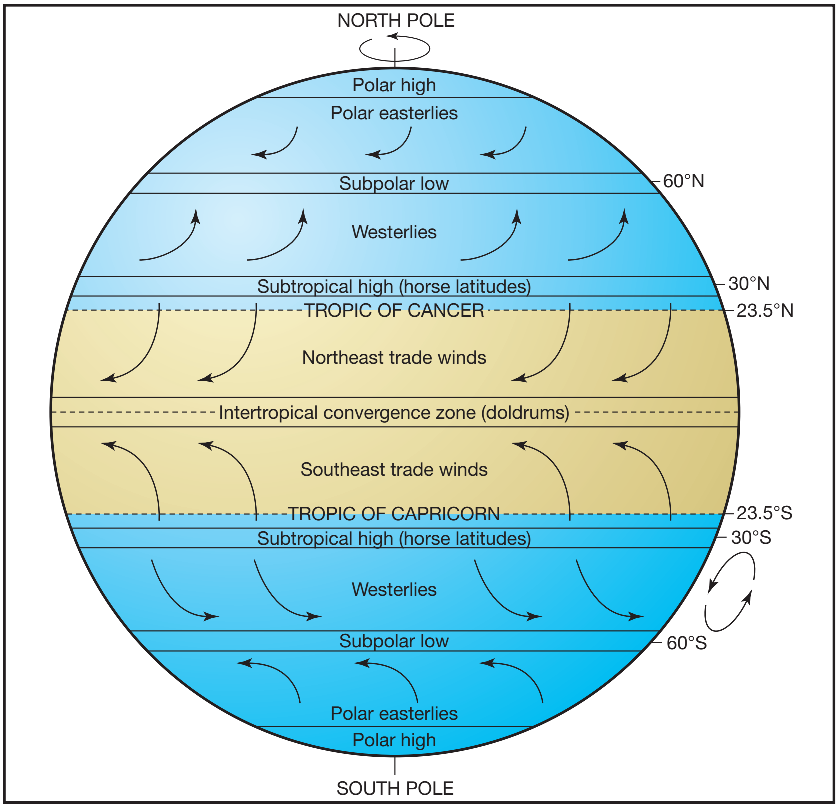
due to compression caused by atmospheric pressure (atmospheric pressure increases closer to the planet's surface). During its descent, the warming air pushes the air below it back toward the equator, since air flows always move toward areas of low pressure. Passing over land on its way back to the equator, the now heated, dry air evaporates any moisture in the air, creating dry regions or deserts.

These wind patterns explain the formation of many of the world's deserts in the area between 15° and 35° latitude north and south of the equator. Although much weaker, similar atmospheric circulation (with heated, dry air evaporating moisture as it moves over Earth's surface) occurs over both poles, creating polar deserts. While heated because of compression by the atmosphere, the air over the polar regions is not as warm as in equatorial regions simply because the Sun is farther away from Earth in these areas. Polar deserts, however, are similar to hot deserts because they have very low humidity and precipitation levels.

The topography (physical features) of Earth in combination with atmospheric pressure creates other deserts around the planet. Rain-shadow deserts are those that lie on the leeward side of mountain ranges located near coasts. As moisture-laden air flows inland from an ocean and encounters a mountain range, it is pushed upward. Cooling as it rises, the air begins to lose its moisture on the windward side of the mountain range through rainfall. Once on the leeward side, in the "shadow" of the mountain range, the air has little moisture left. Heated by compression as it descends, the warm, dry air forms deserts in the slope of the range. All deserts in North America are formed by this action.

The force of wind

Wind is a common element in desert environments because the Sun heats air near the desert surface, causing it to rise. The warmed air is then replaced by cooler air, which is then heated and rises. This constant cycle of air warming, rising, and being replaced results in winds. The lack of desert vegetation also allows winds to blow unrestricted. Strong and unchecked, wind has the ability to transport, erode, and deposit material in the desert, creating and modifying its landforms. The work of the wind



The circulating air patterns in Earth's atmosphere.

is known as eolian (pronounced ee-OH-lee-an; from Aeolus, the god of the winds in Greek mythology).

The wind moves like a fluid, like water, and it can erode only if it is strong enough. Very often, it merely transports material. Very small particles, measuring less than 0.01 inch (0.02 centimeter) in diameter, can be picked up easily by desert winds and carried aloft for hundreds or thousands of miles. Suspended on air currents, whirling high in the atmosphere, dust from Africa's Sahara Desert sometimes crosses the Atlantic Ocean before landing in the west Atlantic and Caribbean Sea. On the other hand, sand particles, which typically measure 0.01 to 0.25 inch (0.02 to 0.64 centimeter) in diameter, can be carried only by extremely strong winds. Silt and other very small-sized particles fill the air during dust storms, but these and most other wind-borne grains are too small to cause erosion or sandblasting of major landforms that stand high above the desert floor.

Scientific experiments have shown that wind-blown sediment causes the most erosion at a height of no more than 10 inches (25 centimeters). Indeed, erosion of the landscape by the wind takes place mainly on the

Cultural Landforms

In the barren Great Sandy Desert in Australia's Northern Territory a red sandstone monolith (tall block of rock), the world's largest, rises 1,143 feet (348 meters) above the surrounding flat sandy plain. Ayers Rock, known as Uluru to the Anangu Aboriginals, the native people of the region, is an inselberg, a prominent steep-sided hill composed of strong, solid rock that sits isolated in a desert plain. Like other inselbergs, Ayers Rock's rounded appearance is caused by weathering in which its durable surface has been eroded in successive layers, like the peeling of an onion skin.

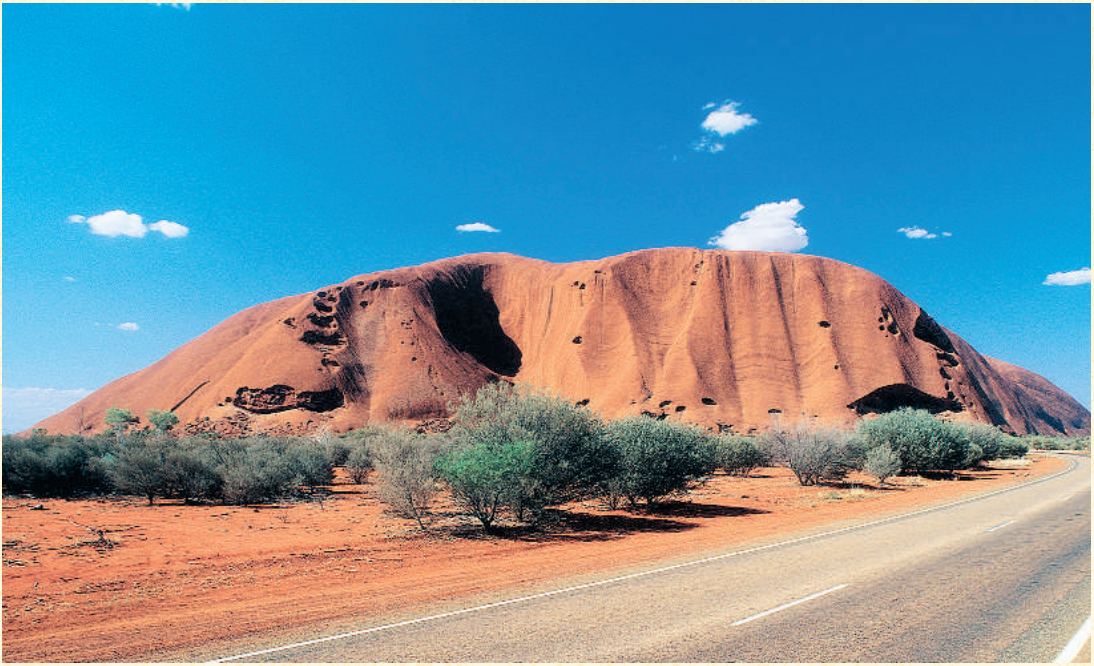
Estimated to be between 400 and 600 million years old, the monolith measures about 1.5 miles (2.4 kilometers) wide and 2.2 miles (3.5 kilometers) in length. Geologists believe that two-thirds of the rock, measuring some 3.7 miles (6 kilometers), lies beneath the desert floor. The rock mound's changing colors as the Sun moves over it, from gray to gold to red to purple, are due to minerals like feldspar contained in the sandstone. The famous red color is also a direct result of iron in the sandstone, which oxidizes or rusts.

Uluru has deep cultural significance for the Anangu. They consider it a sacred place, having been formed by supernatural beings who crossed the Australian landscape, creating various landforms in their wake. In 1985, the Australian government returned Uluru National Park, which contains the monolith, to its original owners. The Aboriginals then leased the area to the Australian National Parks and Wildlife Service.

ground, where the wind removes fine-grained particles causing deflation (lowering of the land surface due to the removal of particles by the wind). This continued action leads to blowouts and desert pavement. Any stone or part of the bedrock that has been abraded or shaped by the wind is known as a ventifact (artifact of the wind). A yardang is one large desert landform that is sculpted by the wind though deflation and abrasion.

The wind transports larger-grained sediments, particularly sand, through the process called saltation. While light enough to be picked up by strong wind, sand is too heavy to remain suspended in the air. As a result, it is moved along Earth's surface by the wind through a series of short jumps and bounces. The vast majority of sand transported in this way travels within 2 feet (0.6 meter) of the ground. As saltating particles crash to the ground, they can dislodge and move slightly larger particles, such as small pebbles. The sliding and rolling movement of these particles is called surface creep.

Sand is finally deposited when the wind encounters some type of an obstacle: rocks, vegetation, or a manmade structure. As wind passes over an obstacle, the wind's velocity, or speed, increases. Once on the other



Ayers Rock, Australia. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

side of the obstacle, its velocity decreases and any sand or particles it was transporting drop out to begin forming a mound. When there is a steady supply of sand carried by a steady wind that comes in contact with an obstacle or irregularity in the flat ground surface, a sand dune forms.

The type of dune formed is influenced by the direction and strength of the wind, the amount of sand it carries, and the shape of the land. All dunes have a gently sloping windward face and a steeply sloping leeward or slip face. The slope of the windward face is usually between 10° and 20°, while the slip face has a slope of a much greater angle, about 32°. The windward face is usually hard packed and smooth, cut occasionally by minor grooves. The slip face is soft and unstable.

As wind passes over the windward face of a dune, it moves sand along the surface through sliding movements and saltation (the jumping movement of sand caused by the wind). Once over the crest of the dune, sand flows down the slip face. This action—the eroding of sand on the windward face and the deposition of sand on the slip face—causes the dune to move or migrate with the wind like a slow wave.

It is rare that a single dune forms in an area. Most often, dunes form in groups called fields on broad flat lands where winds blow steadily and sand is plentiful. Far-reaching fields, such as those in the Arabian Desert in eastern Egypt, are called sand seas or ergs (Arabic for ocean).

The force of water

Deserts are defined by their lack of water, both rainfall and free-standing. Coastal deserts may experience one or two rainfalls a year; those farther inland may receive one or two a decade. Though rare, desert rainfalls are often heavy storms lasting mere minutes or a few hours. The Sahara Desert, which normally receives less than 5 inches (12.7 centimeters) of rain a year, once received 1.7 inches (4.4 centimeters) in three hours.

Water is a natural force of erosion everywhere on the planet, but especially so in the desert. When raindrops strike bare ground that is not protected by vegetation, they loosen particles of soil, spattering them in all directions. During heavy rains on sloped surfaces, the dislodged soil is carried off in a flow of water.

With little vegetation or organic-rich soil to absorb the water, the desert landscape is quickly eroded as the torrent of water surges over it, picking up and transporting as much sediment as it can carry. What takes desert wind a year to accomplish, water surpasses in a day or two. Because of the unexpected, and often violent, nature of rainfall in the desert, more people die of drowning than of thirst in that arid environment.

Aided by gravity and steep slopes, rainfall on high desert elevations flows down over the surface as sheets, picking up sediments along the way. Finding natural depressions, such as gullies and canyons, water continues to race along, gaining speed and power as it is confined and flows downward. Increased velocity allows the water to pick up more and larger sediments and rock debris, eroding them and the surface below as it rushes along. Often clogged with so much debris, the water can resemble a mudflow (a thick mixture of water, mud, and other surface fragments).

Arroyos, dry streambeds created by previous rains, again fill with water. When an arroyo finally opens onto a flat, broad plain, the rushing water flows out and drops its load of sediments, forming a new alluvial fan. In other areas, basins or depressions in the desert floor fill with water, forming playa lakes that soon evaporate, leaving a dry, cracked, salty lake bed that will remain until the next rain.

Spotlight on famous forms

Algodones Sand Dunes, California

The Algodones Sand Dunes, also known as the Imperial Sand Dunes, stretch more than 40 miles (64 kilometers) northward from the U.S.-Mexico

Rippled sand dunes of the Algodones Sand Dunes, California. The dune system, one of the largest in North America, covers an area of about 1,000 square miles in the southeastern portion of the state of California. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

border along the eastern edge of the Imperial Valley agricultural region in southeastern California. The dune system, the largest in the state and one of the largest in the country, formed approximately ten thousand to twenty thousand years ago. Some geologists believe that blowing sands from Lake Cahuilla (pronounced kah-WEE-ah), an ancient freshwater lake located just west of the present-day area, helped create the dunes.

The dune system, which lies within the Sonoran Desert, varies in width from 5 to 8 miles (8 to 12.9 kilometers). Prevailing westerly winds cause the dunes to migrate to the southeast at a rate of approximately 1 foot (0.3 meter) a year. The crests of the largest dunes often reach 300 feet (91 meters) above the surrounding landscape. With summer temperatures rising above 110°F (43°C) and annual rainfalls of less than 2 inches (5 centimeters), the system supports very little vegetation. Often, the dunes stretch uninterrupted by any life for miles, a vast pile of pure golden sand against a dry blue sky. This unspoiled environment has been used as the set for many films, including *Star Wars* (1977) and *Return of the Jedi* (1983).

This ancient and fragile dune system is threatened by uncontrolled and intense use of off-road vehicles. The U.S. Bureau of Land Management has set aside over 70,000 acres (28,000 hectares) of the dune system as a protected environment free from such recreational activity.

Lut Desert yardangs, Iran

The Lut Desert or Dasht-e Lut ("Desert of Emptiness") lies in Iran's southeastern province of Kerman. The great sand and stone desert covers an area almost 300 miles (480 kilometers) in length and almost 200 miles (320 kilometers) in width. Among the driest places on the planet, it receives an average of only 1.2 inches (3 centimeters) of rain a year. Certain areas of the desert reportedly receive no rain. Extremely barren, the desert contains the only region free from any life, including the existence of bacteria, on Earth.

In the western part of this desolate environment lie some of the world's most prominent yardangs. Rising up to 282 feet (80 meters), these streamlined ridges have been carved by the wind out of the silty clay and sand lining the desert floor. Lying parallel to the prevailing north-northwest winds, the yardangs are separated by troughs measuring 330 feet (100 meters) or more. The crests or summits of the largest of these yardangs are rounded or flat; all others are narrow. Geologists have found no evidence that water has played any significant part in their creation and continued erosion.

Racetrack Playa, Death Valley, California

Death Valley, located in eastern California, lies between the Panamint Mountains on the west and the Amargosa Range on the east. A desert basin, much of which lies below sea level, Death Valley contains a small pool, Badwater, that is the lowest point in the Western Hemisphere: 282 feet (86 meters) below sea level. Death Valley is also the hottest place on the North American continent, with summer temperatures often exceeding 120°F (49°C). Rainfall seldom measures more than 2 inches (5 centimeters) a year.

Located within Death Valley National Park is a playa known as Racetrack Playa. Like other dry lakebeds in other deserts around the world, Racetrack Playa temporarily fills with water during heavy storms, collecting the runoff from nearby mountain slopes. Under the hot Sun, the thin sheet of water quickly evaporates, leaving the almost perfectly flat clay surface of the playa dry and cracked in a mosaic pattern.

What makes Racetrack Playa unique, and world-famous, are the rocks that slide across its surface and the mystery behind their movements. Periodically, rocks from rock formations around the playa break off and drop

to the floor of the dry lakebed. Some of these rocks are actually boulders, weighing up to 705 pounds (320 kilograms). Instead of being concentrated in one area, these rocks are scattered across the playa, with grooved trails stretching behind them, some straight, some curved, some extending as long as 2,896 feet (880 meters). Until recently, geologists have been at a loss to explain the possible reason behind their movement.

The mysteriously "sliding" rocks of Racetrack Playa in Death Valley, California. Researchers believe the movement is the effect of strong winds at a time when the normally dry lake bed becomes muddy from rain. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Now, geologists believe the rocks slide because of a combination of water and wind. After the playa becomes wet with rainwater, and before the water completely evaporates, the surface of the clay-filled lakebed is extremely slick. Winds, channeled by low points in the surrounding mountains, stream across the playa in natural wind tunnels. Some of the winds reach 70 miles (113 kilometers) per hour. Geologists believe the winds are strong enough to set even the heaviest boulders sliding across the slippery playa surface.

Sahara Desert dunes, North Africa

The Sahara Desert, the world's largest, spreads across the upper third of the African continent from the Atlantic Ocean to the Red Sea. From north to south, it extends about 1,200 miles (1,930 kilometers). In all, it

Shuttles on the Playa

Edwards Air Force Base, home of the U.S. Air Force Test Center, is located in the Mojave Desert about 100 miles (161 kilometers) northeast of Los Angeles, California. Adjacent to the main Edwards complex lies a 44-square-mile (114-square-kilometer) playa known as Rogers Dry Lake. For more than forty years, the dry lakebed has been used for emergency and test landings of experimental and standard aircraft. Since 1977, the playa has served as the landing site for many space shuttle tests and operational flights.

Formed some 2.5 million years ago during the Pleistocene Epoch, Rogers Dry Lake is the largest geological formation of its kind in the world. Its extremely flat, hard surface of parched clay and silt undergoes a cycle of renewal each year. Desert winds sweep water from winter rains back and forth across its surface, smoothing it out to an almost glassy flatness. Its surface is so perfect, in fact, that runways can merely be painted on the ground. There are seven outlined runways on the playa, the longest of which extends 7.5 miles (12 kilometers).

Many aviation milestones have been reached on the playa. In 1947, U.S. Air Force Captain Chuck Yeager became the first person to break the sound barrier when he piloted the rocket-powered Bell X-1 over the playa to a speed of Mach 1.06, exceeding 662 miles (1,065 kilometers) per hour at 40,000 feet (12,192 meters) elevation.

Just thirty years later, the U.S. space shuttle *Enterprise* successfully completed a landing and roll out on Rogers Dry Lake after it had been launched from the back of a 747 aircraft. This, along with four subsequent tests, demonstrated the soundness of the shuttle design. In the early days of the space shuttle program, most shuttles landed on the playa. Present-day shuttles continue to land there if weather conditions are poor at the Kennedy Space Center in Cape Canaveral, Florida, home to the space shuttle program.

covers about 3.5 million square miles (8.8 million square kilometers), an area almost as large as the United States. Countries that fall at least partly within the Sahara include Morocco, Algeria, Tunisia, Libya, Egypt, Mauritania, Mali, Niger, Chad, and Sudan.

The desert's landforms, which tend to have a golden color, range from rocky mountains and wind-eroded highlands (known as hammada) to rock-filled plains (known as reg) and deep, narrow canyons. Oases dot the landscape, providing native people, plants, and animals the chance to exist.

Overshadowing all these distinct landforms, however, are the great Saharan sand seas or ergs, which compose 15 percent of the desert. Confined to large basins, the ergs are separated by plateaus and low mountain ridges. Dunes in the ergs can soar to 1,000 feet (305 meters). While some dunes in

Space shuttle on the back of a 747 at Rogers Dry Lake, California. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

the Sahara are stationary, others are in constant motion. As they migrate with the wind, dunes may emit strange singing or booming sounds as the sand grains move against each other, tumbling down the slip faces of the dunes.

It is not uncommon for dune fields in the Sahara to stretch for hundreds of miles without a break or any sign of life. The Libyan Erg, located near Egypt, holds the greatest mass of dunes on Earth. It covers more than 200,000 square miles (518,000 square kilometers), an area almost as large as France.

White Sands National Monument, New Mexico

Of North America's four deserts—the Chihuahuan, the Great Basin, the Mojave, and the Sonoran—the Chihuahuan is the farthest east and the farthest south. Extending north from Mexico, the desert reaches into

Beni Abbes Dunes in the Sahara Desert, Africa. The Sahara Desert is the world's largest desert, covering about 3.5 million square miles—an area almost as large as the United States. **PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.**

southern New Mexico, southeastern Arizona, and southwestern Texas. At the desert's northern end in New Mexico lies a mountain-ringed valley called the Tularosa Basin. Covering 275 square miles (712 square kilometers) of this basin is a dune field unlike any other in the world.

The glistening white dunes in this basin form the largest pure gypsum dune field in the world. Most sand on the planet is made of quartz, one of the most abundant rock-forming minerals found in Earth's crust. Gypsum is a mineral composed of calcium sulfate (calcium, sulfur, and oxygen) and water. It rarely forms sand because it is soluble (can be easily dissolved) in water.

Precipitation that falls on the mountains surrounding Tularosa Basin, averaging 8 inches (20 centimeters) a year, dissolves gypsum contained in the rocks. The flowing water then carries the gypsum and other sediments down into the basin into a playa, Lake Lucero, which lies a few miles southwest of the dune field. With no watercourse, such as a river, to carry the water away, it evaporates, leaving the now-crystallized gypsum on the surface of the dry lakebed. Strong southwest winds blowing across the playa transport the gypsum to the nearby dune field. Quite dynamic, many dunes in the field migrate with the wind, moving northeast as much as 30 feet (9 meters) a year.

White Sands National Monument, in the northern end of the Chihuahuan Desert, New Mexico. Here, wavelike dunes of gypsum sand have engulfed 275 square miles of the desert, creating the largest gypsum dune field in the world. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

A large portion of the dune field, 115 square miles (298 square kilometers), is enclosed in the White Sands National Monument, which helps preserve the ecological integrity of the region. Surrounding the park is the White Sands Missile Range, a military base used for testing various weapons. Within the base lies Trinity Site, an area where the first atomic bomb was detonated on July 16, 1945.

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ENCYCLOPEDIA OF

LANDFORMS

AND OTHER GEOLOGIC FEATURES

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2

Fault
Floodplain
Geyser and hot spring
Glacial landforms and features
Landslide and other gravity movements
Mesa and butte
Meteorite crater
Mountain

Rob Nagel

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Contents

Reader's Guide

From the perspective of human time, very little changes on the surface of Earth. From the perspective of geologic time, the period from Earth's beginning more than 4.5 billion years ago to the present day, however, the surface of the planet is in constant motion, being reshaped over and over. The constructive and destructive forces at play in this reshaping have helped create landforms, specific geomorphic features on Earth's land surface. Mountains and canyons, plains and plateaus, faults and basins: These are but a few of the varied and spectacular features that define the landscape of the planet.

U•X•L Encyclopedia of Landforms and Other Geologic Features explores twenty-two of these landforms: what they are, how they look, how they were created, how they change over time, and major geological events associated with them.

Scope and Format

In three volumes, *U•X•L Encyclopedia of Landforms and Other Geologic Features* is organized alphabetically into the following chapters:

Basin	Canyon
Cave	Coast and shore
Continental margin	Coral reef
Delta	Dune and other desert features
Fault	Floodplain
Geyser and hot spring	Glacial landforms and features
Landslide and other gravity movements	Mesa and butte

Meteorite crater
Mountain
Ocean basin
Plain
Plateau
Stream and river
Valley
Volcano

Each chapter begins with an overview of that specific landform. The remaining information in the chapter is broken into four sections:

- **The shape of the land** describes the physical aspects of the landform, including its general size, shape, and location on the surface of the planet, if applicable. A standard definition of the landform opens the discussion. If the landform exists as various types, those types are defined and further described.
- **Forces and changes: Construction and destruction** describes in detail the forces and agents responsible for the construction, evolution, and destruction of the landform. The erosional actions of wind and water, the dynamic movement of crustal plates, the influence of gravity, and the changes in climate both across regions and time are explained in this section, depending on their relation to the specific landform.
- **Spotlight on famous forms** describes specific examples of the landform in question. Many of these examples are well-known; others may not be. The biggest, the highest, and the deepest were not the sole criteria for selection, although many of the featured landforms meet these superlatives. While almost all chapters include examples found in the United States, they also contain examples of landforms found throughout the world.
- **For More Information** offers students further sources for research—books or Web sites—about that particular landform.

Other features include more than 120 color photos and illustrations, "Words to Know" boxes providing definitions of terms used in each chapter, sidebar boxes highlighting interesting facts relating to particular landforms, a general bibliography, and a cumulative index offering easy access to all of the subjects discussed in *U•X•L Encyclopedia of Landforms and Other Geologic Features*.

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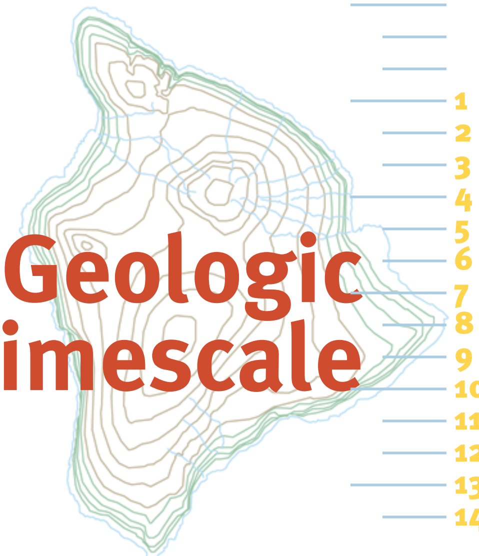
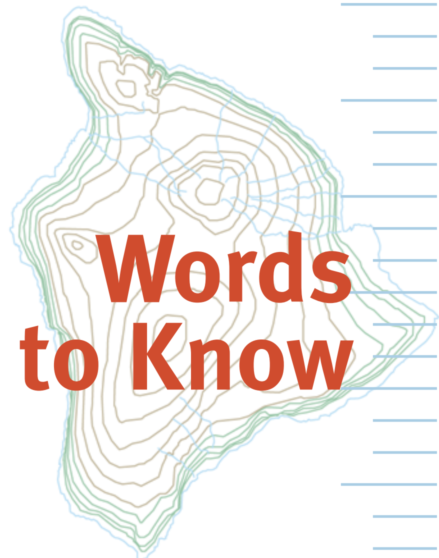
Comments and Suggestions

We welcome your comments on *U•X•L Encyclopedia of Landforms and Other Geologic Features*. Please write: Editors, *U•X•L Encyclopedia of Landforms and Other Geologic Features*, U•X•L, 27500 Drake Rd., Farmington Hills, MI 48331; call toll-free: 1-800-877-4253; fax: 248-699-8097; or send e-mail via http://www.gale.com.

Geologic Timescale



Era	Period	Epoch	Started (millions of years ago)
Cenozoic: 66.4 millions of years ago–present time	**Quaternary**	Holocene	0.01
		Pleistocene	1.6
	Tertiary — **Neogene**	Pliocene	5.3
		Miocene	23.7
	Tertiary — **Paleogene**	Oligocene	36.6
		Eocene	57.8
		Paleocene	66.4
Mesozoic: 245–66.4 millions of years ago	**Cretaceous**	Late	97.5
		Early	144
	Jurassic	Late	163
		Middle	187
		Early	208
	Triassic	Late	230
		Middle	240
		Early	245
Paleozoic: 570–245 millions of years ago	**Permian**	Late	258
		Early	286
	Carboniferous — **Pennsylvanian**	Late	320
	Carboniferous — **Mississippian**	Early	360
	Devonian	Late	374
		Middle	387
		Early	408
	Silurian	Late	421
		Early	438
	Ordovician	Late	458
		Middle	478
		Early	505
	Cambrian	Late	523
		Middle	540
		Early	570
Precambrian time: 4500-570 millions of years ago			4500



Words to Know

A

Ablation zone: The area of a glacier where mass is lost through melting or evaporation at a greater rate than snow and ice accumulate.

Abrasion: The erosion or wearing away of bedrock by continuous friction caused by sand or rock fragments in water, wind, and ice.

Abyssal hill: A gently sloping, small hill, typically of volcanic origin, found on an abyssal plain.

Abyssal plain: The relatively flat area of an ocean basin between a continental margin and a mid-ocean ridge.

Accretionary wedge: A mass of sediment and oceanic rock that is transferred from an oceanic plate to the edge of the less dense plate under which it is subducting.

Accumulation zone: The area of a glacier where mass is increased through snowfall at a greater rate than snow and ice is lost through ablation.

Active continental margin: A continental margin that has a very narrow, or even nonexistent, continental shelf and a narrow and steep continental slope that ends in a deep trench instead of a continental rise; it is marked by earthquake and volcanic activity.

Alluvial fan: A fanlike deposit of sediment that forms where an intermittent, yet rapidly flowing canyon or mountain stream spills out onto a plain or relatively flat valley.

Alluvium: A general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Alpine glacier: A relatively small glacier that forms in high elevations near the tops of mountains.

Angle of repose: The steepest angle at which loose material on a slope remains motionless.

Anticline: An upward-curving (convex) fold in rock that resembles an arch.

Arête: A sharp-edged ridge of rock formed between adjacent cirque glaciers.

Arroyo: A steep-sided and flat-bottomed gully in a dry region that is filled with water for a short time only after occasional rains.

Asteroid: A small, irregularly shaped rocky body that orbits the Sun.

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Atmospheric pressure: The pressure exerted by the weight of air over a given area of Earth's surface.

Atoll: A ring-shaped collection of coral reefs that nearly or entirely enclose a lagoon.

B

Back reef: The landward side of a reef between the reefcrest and the land.

Backshore zone: The area of a beach normally affected by waves only during a storm at high tide.

Backswamp: The lower, poorly drained area of a floodplain that retains water.

Backwash: The return flow of water to the ocean following the swash of a wave.

Bajada: Several alluvial fans that have joined together.

Bar: A ridge or mound of sand or gravel that lies underwater a short distance from and parallel to a beach; also commonly known as a sand bar.

Barrier island: A bar that has been built up so that it rises above the normal high tide level.

Barrier reef: A long, narrow ridge of coral relatively near and parallel to a shoreline, separated from it by a lagoon.

Basal sliding: The sliding of a glacier over the ground on a layer of water.

Basalt: A dark, dense volcanic rock, about 50 percent of which is silica.

Base level: The level below which a stream cannot erode.

Basin: A hollow or depression in Earth's surface with no outlet for water.

Bay: A body of water in a curved inlet between headlands.

Beach: A deposit of loose material on shores that is moved by waves, tides, and, sometimes, winds.

Beach drift: The downwind movement of sand along a beach as a result of the zigzag pattern created by swash and backwash.

Bed load: The coarse sediment rolled along the bottom of a river or stream.

Bedrock: The general term for the solid rock that underlies the soil.

Berm: A distinct mound of sand or gravel running parallel to the shoreline that divides the foreshore zone from the backshore zone of a beach.

Blowout: A depression or low spot made in sand or light soil by strong wind.

Bottomset bed: A fine, horizontal layer of clay and silt deposited beyond the edge of a delta.

Breccia: A coarse-grained rock composed of angular, broken rock fragments held together by a mineral cement.

Butte: A flat-topped hill with steep sides that is smaller in area than a mesa.

C

Caldera: Large, usually circular, steep-walled basin at the summit of a volcano.

Canyon: A narrow, deep, rocky, and steep-walled valley carved by a swift-moving river.

Cap rock: Erosion-resistant rock that overlies other layers of less-resistant rock.

Cave: A naturally formed cavity or hollow beneath the surface of Earth that is beyond the zone of light and is large enough to be entered by humans.

Cavern: A large chamber within a cave.

Cave system: A series of caves connected by passages.

Channel: The depression where a stream flows or may flow.

Chemical weathering: The process by which chemical reactions alter the chemical makeup of rocks and minerals.

Cirque: A bowl-shaped depression carved out of a mountain by an alpine glacier.

Cliff: A high, steep face of rock.

Coast: A strip of land that extends landward from the coastline to the first major change in terrain features.

Coastal plain: A low, generally broad plain that lies between an oceanic shore and a higher landform such as a plateau or a mountain range.

Coastline: The boundary between the coast and the shore.

Comet: An icy extraterrestrial object that glows when it approaches the Sun, producing a long, wispy tail that points away from the Sun.

Compression: The reduction in the mass or volume of something by applying pressure.

Continental drift: The hypothesis proposed by Alfred Wegener that the continents are not stationary, but have moved across the surface of Earth over time.

Continental glacier: A glacier that forms over large areas of continents close to the poles.

Continental margin: The submerged outer edge of a continent, composed of the continental shelf and the continental slope.

Continental rise: The gently sloping, smooth-surfaced, thick accumulation of sediment at the base of certain continental slopes.

Continental shelf: The gently sloping region of the continental margin that extends seaward from the shoreline to the continental shelf break.

Continental shelf break: The outer edge of the continental shelf at which there is a sharp drop-off to the steeper continental slope.

Continental slope: The steeply sloping region of the continental margin that extends from the continental shelf break downward to the ocean basin.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Coral polyp: A small, invertebrate marine animal with tentacles that lives within a hard, cuplike skeleton that it secretes around itself.

Coral reef: A wave-resistant limestone structure produced by living organisms, found principally in shallow, tropical marine waters.

Cordillera: A complex group of mountain ranges, systems, and chains.

Creep: The extremely slow, almost continuous movement of soil and other material downslope.

Crest: The highest point or level; summit.

Crevasse: A deep, nearly vertical crack that develops in the upper portion of glacier ice.

Crust: The thin, solid outermost layer of Earth.

Curtain: A thin, wavy or folded sheetlike mineral deposit that hangs from the ceiling of a cave.

Cut bank: A steep, bare slope formed on the outside of a meander.

D

Debris avalanche: The extremely rapid downward movement of rocks, soil, mud, and other debris mixed with air and water.

Debris flow: A mixture of water and clay, silt, sand, and rock fragments that flows rapidly down steep slopes.

Deflation: The lowering of the land surface due to the removal of fine-grained particles by the wind.

Delta: A body of sediment deposited at the mouth of a river or stream where it enters an ocean or lake.

Desert pavement: Surface of flat desert lands covered with a layer of closely packed coarse pebbles and gravel.

Dip: The measured angle from the horizontal plane (Earth's surface) to a fault plane or bed of rock.

Dissolved load: Dissolved substances, the result of the chemical weathering of rock, that are carried along in a river or stream.

Distributaries: The channels that branch off of the main river in a delta, carrying water and sediment to the delta's edges.

Dune: A mound or ridge of loose, wind-blown sand.

E

Earthflow: The downward movement of water-saturated, clay-rich soil on a moderate slope.

Ecosystem: A system formed by the interaction of a community of plants, animals, and microorganisms with their environment.

Ejecta blanket: The circular layer of rock and dust lying immediately around a meteorite crater.

Emergent coast: A coast in which land formerly under water has gradually risen above sea level through geologic uplift of the land or has been exposed because of a drop in sea level.

Eolian: Formed or deposited by the action of the wind.

Erg: A vast area deeply covered with sand and topped with dunes.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Erratic: A large boulder that a glacier deposits on a surface made of different rock.

Esker: A long, snakelike ridge of sediment deposited by a stream that ran under or within a glacier.

F

Fall: A sudden, steep drop of rock fragments or debris.

Fall line: The imaginary line that marks the sharp upward slope of land along a coastal plain's inland edge where waterfalls and rapids occur as rivers cross the zone from harder to softer rocks.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Fault creep: The slow, continuous movement of crustal blocks along a fault.

Fault line: The line on Earth's surface defining a fault; also known as a fault trace.

Fault plane: The area where crustal blocks meet and move along a fault from the fault line down into the crust.

Fault scarp: A steep-sided ledge or cliff generated as a result of fault movement.

Fault system: A network of connected faults.

Flash flood: A flood that occurs after a period of heavy rain, usually within six hours of the rain event.

Firn: The granular ice formed by the recrystallization of snow; also known as névé.

Fjord: A deep glacial trough submerged with seawater.

Floodplain: An area of nearly flat land bordering a stream or river that is naturally subject to periodic flooding.

Flow: A type of mass wasting that occurs when a loose mixture of debris, water, and air moves down a slope in a fluidlike manner.

Flowstone: The general term for a sheetlike mineral deposit on a wall or floor of a cave.

Fold: A bend or warp in a layered rock.

Foothill: A high hill at the base of a mountain.

Footwall: The crustal block that lies beneath an inclined fault plane.

Fore reef: The seaward edge of a reef that is fairly steep and slopes down to deeper water.

Foreset bed: An inclined layer of sand and gravel deposited along the edge of a delta.

Foreshore zone: The area of a beach between the ordinary low tide mark and the high tide mark.

Fracture zone: The area where faults occur at right angles to a main feature, such as a mid-ocean ridge.

Fringing reef: A coral reef formed close to a shoreline.

Fumarole: A small hole or vent in Earth's surface through which volcanic gases escape from underground.

G

Geyser: A hot spring that periodically erupts through an opening in Earth's surface, spewing hot water and steam.

Geyserite: A white or grayish silica-based deposit formed around hot springs.

Glacial drift: A general term for all material transported and deposited directly by or from glacial ice.

Glacial polish: The smooth and shiny surfaces produced on rocks underneath a glacier by material carried in the base of that glacier.

Glacial surge: The rapid forward movement of a glacier.

Glacial trough: A U-shaped valley carved out of a V-shaped stream valley by a valley glacier.

Glaciation: The transformation of the landscape through the action of glaciers.

Glacier: A large body of ice that formed on land by the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity.

Graben: A block of Earth's crust dropped downward between faults.

Graded stream: A stream that is maintaining a balance between the processes of erosion and deposition.

Granular flow: A flow that contains up to 20 percent water.

Gravity: The physical force of attraction between any two objects in the universe.

Ground moraine: A continuous layer of till deposited beneath a steadily retreating glacier.

Groundwater: Freshwater lying within the uppermost parts of Earth's crust, filling the pore spaces in soil and fractured rock.

Gully: A channel cut into Earth's surface by running water, especially after a heavy rain.

Guyot: An undersea, flat-topped seamount.

H

Hanging valley: A shallow glacial trough that leads into the side of a larger, main glacial trough.

Hanging wall: The crustal block that lies above an inclined fault plane.

Headland: An elevated area of hard rock that projects out into an ocean or other large body of water.

Hill: A highland that rises up to 1,000 feet (305 meters) above its surroundings, has a rounded top, and is less rugged in outline than a mountain.

Horn: A high mountain peak that forms when the walls of three or more glacial cirques intersect.

Horst: A block of Earth's crust forced upward between faults.

Hot spot: An area beneath Earth's crust where magma currents rise.

Hot spring: A pool of hot water that has seeped through an opening in Earth's surface.

I

Igneous rock: Rock formed by the cooling and hardening of magma, molten rock that is underground (called lava once it reaches Earth's surface).

Internal flow: The movement of ice inside a glacier through the deformation and realignment of ice crystals; also known as creep.

Invertebrates: Animals without backbones.

K

Kame: A steep-sided, conical mound or hill formed of glacial drift that is created when sediment is washed into a depression on the top surface of

a glacier and is then deposited on the ground below when the glacier melts away.

Karst topography: A landscape characterized by the presence of sinkholes, caves, springs, and losing streams.

Kettle: A shallow, bowl-shaped depression formed when a large block of glacial ice breaks away from the main glacier and is buried beneath glacial till, then melts. If the depression fills with water, it is known as a kettle lake.

L

Lagoon: A quiet, shallow stretch of water separated from the open sea by an offshore reef or other type of landform.

Lahar: A mudflow composed of volcanic ash, rocks, and water produced by a volcanic eruption.

Landslide: A general term used to describe all relatively rapid forms of mass wasting.

Lateral moraine: A moraine deposited along the side of a valley glacier.

Lava: Magma that has reached Earth's surface.

Lava dome: Mass of lava, created by many individual flows, that forms in the crater of a volcano after a major eruption.

Leeward: On or toward the side facing away from the wind.

Levee (natural): A low ridge or mound along a stream bank, formed by deposits left when floodwater slows down on leaving the channel.

Limestone: A sedimentary rock composed primarily of the mineral calcite (calcium carbonate).

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Longshore current: An ocean current that flows close and almost parallel to the shoreline and is caused by the angled rush of waves toward the shore.

Longshore drift: The movement of sand and other material along a shoreline in the longshore current.

Losing stream: A stream on Earth's surface that is diverted underground through a sinkhole or a cave.

M

Magma: Molten rock containing particles of mineral grains and dissolved gas that forms deep within Earth.

Magma chamber: A reservoir or cavity beneath Earth's surface containing magma that feeds a volcano.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Mass wasting: The spontaneous movement of material down a slope in response to gravity.

Meander: A bend or loop in a stream's course.

Mechanical weathering: The process by which a rock or mineral is broken down into smaller fragments without altering its chemical makeup.

Medial moraine: A moraine formed when two adjacent glaciers flow into each other and their lateral moraines are caught in the middle of the joined glacier.

Meltwater: The water from melted snow or ice.

Mesa: A flat-topped hill or mountain with steep sides that is smaller in area than a plateau.

Metamorphic rock: Rock whose texture or composition has been changed by extreme heat and pressure.

Meteor: A glowing fragment of extraterrestrial material passing through Earth's atmosphere.

Meteorite: A fragment of extraterrestrial material that strikes the surface of Earth.

Meteorite crater: A crater or depression in the surface of a celestial body caused by the impact of a meteorite; also known as an impact crater.

Meteoroid: A small, solid body floating in space.

Mid-ocean ridge: A long, continuous volcanic mountain range found on the basins of all oceans.

Moraine: The general term for a ridge or mound of till deposited by a glacier.

Mountain: A landmass that rises 1,000 feet (305 meters) or more above its surroundings and has steep sides meeting in a summit that is much narrower in width than the base of the landmass.

Mudflow: A mixture primarily of the smallest silt and clay particles and water that has the consistency of newly mixed concrete and flows quickly down slopes.

Mud pot: A hot spring that contains thick, muddy clay.

O

Oasis: A fertile area in a desert or other dry region where groundwater reaches the surface through springs or wells.

Ocean basin: That part of Earth's surface that extends seaward from a continental margin.

Oxbow lake: A crescent-shaped body of water formed from a single loop that was cut off from a meandering stream.

P

Paleomagnetism: The study of changes in the intensity and direction of Earth's magnetic field through time.

Passive continental margin: A continental margin that has a broad continental shelf, a gentle continental slope, and a pronounced continental rise; it is marked by a lack of earthquake and volcanic activity.

Peneplain: A broad, low, almost featureless surface allegedly created by long-continued erosion.

Photosynthesis: The process by which plants use energy from sunlight to change water and carbon dioxide into sugars and starches.

Piedmont glacier: A valley glacier that flows out of a mountainous area onto a gentle slope or plain and spreads out over the surrounding terrain.

Pinnacle: A tall, slender tower or spire of rock.

Plateau: A relatively level, large expanse of land that rises some 1,500 feet (457 meters) or more above its surroundings and has at least one steep side.

Plates: Large sections of Earth's lithosphere separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Playa: A shallow, short-lived lake that forms where water drains into a basin and quickly evaporates, leaving a flat surface of clay, silt, and minerals.

Point bar: The low, crescent-shaped deposit of sediment on the inside of a meander.

Pyroclastic material: Rock fragments, crystals, ash, pumice, and glass shards formed by a volcanic explosion or ejection from a volcanic vent.

R

Rapids: The section of a stream where water flows fast over hard rocks.

Reef crest: The high point of a coral reef that is almost always exposed at low tide.

Regolith: The layer of loose, uncemented rocks and rock fragments of various size that lies beneath the soil and above the bedrock.

Rhyolite: A fine-grained type of volcanic rock that has a high silica content.

Rift valley: The deep central crevice in a mid-ocean ridge; also, a valley or trough formed between two normal faults.

Ring of Fire: The name given to the geographically active belt around the Pacific Ocean that is home to more than 75 percent of the planet's volcanoes.

River: A large stream.

Rock flour: Fine-grained rock material produced when a glacier abrades or scrapes rock beneath it.

S

Saltation: The jumping movement of sand caused by the wind.

Sea arch: An arch created by the erosion of weak rock in a sea cliff through wave action.

Seafloor spreading: The process by which new oceanic crust is formed by the upwelling of magma at mid-ocean ridges, resulting in the continuous lateral movement of existing oceanic crust.

Seamount: An isolated volcanic mountain that often rises 3,280 feet (1,000 meters) or more above the surrounding ocean floor.

Sea stack: An isolated column of rock, the eroded remnant of a sea arch, located in the ocean a short distance from the shoreline.

Sediment: Rock debris such as gravel, sand, silt, and clay.

Sedimentary rock: Rock that is formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Shear stress: The force of gravity acting on an object on a slope, pulling it downward in a direction parallel to the slope.

Shock wave: Wave of increased temperature and pressure formed by the sudden compression of the medium through which the wave moves.

Shore: The strip of ground bordering a body of water that is alternately covered or exposed by waves or tides.

Shoreline: The fluctuating line between water and the shore.

Silica: An oxide (a compound of an element and oxygen) found in magma that, when cooled, crystallizes to become the mineral quartz, which is one of the most common compounds found in Earth's crust.

Silt: Fine earthy particles smaller than sand carried by moving water and deposited as a sediment.

Sinkhole: A bowl-like depression that develops on Earth's surface above a cave ceiling that has collapsed or on an area where the underlying sedimentary rock has been eroded away.

Slide: The movement of a mass of rocks or debris down a slope.

Slip face: The steeply sloped side of a dune that faces away from the wind.

Slope failure: A type of mass wasting that occurs when debris moves downward as the result of a sudden failure on a steep slope or cliff.

Slump: The downward movement of blocks of material on a curved surface.

Slurry flow: A flow that contains between 20 and 40 percent water.

Snow line: The elevation above which snow can form and remain all year.

Solifluction: A form of mass wasting that occurs in relatively cold regions in which waterlogged soil flows very slowly down a slope.

Speleothem: A mineral deposit formed in a cave.

Spit: A long, narrow deposit of sand or gravel that projects from land into open water.

Stalactite: An icicle-shaped mineral deposit hanging from the roof of a cave.

Stalagmite: A cone-shaped mineral deposit projecting upward from the floor of a cave.

Strain: The change in a rock's shape or volume (or both) in response to stress.

Strata: The layers in a series of sedimentary rocks.

Stream: Any body of running water that moves downslope under the influence of gravity in a narrow and defined channel on Earth's surface.

Stress: The force acting on an object (per unit of area).

Striations: The long, parallel scratches and grooves produced in rocks underneath a glacier as it moves over them.

Strike: The compass direction of a fault line.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Submarine canyon: A steep-walled, V-shaped canyon that is cut into the rocks and sediments of the continental slope and, sometimes, the outer continental shelf.

Submergent coast: A coast in which formerly dry land has been gradually flooded, either by land sinking or by sea level rising.

Surface creep: The rolling and pushing of sand and slightly larger particles by the wind.

Suspended load: The fine-grained sediment that is suspended in the flow of water in a river or stream.

Swash: The rush of water up the shore after the breaking of a wave.

Symbiosis: The close, long-term association between two organisms of different species, which may or may not be beneficial for both organisms.

Syncline: A downward-curving (concave) fold in rock that resembles a trough.

T

Talus: A sloping pile of rock fragments lying at the base of the cliff or steep slope from which they have broken off; also known as scree.

Tarn: A small lake that fills the central depression in a cirque.

Terminal moraine: A moraine found near the terminus of a glacier; also known as an end moraine.

Terminus: The leading edge of a glacier; also known as the glacier snout.

Terrace: The exposed portion of a former floodplain that stands like a flat bench above the outer edges of the new floodplain.

Tide: The periodic rising and falling of water in oceans and other large bodies of water that results from the gravitational attraction of the Moon and the Sun upon Earth.

Till: A random mixture of finely crushed rock, sand, pebbles, and boulders deposited by a glacier.

Tombolo: A mound of sand or other beach material that rises above the water to connect an offshore island to the shore or to another island.

Topset bed: A horizontal layer of coarse sand and gravel deposited on top of a delta.

Travertine: A dense, white deposit formed from calcium carbonate that creates rock formations around hot springs.

Trench: A long, deep, narrow depression on the ocean basin with relatively steep sides.

Turbidity current: A turbulent mixture of water and sediment that flows down a continental slope under the influence of gravity.

U

Uplift: In geology, the slow upward movement of large parts of stable areas of Earth's crust.

U-shaped valley: A valley created by glacial erosion that has a profile suggesting the form of the letter "U," characterized by steep sides that may curve inwards at their base and a broad, nearly flat floor.

V

Valley glacier: An alpine glacier flowing downward through a preexisting stream valley.

Ventifact: A stone or bedrock surface that has been shaped or eroded by the wind.

Viscosity: The measure of a fluid's resistance to flow.

Volcano: A vent or hole in Earth's surface through which magma, hot gases, ash, and rock fragments escape from deep inside the planet; the term is also used to describe the cone of erupted material that builds up around that opening.

V-shaped valley: A narrow valley created by the downcutting action of a stream that has a profile suggesting the form of the letter "V," characterized by steeply sloping sides.

W

Waterfall: An often steep drop in a stream bed causing the water in a stream channel to fall vertically or nearly vertically.

Wave crest: The highest part of a wave.

Wave-cut notch: An indentation produced by wave erosion at the base of a sea cliff.

Wave-cut platform: A horizontal bench of rock formed beneath the waves at the base of a sea cliff as it retreats because of wave erosion.

Wave height: The vertical distance between the wave crest and the wave trough.

Wavelength: The horizontal distance between two wave crests or troughs.

Wave trough: The lowest part of a wave form between two crests.

Weathering: The process by which rocks and minerals are broken down at or near Earth's surface.

Windward: On or toward the side facing into the wind.

Y

Yardang: Wind-sculpted, streamlined ridge that lies parallel to the prevailing winds.

Yazoo stream: A small stream that enters a floodplain and flows alongside a larger stream or river for quite a distance before eventually flowing into the larger waterway.

Z

Zooxanthellae: Microscopic algae that live symbiotically within the cells of some marine invertebrates, especially coral.

Fault

Earth's crust, the surface layer of the planet, is not solid and unbroken. The forces that rage inside the planet have fractured this brittle layer. Some of these fractures, called faults, lie beneath the surface of the crust. Other faults, however, have ruptured the surface, cracking the crust into various-sized blocks of rock. These blocks dip and rise along faults in response to pressure underground. One block may move up while the other moves down. Sometimes the movement is enough to form valleys or mountains. Other times that movement is not vertical but horizontal, as one block slips along the fault relative to the block on the other side.

Movement of crustal blocks along faults may be regular and slow or sporadic and sudden. When two blocks are forced to move against each other but are locked into position, stress builds up. When that stress becomes greater than the forces holding the blocks together, the blocks are forced to move suddenly and violently. The ground vibrations accompanying that release of energy are better known as an earthquake. There are more than one million earthquakes a year on Earth, though more than 60 percent of those are too faint to be felt. Crustal movements along faults are occurring continuously across most of the planet's surface.

The shape of the land

A fault is defined as a crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other. (When no movement has occurred, the fracture is known as a joint). When a fault breaks the planet's surface, it may range in length from a few inches to thousands of miles. The line on Earth's surface defining the fault is known as the fault line or fault trace.

Aerial view of the San Andreas Fault slicing through the Carrizo Plain just east of San Luis Obispo, California. The fault runs along most of the entire Pacific coast of California, extending for more than 800 miles. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE U.S. GEOLOGICAL SURVEY.**

A fault may extend downward from the fault line at least several miles into the crust. The area where crustal blocks meet and move along a fault from the fault line down into the crust is known as the fault plane. The fault plane may be vertical in relation to Earth's surface. If so, the fault is known as a vertical fault. If the fault plane is slanted, the fault is known as an inclined fault. The crustal block that lies beneath the fault plane in an inclined fault is referred to as the footwall. The block that is above or seems to rest on the fault plane is referred to as the hanging wall. These terms do not apply if the fault plane is vertical.

Words to Know

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid outermost layer of Earth.

Dip: The measured angle from the horizontal plane (Earth's surface) to a fault plane or bed of rock.

Fault creep: The slow, continuous movement of crustal blocks along a fault.

Fault line: The line on Earth's surface defining a fault; also known as a fault trace.

Fault plane: The area where crustal blocks meet and move along a fault from the fault line down into the crust.

Fault scarp: A steep-sided ledge or cliff generated as a result of fault movement.

Fault system: A network of connected faults.

Footwall: The crustal block that lies beneath an inclined fault plane.

Graben: A block of Earth's crust dropped downward between faults.

Hanging wall: The crustal block that lies above an inclined fault plane.

Horst: A block of Earth's crust forced upward between faults.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Strike: The compass direction of a fault line.

The measure of the angle between Earth's surface and the fault plane is called the fault's dip. Faults are classified according to how steeply they dip and the relative movement of the crustal blocks on either side of a fault. The movement of crustal blocks along a fault has been measured from 0.4 inch (1 centimeter) to 50 feet (15 meters). As mentioned, that movement may be slow or rapid. Slow, continuous movement is known as fault creep. Some faults creep from 0.5 inch (1.3 centimeters) to 4 inches (10 inches) a year.

Normal faults occur when underground pressure causes the crust to stretch or pull apart. When this happens, the hanging-wall block (the one above the fault plane) drops down relative to the footwall block. Most normal faults have dips of about 60 degrees. The resulting steep-sided ledge or cliff created at the top of the footwall block is called a fault scarp.

Normal faults usually occur in elevated regions such as plateaus. They are not often found singly in a landscape; typically, they occur in multiple arrangements, often in pairs of parallel faults. When movement

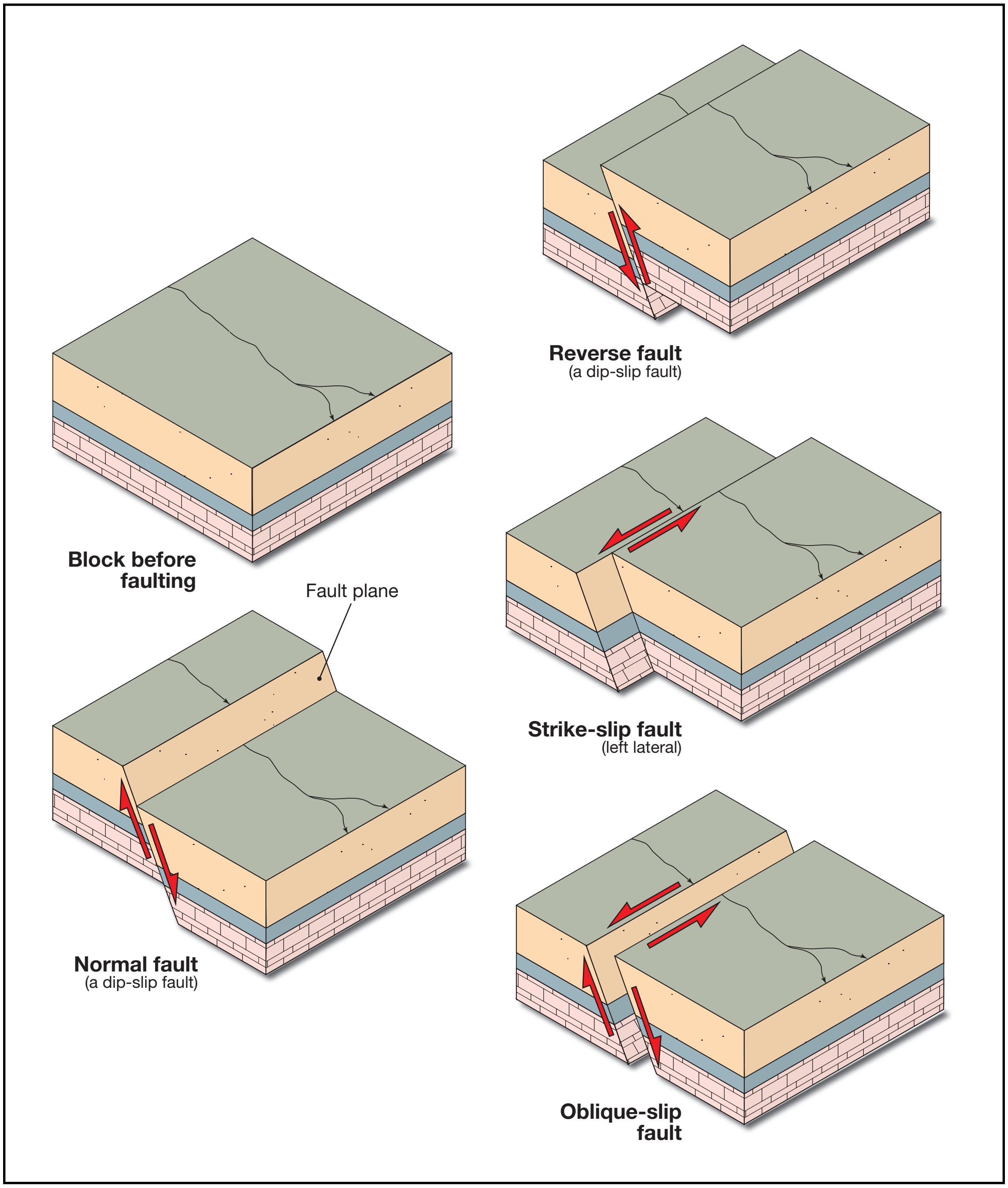
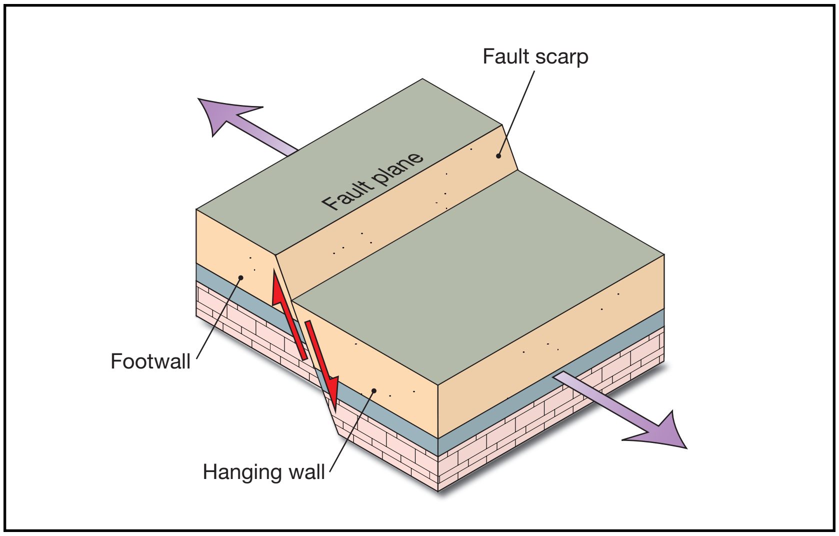


Illustration of four types of faults. Faults are classified according to how steeply they dip and the relative movement of the crustal blocks on either side of a fault. Normal faults, for example, occur when underground pressure causes the crust to stretch or pull apart, whereas reverse faults occur when underground pressure causes the crust to compress.



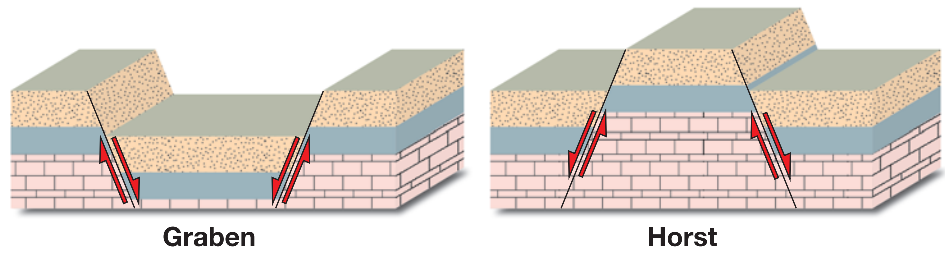
When underground pressure causes the crust of normal faults to stretch or pull apart, the hanging-wall block drops down relative to the footwall block. The resulting steep-sided ledge or cliff created at the top of the footwall block is called a fault scarp.

takes place between parallel normal faults whose fault planes are angled downward toward each other (such as \ /), a crustal block may drop down between them. This down-dropped block, which forms a valley between the opposing footwall blocks, is called a graben (pronounced GRAH-bin). If the fault planes of the parallel faults are angled downward away from each other (such as / \), a crustal block between them may be elevated. This uplifted block is called a horst. A large horst that is lifted high can form a fault-block mountain. (For further information on fault-block mountains, see the **Mountain** chapter.) A series of uplifted and down-dropped blocks across a landscape is called a horst and graben structure. This feature is common in the western United States and northern Mexico.

In contrast, reverse faults occur when underground pressure causes the crust to compress, pushing blocks together. As two blocks are pushed together at a fault, the hanging-wall block is pushed up and over the footwall block. A fault scarp is created, but it takes the form of an overhanging ledge.

A special type of reverse fault is called a thrust fault (sometimes also called an overthrust fault). The fault plane of a thrust fault lies at a low angle to Earth's surface. This angle is less than 30 degrees. Because the angle is so low, the hanging-wall block is thrust up and over the footwall block. The movement is mainly horizontal as the hanging-wall block travels over the footwall block, sometimes for thousands of feet.

These previous faults are all categorized as dip-slip faults because the movement of the fault blocks is up or down along the fault plane. If the



When fault planes are angled downward toward each other, a down-dropped block, called a graben, is formed. If the fault planes of the parallel faults are angled downward away from each other, a crustal block between them may be elevated. This uplifted block is called a horst.

movement is horizontal, with the two fault blocks scraping along side-by-side, the fault is known as a strike-slip fault (sometimes also known as a transcurrent or transverse fault). Strike is the compass direction—north, south, east, west—of the fault line or trace. The fault plane in a strike-slip fault is vertical or nearly vertical. There is little or no fault scarp created along this type of fault.

Strike-slip faults are classified according to the direction of motion of the blocks on either side of the fault. If the block on the opposite side of a strike-slip fault has moved to the left, it is a left-lateral strike-slip fault. If it has moved to the right, it is a right-lateral strike-slip fault. The relative motion, left or right, is the same regardless on which block an observer stands. The famous San Andreas Fault in California is a right-lateral strike-slip fault. Land west of the fault is edging northwest; land east is edging southeast.

In some faults, the movement is neither purely vertical nor horizontal, but a combination of the two. In instances where a fault has both normal and strike-slip movement or reverse and strike-slip movement, it is known as an oblique-slip fault. Although this type of fault is not unusual, it is far less common than normal, reverse, or strike-slip faults.

Forces and changes: Construction and destruction

Any rock subjected to intense stress or pressure over time will deform. At higher temperatures and pressures, rock will soften and bend. Geologists call this ductile deformation. At lower temperatures and pressures, however, rock will break or fracture instead of bending. This type of deformation, called brittle deformation, happens to rock in the upper part of Earth's crust. Faults are a clear example of brittle deformation.

The stress that is continually acting on and deforming Earth's surface may be in different forms: tensional stress, which stretches or pulls rock; compressional stress, which squeezes and squashes rock; and shear stress, which changes the shape of rock by causing adjacent parts to slide past

Blindly Faulting Los Angeles

In 1999, geologists mapped for the first time a major fault located directly beneath the city of Los Angeles, California. Named the Puente Hills Fault, it is a blind thrust fault, a type of thrust fault that does not break Earth's surface. This makes it difficult to identify. Comprised of three sections, it runs for nearly 25 miles (40 kilometers) under downtown Los Angeles, through Santa Fe Springs, and into the Coyote Hills of northern Orange County. The fault is approximately 12.5 miles (20 kilometers) wide. It is located about 2 miles (3.2 kilometers) beneath the surface in the center of Los Angeles, then dips to 10 miles (16 kilometers) underground as it continues northward. The entire fault system covers an area of roughly 250 square miles (650 square kilometers).

In the spring of 2003, geologists released a study reporting that the fault is capable of generating major earthquakes. They estimated that the fault has been responsible for some of the most severe earthquakes to strike southern California in the last 11,000 years. They also believed that the fault was responsible for the 1987 earthquake that hit near the city of Whittier, located about 12 miles (19 kilometers) from the center of downtown Los Angeles. Although a major earthquake along the fault will probably occur only once every 2,000 years, geologists believe many of the buildings in downtown Los Angeles will not be able to withstand such an earthquake when it comes.

one another. All of these stresses are directly related to events occurring deep within the planet. Earth's internal processes, from the core to the crust, have put the surface of the planet in motion, constantly changing its shape.

From the core to the crust

Geologists divide the surface and the interior of Earth into layers. At the very center of the planet is the core. It begins at a depth of about 1,800 miles (2.900 kilometers) beneath the surface and extends to a depth of 3,960 miles (6,370 kilometers). The core is composed of the metal elements iron and nickel, and it has a solid inner portion and a liquid outer portion. Temperatures in the core are estimated to exceed 9,900°F (5,482°C).

Above the core lies the thick mantle, which forms the main bulk of the planet's interior. Above the mantle lies the brittle crust, the thin shell of rock that covers Earth. The upper portion of the mantle is rigid. Geologists call the combination of this section of the mantle the overlying crust and the lithosphere (pronounced LITH-uh-sfeer). The lithosphere measures roughly 60 miles (100 kilometers) thick. The part of the mantle immediately beneath the lithosphere is called the asthenosphere (pronounced as-THEN-uh-sfeer). This layer is composed of partially melted rock that has the consistency of putty and extends to a depth of about 155 miles (250 kilometers).

The driving force in Earth's interior

The heat energy generated in the core is extreme. Earth's interior would melt if this energy were not released in some manner. Much like the circulating currents produced in a pot of boiling liquid on a hot stove, this energy is transported to the surface of the planet through currents called convection currents.

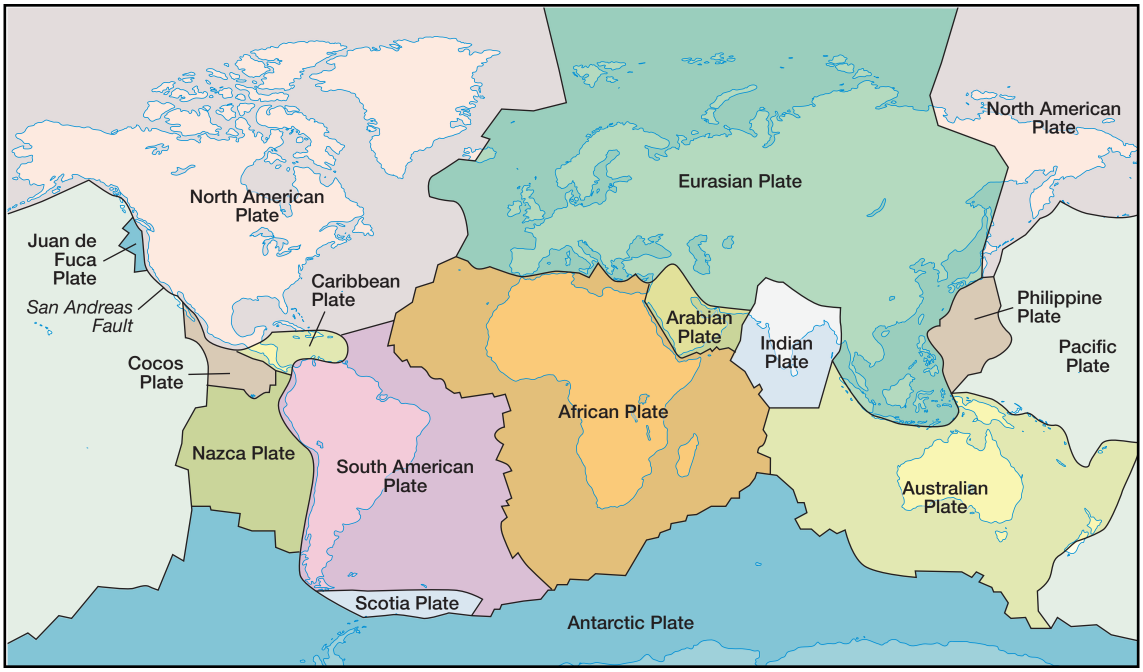
When a liquid in a pot begins to boil, it turns over and over. Liquid heated at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense (lighter). Once at the surface, the heated liquid cools and becomes dense (heavier) once more. It then sinks back down to the bottom to become reheated. This continuous motion of heated material rising, cooling, and sinking forms the circular currents known as convection currents.

Similarly, when mantle rocks near the core are heated, they become less dense than the cooler, upper mantle rocks. These heated rocks then slowly rise through the mantle. When they reach the lithosphere, the heated rocks move along the base of the lithosphere, losing heat. Cooling and becoming denser, they then sink back toward the core, only to be heated once again. Scientists estimate that convection currents move mantle rock only an inch or two a year. It takes about 200 million years for heated rock to make a circular trip from the core to the lithosphere and back again.

Plate tectonics and faults

The slowly moving convection currents are able to release their heat energy near the surface of the planet because the lithosphere is broken into many pieces called tectonic or crustal plates. These plates, which vary in size and shape, "float" on the soft, semi-molten (melted) asthenosphere. As the convection currents move under the lithosphere, they exert dragging forces on the rigid tectonic plates above them. This causes the plates to move. Fitting together like pieces in a jigsaw puzzle, the plates are in constant contact with each other. Because they are interconnected, no single plate can move without affecting others. The movement or activity of one plate can influence another plate located thousands of miles away. The scientific theory explaining plates and their movements and interactions is called plate tectonics (a hypothesis is an educated guess; a theory is a principle supported by extensive scientific evidence and testing).

In general, tectonic plates inch their way across the surface of Earth at a rate no faster than human fingernails grow, roughly 2 inches (5 centimeters)



Earth's surface is broken into seven large and many small tectonic plates. These plates, each about 50 miles thick, move relative to one another an average of a few inches a year.

per year. As they move, the plates slide along each other (transform), move into each other (converge), or move away from each other (diverge). Plate margins are the boundaries or areas where the plates meet and interact.

The stresses that produce faulting are usually related to movements along plate margins. Although associated mainly with plate margins, faults can occur anywhere on Earth where the crust is weak. Normal faults are common in regions where the crust is being stretched and thinned as a result of plates diverging. Reverse faults are common in regions where the crust is being compressed and thickened as a result of plates converging. Thrust faults are even more common at convergent plate margins, where plates are moving toward one another, compressing, and often forming high mountains. Strike-slip faults are formed where unequal pressure causes rock sections to slip past each other. Major strike-slip faults occur between plates that are transforming. These special strike-slip plates are known as transform faults.

Spotlight on famous forms

Denali fault system, Alaska

Denali (pronounced de-NAHL-ee) is the name given by the Athabascan-speaking native people of Alaska to the mountain known as Mount McKinley, the highest mountain in North America at 20,320 feet

The Denali Fault runs for about 750 miles in Alaska and marks the boundary where the Pacific Plate and the North American Plate meet. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

(6,194 meters). Translated, it means "the Great One." Denali is also the name of a great fault system (a network of connected faults) that extends for about 750 miles (1,200 kilometers) from southeast to southcentral Alaska. Predominantly composed of right-lateral strike-slip faults, Denali is one of the longest strike-slip fault systems in the world.

The Denali Fault marks the boundary where the Pacific Plate and the North American Plate meet and interact. Land south of the fault moves westward, and land north of the fault moves eastward. Geologists estimate that the two sides on the fault have slipped roughly 240 miles (386 kilometers) over the last 60 million years. On average, the plates move about 0.4 inch (1 centimeter) a year along the fault.

At times during the Denali Fault's history, the plates along it have locked up. Subsequent pressure builds up until it is finally released in an earthquake. This is what occurred on November 2, 2002, when an earthquake struck the fault about 90 miles (145 kilometers) south of Fairbanks, Alaska. One of the largest ever recorded in the United States, the earthquake measured 7.9 on the Richter scale (a scale developed by American seismologist Charles Richter to describe the amount of energy released by an earthquake). The earthquake ruptured 155 miles (260 kilometers) of the fault. Movement on the fault caused ground north of the fault to move eastward up to 26 feet (8 meters) relative to ground south of the fault.

New Madrid fault system, Central United States

The New Madrid fault system is a series of faults beneath the continental crust in the central United States. The system exists in the middle of the North American plate where tensional stress created a weak spot known as the Reelfoot rift. Called an intraplate fault system, it is a type of fault system that is still not clearly understood by geologists.

The faults along the system—normal, reverse, and strike-slip—lie 10 to 12 miles (16 to 19 kilometers) beneath Earth's surface. They create no fault lines. The New Madrid fault system extends at least 150 miles (240 kilometers) from Cairo, Illinois, to Marked Tree, Arkansas. It runs beneath the lines of five states: Illinois, Kentucky, Missouri, Tennessee, and Arkansas. It runs beneath the Mississippi River in three areas and the Ohio River in two areas. Movement along the system ranges from 1.5 to 2.8 inches (4 to 7 centimeters) a year.

More earthquakes occur in the area of the New Madrid fault system than in any other area of the United States east of the Rocky Mountains. More than 200 earthquakes are recorded on the system each year, but the vast majority of those cannot be felt. Only about 8 to 10 earthquakes a year are large enough to be felt (measuring 3.0 or more on the Richter scale).

In the winter of 1811–1812, three earthquakes centered on the New Madrid fault system were felt across the continent, from Canada to the Gulf of Mexico, and from the Rocky Mountains to the Atlantic coast. Present-day geologists estimate the largest of the earthquakes measured 8.8 on the Richter scale. The effects were widespread and severe. The most intense earthquake altered the course of the Mississippi River and created a depression in northwest Tennessee that filled with water to become Reelfoot Lake. Aftershocks (earthquake tremors that occur after the main shock) were felt around the region for a year afterward.

San Andreas Fault, California

The well-known San Andreas Fault in California is perhaps the most-studied fault in the world. It is the main fault in an intricate fault system; many smaller faults branch from and join the larger fault. The fault system is located along almost the entire Pacific coast of California, extending for more than 800 miles (1,287 kilometers). Its fault plane reaches down at least 10 miles (16 kilometers) into Earth's crust. Its fault line is a zone of crushed and broken rock that ranges from a few hundred feet to 1 mile (1.6 kilometers) wide.

A right-lateral strike-slip fault, the San Andreas Fault represents the boundary where the North American Plate and the Pacific Plate meet. Along the fault, the two plates scrape against each other as the North American Plate slips to the southeast and the Pacific Plate slips to the northwest. The rate of movement along the fault is about 0.8 to 1.4 inches (2 to 3.5 centimeters) a year. Because it is situated between plates that are transforming, the San Andreas Fault is also considered a transform fault.

Geologists believe the San Andreas Fault came into existence about 15 to 20 million years ago. They estimate that the total movement along the fault since that time has been at least 350 miles (563 kilometers). Thousands of earthquakes, most of which are too small to be felt, occur along the fault regularly. Over the last 1,500 years, large earthquakes along the fault have occurred every 150 years or so. The last recorded large earthquake on the southern portion of the fault took place in 1857. In 1906, a devastating earthquake occurred in the San Francisco region. The plates, which had been locked along the fault, ruptured and tore the ground apart along a 290-mile (467-kilometer) stretch. The ground west of the fault shifted northward as much as 21 feet (6.4 meters) in places.

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Floodplain

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

Floodplains are landscapes shaped by running water. As streams and their larger forms, rivers, flow across the surface of land, they transport eroded rock and other material. (Erosion is the gradual wearing away of Earth surfaces through the action of wind and water.) At points along that journey, when their flow slows, the material they carry is dropped to create what are termed depositional landforms. Among these landforms are deltas and floodplains. (For further information on deltas, see the **Delta** chapter.)

The flooding of a stream or river is a natural and recurring event. Ancient cultures that lived along these waterways welcomed the flooding of the adjacent land. The material deposited enriched the soil, increasing its fertility for farming. For those along the Nile River in ancient Egypt, the annual flood was the "gift of the Nile." In many modern societies, however, the lands bordering rivers and streams are sites of homes, businesses, and other urban development. The flooding of this land is often a costly natural disaster.

The shape of the land

A floodplain (sometimes spelled flood plain) is an area of nearly flat land bordering a stream or river that is naturally subject to periodic flooding. A flood occurs when the flow of water in a stream becomes too high to be accommodated in the normal stream channel. The channel of a stream is the trench or depression filled with water as it flows across a landscape. The sides of the channel are known as the stream's banks. The bottom is the stream bed.

In a flood, water flows over the stream's banks, submerging the adjacent land. Depending on the amount of water, the flood may cover all or part of the floodplain. As water flows out of the stream's channel, it

A floodplain, like this one along the Limpopo River in southern Africa, is an area of nearly flat land bordering a stream or river that is naturally subject to periodic flooding. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

immediately slows down. The material carried by the stream—sediment such as gravel, sand, silt, and clay—is deposited on the floodplain. Large particles are deposited first, and much of this material is laid down alongside both banks. This process, repeated over and over, forms low ridges or mounds known as natural levees (pronounced LEH-veez). Levees built by humans along rivers in an effort to control flooding are known as artificial levees. Natural levees are composed primarily of gravel and sand. They are steep on the side facing the stream channel and gently sloping on the other side. Varying greatly in size, levees may be several feet in height and up to a mile or more in width.

The finer sediments transported by the floodwater, silt and clay, are deposited on the floor of the floodplain away from the levees. The general term for sediment deposited by running water is alluvium (pronounced ah-LOO-vee-em). Because floodplains are covered with alluvium, they are often called alluvial plains. Lower, poorly drained areas on the floodplain that not only collect alluvium but also retain water are known as backswamps.

Floodplains are widened as a stream snakes its way across a landscape. Streams and rivers rarely flow in straight lines. They have a natural tendency to flow along a path of least resistance, eroding any soft material along their banks. Because of this, many stream channels form a series of smooth bends or curves called meanders (pronounced me-AN-ders). The term comes from the Menderes River in southwest Turkey, which is noted for its snakelike or winding course. As a stream begins to meander, erosion will take place on the outer parts of the bends or curves where the velocity or speed of water is highest. These eroded areas are called cut banks. Sediment will be deposited along the inner bends where the velocity is lowest. These deposits are known as point bars. As erosion and deposition continues, a stream tends to change shape and shift position across its floodplain, which enlarges in response to the stream's back-and-forth movement.

Eventually, a meander forms a tighter and tighter curve until it almost becomes a complete loop. The stream then shortens its course by eroding through the intervening land or neck of the loop, especially during times of flooding. Sediment is deposited, isolating the meander from the stream. Still filled with water, the crescent-shaped meander is called an oxbow lake (because it resembles the U-shaped collar used with teams of oxen). In Australia, an oxbow lake is known as billabong (pronounced bill-ah-BONG); in Louisiana and Mississippi, it is sometimes called a bayou (pronounced BY-oo). Over time, as the floodplain is repeatedly submerged under water, alluvium fills an oxbow lake, turning it into a marsh and eventually into a meander scar. The dry meander scar, which typically only holds water during rains, still retains the shape of the original meander.

Words to Know

Alluvium: A general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Backswamp: The lower, poorly drained area of a floodplain that retains water.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Levee (natural): A low ridge or mound along a stream bank, formed by deposits left when floodwater slows down on leaving the channel.

Meander: A bend or loop in a stream's course.

Oxbow lake: A crescent-shaped body of water formed from a single loop that was cut off from a meandering stream.

Silt: Fine earthy particles that are smaller than sand and carried by moving water and deposited as a sediment.

Terrace: The exposed portion of a former floodplain that stands like a flat bench above the outer edges of the new floodplain.

Yazoo stream: A small stream that enters a floodplain and flows alongside a larger stream or river for quite a distance before eventually flowing into the larger waterway.

A small stream that enters a floodplain and flows alongside a larger stream or river for quite a distance is known as a yazoo stream or yazoo tributary. It helps drain the floodplain, but is often prevented from joining the main stream by the stream's natural levee. Only when it finds a low or weak place in the levee does it flow naturally into the larger stream. The term describing this type of small stream comes from the Yazoo River, which flows parallel to the Mississippi River for 175 miles (282 kilometers) before it joins with the larger river.

Over long periods of time, a stream or river may erode its bed down to a lower level, putting its old floodplain out of reach of flooding. A new floodplain then forms with the old floodplain standing above its outer edges in the form of a flat bench. This exposed portion of the former floodplain is known as a terrace. (For more information, see the **Stream and river** chapter.)

Forces and changes: Construction and destruction

Running water is the primary force of erosion on the planet. Streams and major rivers are continuously at work moving rock fragments and dissolved materials from elevated landmasses to oceans, lakes, and other streams and rivers. Worldwide, streams transport 16 billion tons (14.5 billion metric tons) of sediment per year. They alter landscapes through both erosion and deposition.

Life of a stream

Geologists characterize streams as youthful, mature, and old. When a stream is in its youthful stage, it has a fairly straight channel and a steep gradient (the slope it runs down). It generally flows in a V-shaped valley in a highland or mountainous area. Its velocity is high, and it is actively lowering its channel through erosion in order to reach base level. This refers to the point at which the stream or river reaches the elevation of the large body of water, such a lake or ocean, into which it drains. While aided by gravity, a stream will downcut or erode its channel deeper and deeper in order to reach the level of its final destination as quickly as possible. If the difference in height between the stream or river and its destination is great, so will be the erosive or cutting force of the stream. In this stage, a stream has little, if any, floodplain.

By the time a stream reaches its mature stage, its gradient and velocity are moderate. The valley it flows through is more U-shaped with rounded hills. Because it has slowed down, the stream begins to meander. While it is still eroding downward, the stream's main force of erosion is lateral (horizontal) as it begins winding back and forth, carving out a valley floor between valley walls or bluffs. Periodically, the stream will flood all or a part of its valley, depositing alluvium on its developing floodplain.

An old age stream has reached its base level, and its gradient and velocity are very low. It has lost its ability to erode downward. In fact, it deposits as much material as it erodes. The stream meanders greatly in its nearly flat valley. It has an extensive, well-developed floodplain marked with oxbow lakes.

Moving material

Streams and rivers are conduits for transporting sediment. The ability of a stream to move sediment depends on the velocity of water in the stream and the size of the sediment particles. Water moving at a low velocity can move only small, fine particles such as sand, silt, and clay. Sand is a mineral particle with a diameter between 0.002 and 0.08 inch (0.005 and 0.2 centimeter); silt is a mineral particle with a diameter between 0.00008 and 0.002 inch (0.0002 and 0.005 centimeter); clay is a mineral particle with a diameter less than 0.00008 inch (0.0002 centimeter). Water moving at a high velocity can move both small particles and large, coarse particles such as boulders.

A stream will continue to carry its load of sediment as long as its velocity remains constant or increases (if it increases, it can carry an even larger load). Any change in the geography of the landscape that causes a stream channel to bend or rise will slow the flow of water in a stream. As soon as a stream's speed decreases, it loses the ability to carry all of its load and a portion will be deposited, depending on how much the stream slows down. Particles will be deposited by size with the largest settling out first.

What Is a 100-year Flood?

Large floods are often given designations that describe the statistical probability or chance when they might occur. A flood can be termed a 10-, 20-, 50-, 100-, or 500-year flood based on its expected recurrence. The larger the flood, the larger the "year." A 100-year flood, for example, is determined to be the maximum amount of flood to be expected in a 100-year period. A 20-year flood is the maximum amount of flood to be expected in a 20-year period.

This does not mean, however, that a 100-year flood will strike only once every one hundred years. It means that there is a one in one hundred, or 1 percent, chance of a flood of such magnitude occurring in any given year. Depending on rain and other weather conditions, a 100-year flood may be followed by another similar flood only a month, a year, or twenty years later.

In March 1973, as a result of rain and snow melt, a 100-year flood occurred on the Mississippi River. Just twenty years later, the Mississippi River was subjected to an even larger flood. One of the largest floods in U.S. history, it affected some 16,000 square miles (41,000 square kilometers) and caused property damage in excess of $15 billion. Forty-eight people died in the severe flooding.

Floods

Floods occur when excessive rainfall or melting snow produces more water than the soil can absorb and a stream can normally carry in its channel. Several things happen to a stream when it floods. The increase in the amount of water causes the stream to flow much more rapidly than usual. This, in turn, greatly increases the amount and size of the sediment the stream can transport. Large boulders in stream beds are moved during floods.

When a stream overflows its banks, its floodplain increases the area of the stream's channel. Flowing in this now much-wider channel, the water immediately loses velocity, and its load of sediment is deposited. As is always the case, larger particles drop out first, forming levees alongside the stream. The finer-grained silts and clays are carried farther out onto the floodplain where they settle after the waters of the flood recede.

A floodplain becomes flooded on average once every year or two, most often during the season with the highest amount of rainfall. As the flooding process occurs over and over, meander curves enlarge, alluvium is constantly reworked, and the floodplain widens. The continual wetting and drying causes the sediment to be compacted in the levees. The highest points on a floodplain, natural levees may grow large enough to control the amount of flooding that occurs.

The Tonle Sap Great Lake in Cambodia is the largest freshwater lake in Southeast Asia. Every year the waters of the Mekong River flood into the lake to inundate some 1.25 million hectares of land for a period of several months. Cambodian culture has adapted to and flourished with the annual flooding, and life there is closely connected with the rise and fall of the waters. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Sought-after land

Silt and clay deposited on a floodplain make the soil there extremely fertile. As a result, a floodplain is rich agricultural land. The disadvantage of farming on a floodplain is the natural hazard of floods. Ancient civilizations were aware of the recurring nature of floods on streams and rivers, and they planned their plantings accordingly. In the present day, rivers are important sources of water, power, and transportation. Fertile floodplains are sites of increasing urban development.

To control small annual floods that threaten homes and businesses, many communities have erected artificial levees. These walls built along a river to prevent high water from leaving the channel seem to work well for small floods. However, the levees upset the natural function of a floodplain, which acts as a reservoir for the excess water. Instead, the flood moves downstream until it finds a place not protected by artificial levees. And no artificial levee can be constructed high enough to contain very large, unpredictable floods.

The building of dams is another method used to control flooding, and these structures work to a degree. They store water in artificial reservoirs that can be used during dry seasons or at other times when water levels are low. The release of that stored water in a controlled manner can also help generate electricity.

Like artificial levees, however, dams may be overwhelmed by large floods, leading to disaster for those living downstream of the dam. Dams also trap sediment, so land downstream is deprived of material that would make it fertile. The natural conditions on a floodplain are destroyed, and farmers must turn to chemical fertilizers and other artificial means to help crops grow. This increases both economic and environmental cost. Over the course of perhaps a few hundred years, the sediment trapped by a dam will eventually fill its reservoir, and the dam will become useless.

Spotlight on famous forms

Mississippi River floodplain, United States

The Mississippi River is one of the world's great rivers in terms of both the amount of water it carries and its length. It flows south across the United States, somewhere east of the country's center, and empties into the Gulf of Mexico in a great delta. It runs for about 2,350 miles (3,780 kilometers). It has many tributaries, the most important of which are the Arkansas, Ohio, and Missouri Rivers.

The Mississippi River is divided into two main sections: the upper Mississippi runs from its source in Minnesota to the city of Thebes in southern Illinois where it meets the Ohio River, and the lower Mississippi runs from this point south to the Gulf of Mexico. The river's floodplain encompasses more than 30 million acres (12 million hectares). Most of this floodplain, approximately 25 million acres (10 million hectares), occurs adjacent to the lower Mississippi, which meanders in great loops. Natural levees, oxbow lakes, and marshes mark this area.

The Mississippi River is one of the most heavily engineered natural features in the United States. The character of its floodplain has changed to accommodate agriculture and urban development. Ninety percent of the floodplain lies behind levees, many of which have been artificially created. Twenty-eight locks and dams were constructed on the upper Mississippi River to allow the passage of ships. As a result, much of the river's floodplain fails to receive its revitalizing seasonal floods. Extensive water pollution has also affected the river and its floodplain.

Nile River floodplain, Egypt

The Nile River is the longest river in the world. It runs approximately 4,160 miles (6,695 kilometers) from the Luvironza River in Burundi in central Africa to the Mediterranean Sea on the northeast coast of Egypt.

It flows toward the Mediterranean, draining about 1,100,000 square miles (2,850,000 square kilometers) of land, which is about one-tenth of the area of the African continent.

In ancient times, the Nile River flooded annually, caused by rains in central Africa and melting snow and rains in the Ethiopian highlands. The river was at its lowest point in May, but from June to August it rose rapidly, carrying great quantities of silt in its waters that flowed out over the river's floodplain. The flood was at its highest point in mid-September. By October the waters began to recede, leaving pools of water in backswamps. After the water was absorbed by the soil, the ancient Egyptians planted their crops in the fertile floodplain.

Part of the upper Mississippi River cutting through sandstone. The river's floodplain encompasses more than 30 million acres and mostly occurs adjacent to the lower Mississippi. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

In 1970 the Egyptian government completed construction of the Aswan High Dam on the Nile just south of the city of Aswan, ending the annual floods on the river. The dam, which formed the artificial Lake Nasser behind it, helps provide hydroelectric power and water for irrigation projects. It has also prevented silt from being carried further downstream, trapping 98 percent of the river's rich sediments. Since then, farmers along the Nile have been forced to use large amounts of chemical fertilizers, which have washed into the river, contaminating it and other

The Pantanal, which covers more than 77,000 square miles in Brazil, is considered one of Earth's richest ecosystems. It is a landscape of swamps, seasonally flooded grasslands and woodlands, and different types of forest. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

water sources. Because the river does not bring new sediment to areas downstream, soil erosion has become an additional problem.

Pantanal, Brazil

The Pantanal (pronounced pen-te–NAL; Portuguese for "swamp") is a land area covering approximately 77,220 square miles (200,000 square kilometers). Lying mostly in west-central Brazil, the Pantanal also reaches into eastern Bolivia and northeastern Paraguay. During the wet season, from November to April, this vast floodplain of the Paraguay River and its tributaries becomes partially submerged. Average annual rainfall in this area measures between 39 and 55 inches (100 and 140 centimeters).

The slope of the land is very slight, and the rivers and streams cannot carry the excess amount of water. The floodplain is swamped by a flood that takes six months to travel the length of the Pantanal from north to south. Areas of the floodplain are alternately flooded, then left dry with only a few spots of water remaining.

The Pantanal is considered one of Earth's richest ecosystems (an ecosystem is a system formed by the interaction of a community of plants, animals, and microorganisms with their environment). It is a landscape of swamps, seasonally flooded grasslands and woodlands, and different types of forest. This mixture helps the Pantanal house the highest concentration of wildlife in both North and South America. Approximately 700 species of birds inhabit the area. It is also one of the last refuges for many threatened South American mammals, including jaguars, pumas, manned wolves, giant otters, giant anteaters, giant armadillos, and marsh deer.

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Geyser and hot spring

An eponym (pronounced EH-puh-nim) is something or someone that gives its name to everything of its type. In geology, two general landforms derive their names from those of specific examples. Vulcano is the name of an island in the Tyrrhenian Sea north of Sicily. Every volcano on the planet owes its name to this small volcanic island. Geysir (Icelandic for "gusher") is the name of an erupting flow of heated water from the ground in Iceland. The name, in the form geyser, is applied to all such landforms that eject a column of hot water.

Volcano and geyser share more than the fact they derive from eponyms. Both arise as the result of volcanic activity. Whereas volcanoes spew lava (called magma when it is beneath Earth's surface), geysers emit hot water and steam. The activity of geysers is labeled hydrothermal (from the Greek words *hydro*, meaning "water," and *therme*, meaning "heat"). Hydrothermal activity also creates hot springs, fumaroles, and mud pots. Some of these landforms emit small-scale eruptions; all are beautiful and delicate.

The shape of the land

A geyser is considered a type of hot spring, which is a pool of hot water that has seeped through a vent or opening in Earth's surface. By definition, the temperature of the water is at least 15°F (8.3°C) warmer than the average temperature of the surrounding air. It can reach as high as 200°F (93°C). Normal hot springs do not erupt, but may seem to churn and "boil" as gases from underground pass through them. When the water that feeds a hot spring passes through rocks underground, it may dissolve minerals from the rocks and bring them to the surface. If those rocks are volcanic, then the water carries silica to the surface. (Silica is the most abundant element found in magma.) At the surface, the water cools and

the silica forms geyserite (pronounced GUY-zuh-rite), a white or grayish cauliflowerlike deposit that creates rims or terraces around the spring. This deposit is also known as sinter. If the water passes through limestone, then it carries calcium carbonate to the surface. There the mineral crystallizes to form travertine (pronounced TRA-ver-teen). This dense, white rock also creates ledges and other rock formations around the spring. The water and rocks in hot springs may be multicolored. Brilliant rings of red, blue, brown, green, orange, and yellow are formed by the different species of algae and bacteria that flourish in the hot spring environment.

A geyser is a hot spring that periodically erupts through an opening in Earth's surface, spewing hot water and steam up to hundreds of feet above the ground. Essential geological conditions must be met for a geyser to exist: among other conditions, it must have an abundant water supply, an intense heat source, and a special plumbing system. Because of this, geysers are rare. There are only approximately seven hundred geysers known to exist on Earth. Yellowstone National Park, which lies in northwest Wyoming and extends into Montana and Idaho, contains more than four hundred geysers. The two types of geysers are fountain geysers and cone geysers. As their name implies, fountain geysers erupt like a fountain in various directions through a pool that fills an open crater before or during the eruption. After the eruption, the pool may drain completely into the geyser's vent. Cone geysers erupt in a fairly narrow jet from a vent in a conelike mound formed of geyserite.

A fumarole (pronounced FYOO-ma-role) is a small hole or vent in Earth's surface through which volcanic gases escape from underground. Fumaroles are also known as steam vents because the most common gas they emit is water vapor or steam. These types of hot springs have little water in their system. What does enter the system is boiled away before it reaches the surface. This leaves only steam and small amounts of foul-smelling gases such as hydrogen sulfide (the aroma of rotten eggs) and sulfur dioxide (the initial biting aroma of a lit match). Sometimes as the sulfur dioxide cools when it escapes from the vent, the sulfur in the vapor crystallizes around the vent, forming yellow deposits. The temperature of the gases emitted from a fumarole may reach as high as 750°F (400°C).

A mud pot (sometimes spelled mudpot) is a type of hot spring that contains thick muddy clay. Although mud pots have slightly more water than fumaroles, they also contain the volcanic gases present in the steam vents. In particular, they contain hydrogen sulfide. When this gas

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OPPOSITE The Pohutu Geyser, New Zealand, rises up to 59 feet and is the most significant in a major geyser field of more than five hundred hot springs and other forms of geothermal activity. **PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.**

Words to Know

Crust: The thin, solid outermost layer of Earth.

Fumarole: A small hole or vent in Earth's surface through which volcanic gases escape from underground.

Geyser: A hot spring that periodically erupts through an opening in Earth's surface, spewing hot water and steam.

Geyserite: A white or grayish silica-based deposit formed around hot springs.

Groundwater: Freshwater lying within the uppermost parts of Earth's crust.

Hot spring: A pool of hot water that has seeped through an opening in Earth's surface.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Mud pot: A hot spring that contains thick, muddy clay.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Rhyolite: A fine-grained type of volcanic rock that has a high silica content.

Travertine: A dense, white deposit formed from calcium carbonate that creates rock formations around hot springs.

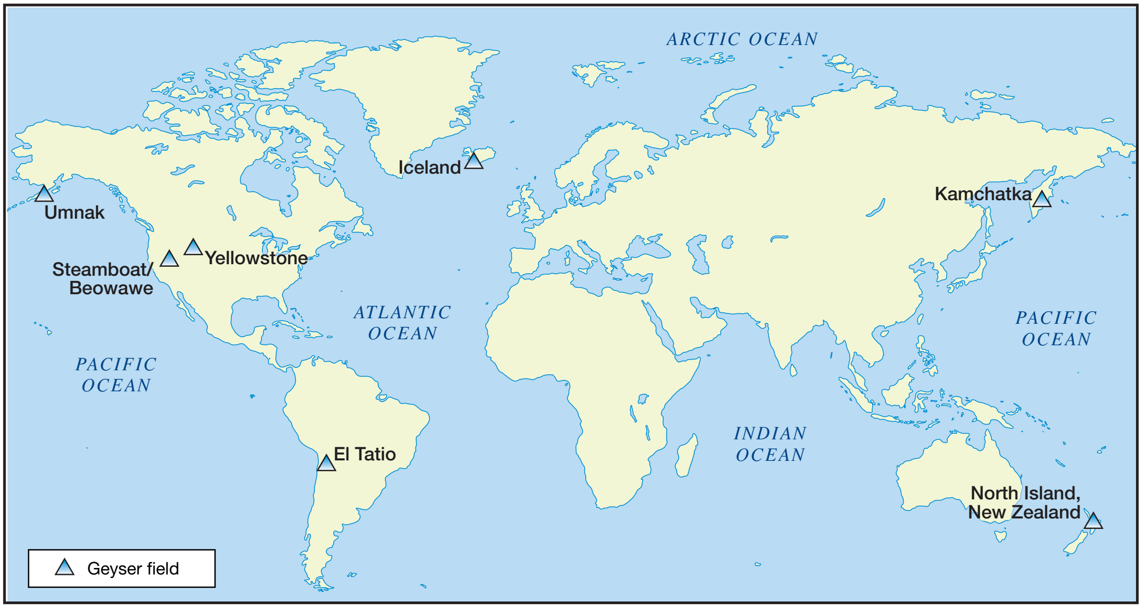
combines with water, it forms sulfuric acid. At a mud pot's surface, the acid dissolves the surrounding surface rock, thickening the water with muddy clay. Steam and other gases bubble up through the layers of mud, often explosively so. Mud pots are usually gray or light brownish-gray in color. Sometimes, minerals from the dissolved rocks tint the mud with shades of pink, red, and other colors. When this occurs, the mud pot is also called a paint pot.

Forces and changes: Construction and destruction

Hydrothermal activity occurs around the world, but it is most abundant (and spectacular) in Iceland, the North Island of New Zealand, and in Yellowstone National Park. In these areas, water underground comes in contact with heated rocks and magma, then travels up to the planet's surface through a maze of cracks and fractures, an underground plumbing system. Without this water and this heat, and a way for their creation to reach the surface, these boiling, bubbling, hissing, spewing, spouting, and gushing landforms would never exist.

Water under the surface

The thin, rocky outer layer that forms Earth's surface is the crust. Lying within it is a layer of freshwater of varying thickness that fills the pore spaces



Location of the major geyser fields around the world. Hydrothermal activity occurs around the world, but it is most abundant in Iceland, the North Island of New Zealand, and in Yellowstone National Park.

and microscopic openings in rocks and sediment. These openings include the spaces between grains of sand as well as cracks and fractures in rocks. As rain or melted snow seeps through the ground, some of it clings to particles of soil or to roots of plants. Water not used by plants moves ever deeper into the crust, drawn downward by gravity, until it reaches a layer of rock or sediment through which it cannot easily pass. It then fills the empty spaces and cracks above that layer. This water is known as groundwater. The volume of groundwater held in Earth's crust is forty times greater than all the freshwater in the planet's lakes and streams.

The area where groundwater fills all the spaces and pores underground is called the zone of saturation. The top surface of this zone is called the water table. Above it, the pores and spaces in rock hold mainly air, along with some water. This is called the zone of aeration. In places where rainfall is plentiful, the zone of aeration is usually less than 100 feet (30 meters) thick. In certain areas, such as at a pond's edge, the zone of saturation comes to the surface and the zone of aeration has essentially no thickness. In other areas, such as under some deserts, the zone of aeration may extend down from the surface for hundreds of feet before the water table is reached.

Earth's heated interior

On average, the temperature of the crust increases with increasing depth. The temperature of the first 10 to 15 feet (3 to 5 meters) or so of the crust below the surface is the same as the average annual temperature of the external air. Below that, the temperature increases roughly 4.5°F every 330 feet (2.5°C every 100 meters). In the mantle, the thick layer of rock lying beneath the crust, the temperature continues to rise, though not at the same rate. It may do so slowly, or it may do so quickly, perhaps at a rate more than ten times that in the crust. In the core at the center of the planet, temperatures are believed to exceed 9,900°F (5,482°C).

If the heat energy generated by the extreme temperatures at Earth's core were not released in some manner, the interior of the planet would melt. This energy is carried to the surface of the planet by convection currents, the circular movement of molten material deep within Earth. What occurs is similar to what takes place in a pot of boiling water or other liquid. When a liquid in a pot begins to boil, it turns over and over. Liquid heated at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense (lighter). Once at the surface, the heated material cools and becomes denser (heavier) once more. It then sinks back down to the bottom to become reheated. This continuous motion of heated material rising, cooling, and sinking forms the circular-moving convection currents.

Near the core, mantle rocks are heated, becoming less dense and lighter than the surrounding material. They then rise toward the rigid lithosphere (pronounced LITH-uh-sfeer; the upper section of the mantle combined with the overlying crust) at a rate of about a few inches per year. While this occurs, colder, denser, and heavier rocks near base of the lithosphere tend to sink. Near the core, they become heated and rise to the surface once again, and the cycle continues.

The pressure created by the movement of the convection currents under the lithosphere has broken that rigid layer into sections that move about the planet's surface in response to the moving currents. Geologists call these sections plates. The scientific theory explaining how and why the plates move is known as plate tectonics. The movement of the plates—into one another, away from one another, or under one another—has directly or indirectly created (and continues to create) many of the geologic features on the surface of Earth.

Hydrothermal activity: Water and heat

Hydrothermal landforms—hot springs, geysers, fumaroles, and mud pots—are primarily found above areas in the crust where magma or molten rock has risen to a shallow depth beneath the surface. In such instances, the magma may exist in a chamber or reservoir 3 to 6 miles (5 to 10 kilometers) beneath Earth's surface. This magma may be part of heated rock from a convection current or may be part of the leading edge of a plate that has moved under another plate. Geologists called this type

Ancient Water

The total amount of water that exists on the planet—in the oceans, lakes, rivers, ice caps, groundwater, and atmosphere—is a fixed quantity. That amount is about 500 quintillion gallons (1,900 quintillion liters). Scientists believe this amount has not changed in the last three billion years. The water that existed then exists now.

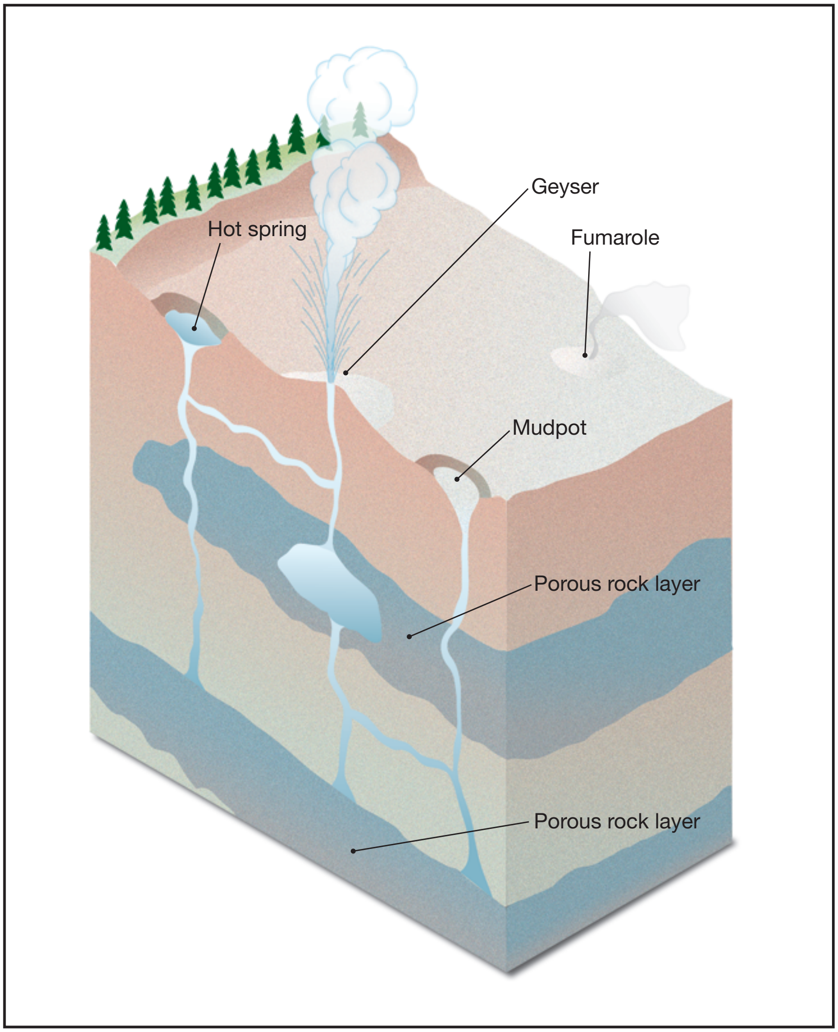
Scientists estimate the amount of time for groundwater to circulate downward, become heated, and reappear on the surface of the planet in the form of a geyser is about 500 years. The water spouting from geysers in the present day fell to the surface of Earth as rain or snow at about the time Europeans discovered North America. The water gushing from the hot springs in Hot Springs National Park in Arkansas is even older: scientists have determined that this water is over 4,000 years old.

of plate movement subduction. It occurs when an oceanic plate moves into another oceanic plate or into a continental (land) plate. Because the oceanic plate is dense, it slides under the other plate. As it travels downward into the mantle, high temperature and pressure melt the rock at the leading edge of the plate, forming thick, flowing magma. Since it is less dense than the rock that typically surrounds it deep underground, magma tends to rise toward Earth's surface. Driven by pressure created by gas bubbles within it, the magma forces its way through weakened layers of rock to collect in magma chambers. Sometimes pressure builds up within the chamber, forcing the magma through cracks or vents onto the surface of the planet. The vents through which the magma passes are known as volcanoes. (For more information on volcanoes, see the **Volcano** chapter.)

In fact, most hot springs, geysers, fumaroles, and mud pots are found in regions where volcanic activity is very young or has become inactive. In both cases, hot magma does not erupt onto the surface of the planet but exists to heat groundwater that enters the region above it. For example, geologists believe an incredible volcanic explosion 600,000 years ago left a partially molten magma chamber beneath the central portion of present-day Yellowstone National Park. It continues to supply the heat that helps create the many and varied hydrothermal landforms that mark the park. Geologists estimate that rocks in old magma chambers may remain hot for one million years or more.

In rare cases, hot springs may exist in areas where magma does not lie close to Earth's surface. Cracks in the crust and mantle may allow groundwater to seep thousands of feet underground. The natural heat of the surrounding rocks, ever increasing at greater depths, heats the water before it makes its way back to the surface.

The underground plumbing system of hot springs, fumaroles, mud pots, and geysers.



Plumbing systems

Hot springs, fumaroles, mud pots, and geysers all require some type of "plumbing system" to bring water, steam, and gases from several thousand feet underground to the surface. This underground system of cracks and fissures may be relatively open, allowing hot water to bubble slowly and continuously to the surface. Or the system may be restricted, keeping hot water and stream under pressure until it finally spews from the surface.

Hot springs form when there is an abundant supply of groundwater that collects in some sort of reservoir or cavity above heated rock or magma. The water is heated to temperatures exceeding 400°F (205°C). Even though water normally boils and begins to turn into steam at 212°F (100°C), this

Steam rising from a thermal pool in Yellowstone National Park, Wyoming. The park contains the greatest number of geysers in the world. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

superheated water remains in a liquid state because it is under intense pressure caused by the overlying rock and other groundwater. As the water becomes heated, it also becomes less dense than the cooler groundwater sinking in around it. Convection currents, much like in the mantle, are created that begin to carry the lighter, superheated water to the surface.

As it makes its way upward through its plumbing system, the hot water is able to dissolve minerals from the rocks lining the system. Most often, those rocks are rhyolite (pronounced RIE-uh-lite), a fine-grained type of volcanic rock that has a high silica content. Some of the dissolved silica forms geyserite that lines the walls of the plumbing system (the rest is carried to the surface where it forms geyserite there). This helps seal the system, preventing water from escaping into the surrounding rock. The closer the water is to the surface, the lower the pressure exerted on it. When it finally reaches the surface, the hot water does not burst forth, but merely fills the hot spring pool.

Oldest Geyser

Located in the Upper Geyser Basin area of Yellowstone National Park is perhaps the world's oldest active geyser. Castle Geyser is a cone geyser that erupts every 9 to 11 hours. For the first 20 minutes of its eruption, the geyser shoots out a jet of water to heights between 60 and 90 feet (18 and 27 meters). For the following 40 minutes, it releases a column of noisy steam. The geyser is dramatic even when not erupting. Its geyserite cone stands 12 feet (3.7 meters) high, surrounded by terraces formed of travertine.

Geologists estimate that it has taken 5,000 to 15,000 years for Castle Geyser's cone to reach that height. What is remarkable is that the cone sits on top of an even more massive geyserite formation deposited by an earlier spring. Since geologists believe hot spring activity has been taking place at Yellowstone for at least 200,000 years, it is possible that this underlying formation is that old.

Fumaroles and mud pots differ from hot springs in the amount of water they hold in their plumbing systems. Fumaroles contain the least amount of water. The small amount of water that does collect underground above magma or heated rocks is boiled and converted to steam. The steam combines with gases released by the underground magma and rushes upward, creating a hissing or roaring sound as it escapes the opening at the surface. Mud pots, on the other hand, contain more water than fumaroles, though far less than hot springs. Only some of the water may be converted to steam. The rest rises to the surface in a heated state along with volcanic gases. At the surface, there is not enough water to wash away the sticky clay and mud formed when sulfuric acid dissolves the surrounding rock.

Geysers have the most complex plumbing system. Like hot springs, they have a reservoir that fills with groundwater deep underground. The water is heated by magma or hot rocks, but does not turn to steam because it is under pressure. Unlike hot springs, the water in geysers does not flow freely to the surface. Along a geyser's plumbing system, there are constrictions or bends that block that flow. Unable to flow upward, the water at the bottom is heated even more. Still, it does not completely vaporize because of the weight of the water above it. The steam that is created does flow upward in bubbles, collecting in the system's tight areas when they become too large or numerous to pass through. At a certain critical point, the bubbles then lift the water above, forcing some of it out of the geyser at the surface. This allows the pressure in the system to decrease. With a sudden drop in pressure, much of the superheated water in the system turns quickly into steam, which expands to over 1,500 times its original,

Despite the fact that it has been inactive for decades, the Great Geysir, in Iceland, is the most famous geyser on the island. Iceland has more hot springs than any other country in the world. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

liquid volume. This tremendous expansion forces the water out of the geyser in an eruption. As the eruption continues, the heat and pressure in the system decrease. When the water in the reservoir is depleted, the eruption stops. Groundwater then begins to refill the reservoir, and the cycle begins again.

Temporary features

Providing the groundwater supply is constant, geysers erupt at regular intervals. However, geysers are often temporary features geologically. They do not last for millions of years. They may only last for a few thousand. Along with hot springs, fumaroles, and mud pots, geysers are natural features whose structure may be easily disturbed by changes in the crust. Earthquakes and tremors may shift the ground, changing the flow of groundwater or altering the plumbing system. And, unfortunately, the beauty of these landforms may bring about their destruction. Eager to see an eruption of any type, people have thrown material into the vents and pools. Coins, logs, rocks, blankets, laundry: the list of material is endless. Instead of coaxing an eruption, this has often disturbed the delicate condition under which these landforms exist.

Spotlight on famous forms

Great Geysir, Iceland

The geyser that gave its name to all others lies in a valley named Haukadalur in southern Iceland. A volcanic island (marked by more than two hundred volcanoes), Iceland boasts more hot springs and other hydrothermal activity than any other country. Of the almost eight hundred hot springs on the island, the most famous is the Great Geysir. Geologists estimate that it was created at the end of the thirteenth century when a series of earthquakes shook the valley in which it is located, opening cracks in the ground. After its creation, it reportedly erupted every three hours with thunderous jets of water and steam shooting 200 to 260 feet (60 to 80 meters) above the ground.

The geyser continued to erupt on a regular basis until the beginning of the nineteenth century. From then on, it erupted at progressively longer intervals until 1916, when it stopped completely. It came to life briefly in 1935, but since then has not erupted on its own accord.

Geologists believe that part of the reason Geysir has stopped erupting is due to the accumulation of rocks and other matter thrown into its vent by tourists over the centuries. These objects most likely damaged the geyser's plumbing system. Despite the inactivity of the Great Geysir, the surrounding area remains quite active. Many smaller hot springs surround the geyser, and nearby is another geyser, named Stokkur. It erupts roughly every 10 minutes, shooting a column of water 65 to 100 feet (20 to 30 meters) above its vent.

Hot Springs National Park, Arkansas

Covering more than 5,550 acres (2,220 hectares) of land in Arkansas, the Hot Springs National Park contains 47 natural hot springs. To protect and preserve these springs, the U.S. Congress designated the area a reservation in 1832, and then made it a national park in 1921.

OPPOSITE Considered the most famous geyser in the world, Old Faithful, in Yellowstone National Park, Wyoming, shoots water and steam up to 184 feet about every 90 minutes. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Unlike the water in many other hot springs, the water in the springs of Hot Springs National Park is not heated by underground magma. There is no evidence that volcanic activity has occurred in this area. Instead, the rainwater that feeds the springs has traveled downward to depths between 2,000 and 8,000 feet (610 and 2,438 meters). Here, as groundwater, it is heated by the naturally hot rocks. The heated water then rises quickly—the journey upward takes about one year—through cracks and faults to emerge as hot springs. The total amount of water that comes out of the springs averages about 850,000 gallons (3,217,250 liters) a day.

At the surface, the average temperature of the water in the hot springs is 147°F (64°C). What is noteworthy about the water is that it is sterile: no bacteria are found in it.

Old Faithful, Yellowstone National Park, Wyoming

Although not the biggest or the most regular, Old Faithful in the Upper Geyser Basin in Yellowstone National Park is considered by many to be the world's most famous geyser. It was named in 1870 by members of the Washburn Expedition, the first official expedition to Yellowstone (the park became the world's first national park in 1872). They were awed by the geyser's size and the frequency of its eruptions.

Its eruptions, which last from 1.5 to 5 minutes, spray water and steam from 90 to 184 feet (27 to 56 meters) above the ground. The intervals between eruptions range from 35 to 120 minutes, depending on the length of the eruption. The shorter the eruption, the shorter the interval until the next eruption. At one point, the average interval was every 76 minutes, but earthquakes in the area in the winter in the late twentieth century changed that. At present, the geyser erupts on average every 90 minutes or so, spouting from 3,700 to 8,400 gallons (14,005 to 31,794 liters) of water that has a temperature underground of 204°F (96°C).

Old Faithful is a cone geyser. By measuring the geyserite deposited around the vent of the geyser, scientists estimate that Old Faithful is approximately 300 years old. Before that, the geyser existed as a regular hot spring for several hundred years.

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Glacial landforms and features

During the last Ice Age, which ended approximately 10,000 years ago, 32 percent of Earth's land area was covered with glaciers. At present, glaciers cover roughly 10 percent of the land area. A vast majority of that glacial ice overlies much of the continent of Antarctica. Most of the rest covers a great portion of Greenland; a small percentage is found in places such as Alaska, the Canadian Arctic, Patagonia, New Zealand, the Himalayan Mountains, and the Alps.

Glaciers are not landforms. The action of glaciers, however, creates landforms. It is a process known as glaciation. Glacial ice is an active agent of erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. Glaciers move, and as they do, they scour the landscape, "carving" out landforms. They also deposit rocky material they have picked up, creating even more features. The work of present-day glaciers, however, is slow and confined to certain areas of the planet. Less obvious but far more reaching has been the work of Ice Age glaciers. Many of the distinctive features of the northern landscapes of North America and Europe were formed by glaciers that once covered almost one-third of the planet's land surface.

The shape of the land

A glacier is a large body of ice that formed on land from the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity. Two types of glaciers exist: relatively small glaciers that form in high elevations near the tops of mountains are called alpine or mountain glaciers; glaciers that form over large areas of continents close to the poles (the North and South Poles; the extreme northernmost and southernmost points on the globe) are called continental glaciers or ice sheets. Two continental glaciers are found on Earth: one covers 85 percent of Greenland in the Northern

Words to Know

Ablation zone: The area of a glacier where mass is lost through melting or evaporation at a greater rate than snow and ice accumulate.

Accumulation zone: The area of a glacier where mass is increased through snowfall at a greater rate than snow and ice is lost through ablation.

Alpine glacier: A relatively small glacier that forms in high elevations near the tops of mountains.

Arête: A sharp-edged ridge of rock formed between adjacent cirque glaciers.

Basal sliding: The sliding of a glacier over the ground on a layer of water.

Cirque: A bowl-shaped depression carved out of a mountain by an alpine glacier.

Continental glacier: A glacier that forms over large areas of continents close to the poles.

Crevasse: A deep, nearly vertical crack that develops in the upper portion of glacier ice.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Erratic: A large boulder that a glacier deposits on a surface made of different rock.

Esker: A long, snakelike ridge of sediment deposited by a stream that ran under or within a glacier.

Firn: The granular ice formed by the recrystallization of snow; also known as névé.

Fjord: A deep glacial trough submerged with seawater.

Glacial drift: A general term for all material transported and deposited directly by or from glacial ice.

Glacial polish: The smooth and shiny surfaces that are produced on rocks underneath a glacier by material carried in the base of that glacier.

Glacial surge: The rapid forward movement of a glacier.

Glacial trough: A U-shaped valley carved out of a V-shaped stream valley by the movement of a valley glacier.

Glaciation: The transformation of the landscape through the action of glaciers.

Glacier: A large body of ice that formed on land by the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity.

Ground moraine: A continuous layer of till deposited beneath a steadily retreating glacier.

Hemisphere and the other covers more than 95 percent of Antarctica in the Southern Hemisphere.

Both types of glaciers create landforms through erosion. These erosional features may be as large as the Great Lakes of North America or as small as scratches left in pebbles. As a glacier moves, it scours away material underneath it, plucking up rocks, some of which may be house-sized boulders. This material then becomes embedded in the ice at the base of a glacier. As the glacier continues to move, the embedded material abrades or scrapes the rock underneath. The slow scraping and grinding produces a fine-grained material known as rock flour. It also produces long parallel scratches and grooves known as striations in the underlying rocks. Because they are aligned parallel

Hanging valley: A shallow glacial trough that leads into the side of a larger, main glacial trough.

Horn: A high mountain peak that forms when the walls of three or more glacial cirques intersect.

Internal flow: The movement of ice inside a glacier through the deformation and realignment of ice crystals; also known as creep.

Kame: A steep-sided, conical mound or hill formed of glacial drift that is created when sediment is washed into a depression on the top surface of a glacier and then deposited on the ground below when the glacier melts away.

Kettle: A shallow, bowl-shaped depression formed when a large block of glacial ice breaks away from the main glacier and is buried beneath glacial till, then melts. If the depression fills with water, it is known as a kettle lake.

Lateral moraine: A moraine deposited along the side of a valley glacier.

Medial moraine: A moraine formed when two adjacent glaciers flow into each other and their lateral moraines are caught in the middle of the joined glacier.

Meltwater: The water from melted snow or ice.

Moraine: A general term for a ridge or mound of till deposited by a glacier.

Piedmont glacier: A valley glacier that flows out of a mountainous area onto a gentle slope or plain and spreads out over the surrounding terrain.

Rock flour: Fine-grained rock material produced when a glacier abrades or scrapes rock beneath it.

Snow line: The elevation above which snow can form and remain all year.

Striations: The long, parallel scratches and grooves produced in rocks underneath a glacier as it moves over them.

Tarn: A small lake that fills the central depression in a cirque.

Terminal moraine: A moraine found near the terminus of a glacier; also known as an end moraine.

Terminus: The leading edge of a glacier; also known as the glacier snout.

Till: A random mixture of finely crushed rock, sand, pebbles, and boulders deposited by a glacier.

Valley glacier: An alpine glacier flowing downward through a preexisting stream valley.

to the direction of ice flow, glacial striations help geologists determine the flow path of former glaciers. Another small-scale erosional feature is glacial polish. This is a smooth and shiny surface produced on rocks underneath a glacier when material encased in the ice abrades the rocks like fine sandpaper.

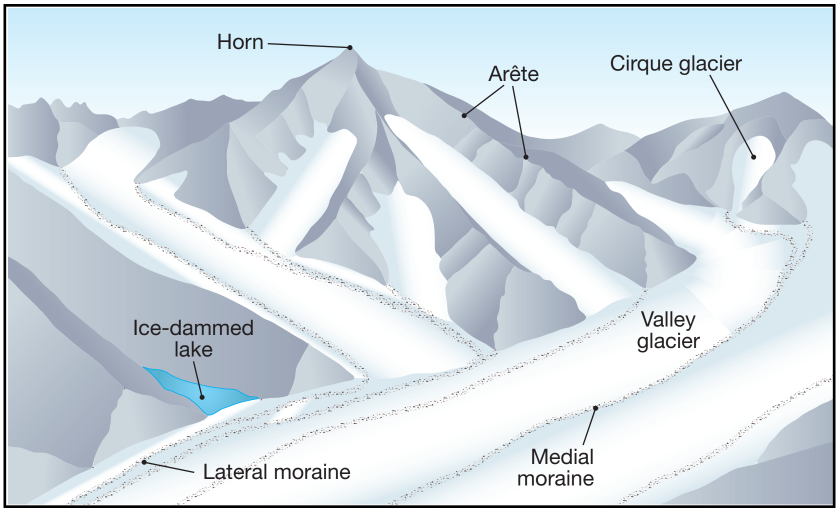
Moving ice sculpts a variety of landforms out of the landscape. Larger-scale erosional features include bowl-shaped, steep-walled depressions carved out of the side of mountains. These depressions are called cirques (pronounced SIRKS), and the relatively small alpine glaciers that fill them are called cirque glaciers. If the glacier melts and a small lake fills the central depression in a cirque, that lake is known as a tarn. Two or more glacial cirques may form on a mountainside, eroding away the rock between them to create a steep-sided, sharp-edged ridge known as an arête (pronounced ah-RHET). When the walls of three or more glacial cirques meet, they may form a high mountain peak known as a horn.

When a cirque glacier expands outward and flows downward through a stream valley that already exists, it becomes a valley glacier. Through erosion, valley glaciers turn V-shaped stream valleys into U-shaped glacial troughs. Smaller valley glaciers, known as tributary glaciers, may form alongside a main valley glacier and eventually flow into it. The shallower glacial troughs created by these glaciers are known as hanging valleys. A valley glacier that flows out of a mountainous area onto a gentle slope or plain and spreads out over the surrounding terrain is a piedmont glacier. A valley glacier may flow all the way to a coastline, carving out a narrow glacial trough. If the glacier melts and the valley fills with seawater, it is known as a fjord (pronounced fee-ORD). Although prominent along the west coast of Norway, fjords are also found along the coasts of Alaska, British Columbia, Chile, Greenland, New Zealand, and Scotland.

Glaciers leave their mark on the landscape not only through erosion, but also through deposition. Deposition involves carrying loose materials from one area and leaving, or depositing, these materials in another area. Depositional features are created by the release of rocky material from a glacier. They vary widely in scale and form. All sediment (rock debris ranging from clay to boulders) deposited as a result of glacial erosion is called glacial drift. Like a stream, a glacier picks up and carries sediment particles of various sizes. Unlike a stream, a glacier can carry part of that sediment load on its bottom, its sides, or its top (sediment on top has fallen onto the glacier from the valley walls). Another difference between the two is that when a stream deposits its load of sediment, it does so in order of size and weight: large, heavy particles are deposited first, followed by particles that are increasingly smaller and lighter. When a glacier deposits sediment, there is no such order. The particles are unsorted, with large and small particles mixed together. This random mixture of finely crushed rock, sand, pebbles, and boulders deposited by a glacier is referred to as till.

Since a glacier can carry rocks for great distances before depositing them, those rocks generally differ from the surrounding native rocks in that area. In fact, because they are derived from a very large area eroded by a glacier, glacial deposits contain the widest variety of rock types. A glacially deposited large boulder that differs in composition from the rocks around it is called an erratic.

A deposit of till that forms a ridge or mound is called a moraine (meh-RAIN). Moraines deposited along the sides of alpine glaciers are called lateral moraines. When two valley glaciers converge to create a single larger glacier, their opposing lateral moraines merge to form a ridge that



Major features of glaciation, or the action of glaciers on a landscape.

runs down the middle of the new glacier. This is a medial moraine. A moraine deposited at the leading edge of a glacier, marking its farthest advance, is a terminal or end moraine. Finally, a continuous layer of till deposited beneath a steadily retreating glacier is a ground moraine.

Another common glacial landform is the drumlin. This tear-drop-shaped hill forms underneath a glacier. The tail of the drumlin points in the direction of the ice movement. Geologists are unsure exactly how drumlins form, whether a glacier scrapes up material beneath it or deposits material it already carries or a combination of both. Drumlins may be quite large, measuring up to 200 feet (60 meters) in height and 0.6 mile (1 kilometer) in length.

As a glacier melts, it produces meltwater that flows on top, within, and underneath the glacier through channels. This meltwater moves large quantities of sediment from the glacier. At the leading edge of the glacier, also known as the terminus or glacier snout, the meltwater emerges in large streams that carry it away from the glacier. The sediment in the meltwater is then deposited, forming a broad, sweeping plain called an outwash plain. Since the sediment was carried in water, it is deposited in a sorted manner, with the largest particles first and the smallest particles last. If a glacier melts and retreats, curving, snakelike ridges of sediment may mark the former locations of streams that existed under the glacier. These long, twisting ridges are called eskers.

Two other features that result from the melting of glaciers are kames and kettles. As a glacier begins to melt, a depression may form on its top surface, filling with water and sediment. When the glacier finally melts away, the sediment is set down on the surface of the ground, forming a

Loess

Loess (pronounced LUSS; a German word meaning "loose") is a deposit of fine, yellowish-gray, silty sediment. Composed of mineral particles finer than sand but coarser than dust or clay, loess forms fertile topsoils. Areas with large loess deposits are found in the central and northwestern United States, in central and eastern Europe, and in eastern China.

The majority of loess was formed by the action of glaciers and wind (some loess comes from the transport of sediment from desert areas). After the last ice age, meltwater streams from the retreating continental glaciers transported vast amounts of rock flour and other fine sediment away from the glaciers. Strong winds blowing off the glaciers (because glacial ice cools the air and cold air moves to lower elevations at the front of the glacier) picked up the fine sediment and carried it far beyond the outwash plains before it was deposited.

Since loess is transported in the air, it is very well sorted, and is mostly silt combined with a small amount of clay. Loess is generally deposited as a blanket over everything, both hills and valleys. It is often removed by wind and water to fill up basins and depressions.

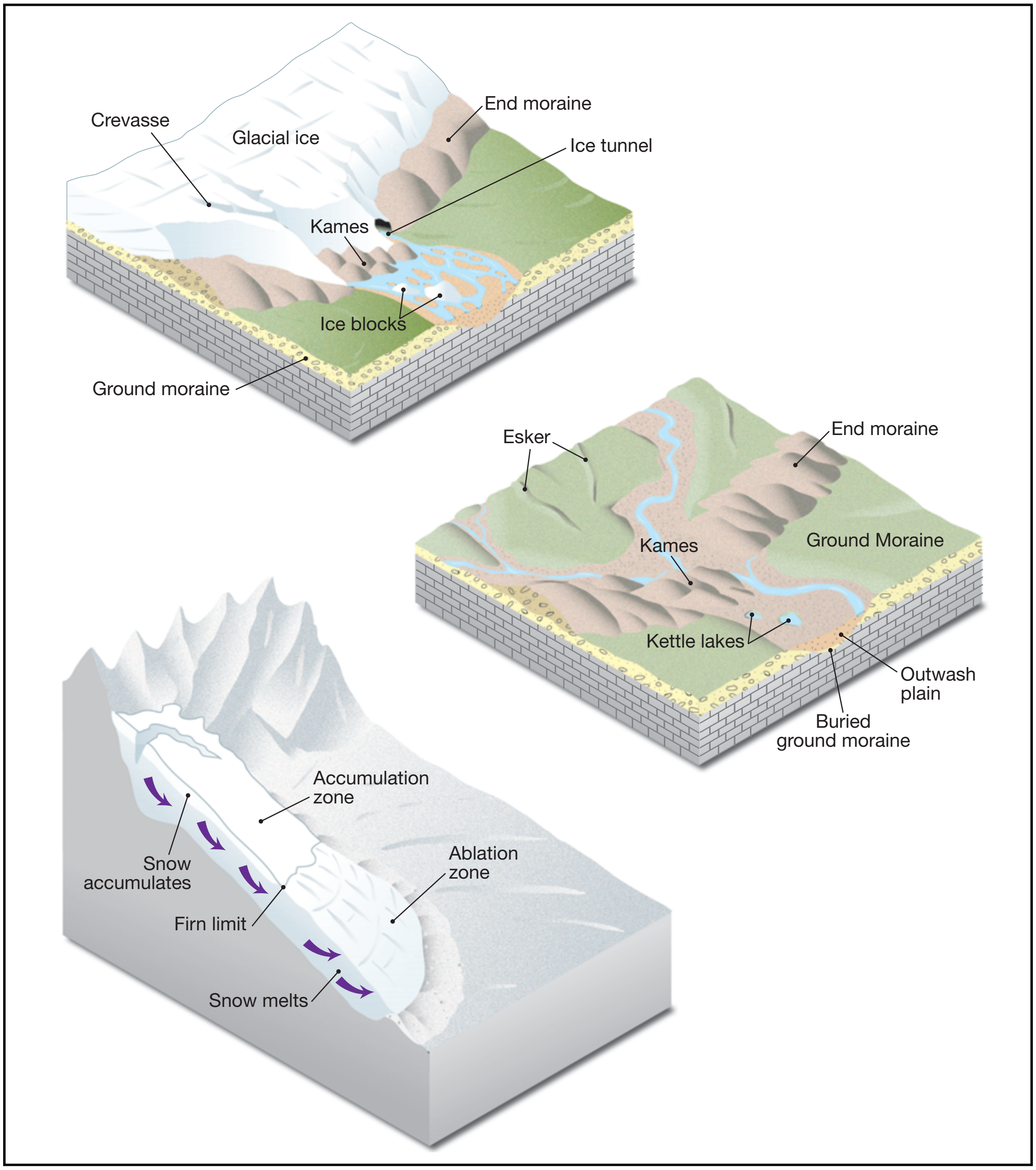
steep-sided, conical mound or hill known as a kame. A kettle forms when a large chunk of ice separates from the main glacier. Buried by glacial till, the ice then melts, leaving a depression in the landscape. This eventually becomes filled with water, forming a kettle lake.

Forces and changes: Construction and destruction

Glaciers are moving ice. They can range in size from small patches to ice sheets covering millions of square miles. The world's largest alpine glacier is the Siachen Glacier in the Karakoram Mountains of Pakistan. Measuring 47 miles (75 kilometers) in length, it contains more than 13.6 cubic miles (56.7 cubic kilometers) of ice. The Antarctic ice sheet is the largest single mass of ice on Earth. It covers an area of almost 5.4 million square miles (14 million square kilometers) and contains over 7 million cubic miles (29 million cubic kilometers) of ice.

Glacial formation

A glacier does not start out as a glacier. All that ice began to form when snow—delicate, feathery crystals of ice—fell in areas above the snow line, the elevation above which snow can form and remain all year. It takes snow on top of snow on top of more snow to create a glacier; it also takes a long time. On average, 10 feet (3 meters) of snow will turn into 1 foot (0.3 meter) of ice. In polar regions, where annual snowfall is



Glacial effects and features.

generally very low because the air is too cold to hold much moisture, it may take snow about 1,000 years to turn into ice.

In time, if snow does not melt but is buried beneath additional layers of snow, it will begin to compress. This forces the snow crystals to recrystallize, forming grains similar in size and shape to cane sugar. As new snow piles on top and the snow below becomes further compressed, the grains grow larger and the air spaces between them become smaller. Over a short period of time, perhaps the span of two winters, the compressed snow turns into a granular material known as firn or névé (pronounced nay-VAY). The density (amount of mass in a given volume) of regular snow is about 10 percent that of water. The density of firn is about 50 percent that of water. Once the thickness of the overlying snow exceeds about 165 feet (50 meters), the firn turns into a solid mass of glacial ice.

Additions to a glacier's mass are called accumulation; losses through melting, erosion, or evaporation are called ablation (pronounced ah-BLAY-shun). A glacier may be divided into two distinct zones. Where snow and ice accumulate faster than they melt away or evaporate is the accumulation zone; where melting and evaporation occur faster than accumulation is the ablation zone. The upper part of a glacier is its accumulation zone, while the lower part is its ablation zone. The boundary between the two zones is called the firn limit.

Over a period of years, depending on the amount of snowfall and seasonal temperatures, a glacier may gain more mass than it loses. If this occurs, the terminus of the glacier will likely advance. If the opposite happens, with the glacier losing more mass than it gains, its terminus will likely retreat. Thus, depending on the balance between accumulation and ablation, a glacier may grow or shrink.

Ice flow

A glacier always moves in the same direction whether it is advancing or retreating. It moves to lower elevations under the force of gravity by two different processes: internal flow and basal sliding. The glacial ice beneath the firn in a glacier is so dense and under such pressure that it begins to behave like thick tar or what geologists term "plastic." The individual ice crystals in this area respond to pressure and the force of gravity by deforming yet again. They are forced into the same orientation or direction, all realigning parallel to the direction of flow. Like cards in a deck of playing cards, they then slide over and past one another. Glacial movement through internal flow, also known as creep, is very slow: on average, it measures only an inch or two (a few centimeters) a day. In a valley glacier, ice in the upper central part moves faster than ice at the sides, where it is in contact with the valley walls.

Confined by high pressures, ice deep in a glacier does not crack during internal flow. However, near the surface of the glacier where there is less pressure, the ice is brittle. When the lower portion of a glacier moves by internal flow, especially over abrupt changes in slope, large cracks may

Ice Ages

Ice ages were periods in Earth's history when vast glaciers covered large portions of the planet's surface. Earth's average annual temperature varies constantly from year to year, from decade to decade, and from century to century. During some periods, that average annual temperature has dropped low enough to allow fields of ice to grow and cover large areas of Earth. Annual variations of only a few degrees can result in the formation of extensive continental glaciers.

Over the last 2.5 million years, about twenty-four ice ages have occurred. This means that Earth's average annual temperature shifted upwards and downwards about two dozen times during that period. In each case, an episode of significant cooling was followed by an episode of significant warming, called an interglacial period, after which cooling took place once more. At present, Earth is in an interglacial period.

The exact causes for ice ages have not been proven. Scientists believe that ice ages are the result of a complicated interaction between such things as variations in the Sun's energy output, the varying distance of Earth from the Sun, variations in the tilt of Earth's axis, the changing position and height of the continents, changing oceanic circulation, and changes in the composition of the atmosphere.

develop in the upper 150 feet (45 meters) or so of ice. These deep, nearly vertical cracks are called crevasses (pronounced kri-VASS-ez).

Glaciers in polar regions are frozen to the ground and move only through internal flow. Glaciers elsewhere are normally warm enough at their bases to have a layer of water form between their ice and the ground. The water reduces friction by lubricating the ground and allowing the glacier to slide on its bed in what is called basal sliding. This second type of glacial movement occurs because high pressure reduces the temperature at which ice will melt. Ice underneath a 7,220-foot (2,200-meter) glacier will melt at roughly 29°F (–1.6°C), rather than at 32°F (0°C). The thicker the glacier, the greater the pressure at its base, and the lower the temperature at which its ice will melt.

Other factors may also contribute to basal sliding. Because ice acts like a blanket, a glacier traps heat that escapes from the surface of Earth. Although not much, this heat may be enough to raise the temperature of ice at the base of a glacier to a little above the pressure-melting point. Meltwater from the top or inside a glacier may also make its way down through cracks and channels to the glacier's base, contributing to the layer of water formed there. Glacial movement due to basal sliding may be ten times faster than that due to internal flow. Because of this, basal sliding plays an

The Literary Landscape

"These islands of ice and black basalt, now and then tinged russet or blue by oozings of iron or copper, rise over 600 meters. Their hearts are locked under deep glaciers, a crystal desert forever frozen in terms of our short life spans, but transient in their own time scale. Sometimes one sees only the cloud-marbled glacial fields, high in the sun above hidden mountain slopes and sea fog, Elysian plains that seem as insubstantial as vapor. The interiors of the glaciers, glimpsed through crevasses, are neon blue. Sliding imperceptibly on their bellies, the glaciers carve their own valleys through the rock, and when they pass over rough terrain they have the appearance of frozen rapids, which is in fact what they are, cascading at a rate of a centimeter a day."

—David C. Campbell, *The Crystal Desert: Summers in Antarctica*, 1992.

important role in how much a glacier erodes a landscape and creates landforms.

On rare occasions, an alpine glacier may unexpectedly surge downslope, moving at a rate of 165 to 330 feet (50 to 100 meters) per day. This results in a jumbled mass of ice along the terminus of the glacier and many crevasses along its top. Although geologists do not completely understand the reasons for glacial surging, they believe it may be caused by a buildup of meltwater at the base of a glacier that reduces the normal friction and allows unusually fast basal sliding. The fastest-recorded glacial surge was that of the Kutiah Glacier in northern Pakistan. Over a three-month period in 1953, the glacier slid more than 7.5 miles (12 kilometers), averaging about 367 feet (112 meters) per day.

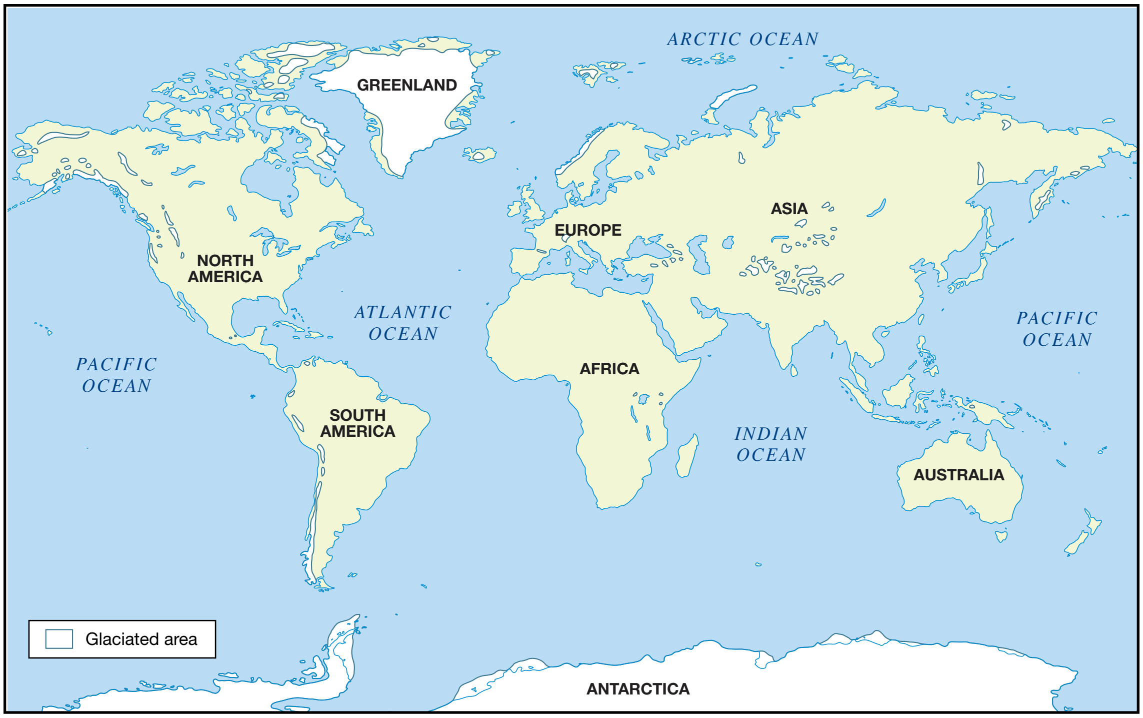
Through the combination of internal flow and basal sliding, glaciers move over a landscape, scraping and plucking the rock surfaces over which they move. They transport unsorted sediment both internally and on their surfaces. During warmer periods, a glacier may lose part of its mass, its ice turning to meltwater, which carries sediment away from the terminus of the glacier. Even as a glacier's terminus retreats, the flow of ice in the glacier continues to move downward under the influence of gravity.

Scientific measurements at the beginning of the twenty-first century showed that most glaciers worldwide were retreating. Glaciers in the Himalayan Mountains were wasting away the quickest. Scientists who conducted the research found a connection between increasing temperatures around the world and the glacial retreat. It is known that over the last 100 years, global sea levels have risen 4 to 10 inches (10 to 25 centimeters). Scientists estimate that the melting of glaciers has contributed 1 to 2 inches (2.5 to 5 centimeters) to that rise.

Spotlight on famous forms

Glacier National Park, Montana

Located in northwestern Montana on the border between the United States and Canada are 1,013,572 acres (410,497 hectares) of pristine



Map of glaciers around the world. Glaciers cover roughly 10 percent of Earth's land area. A vast majority of that, 90 percent, overlies the continent of Antarctica.

wilderness. Glacier National Park, established in 1910 as the country's tenth national park, contains some fifty glaciers and more than two hundred glacier-fed lakes. The valleys and other geologic features of the park were all eroded and carved by the action of glaciers over the last two billion years. Several times over the past two million years, huge glaciers carved the mountains and valleys and then retreated, leaving a newly sculpted landscape. The most recent continental glacier that covered the upper section of North America retreated over ten thousand years ago. The fifty alpine glaciers in the park formed during the last few thousand years.

The park is filled with many glacial features: arêtes, cirques, hanging valleys, horns, and moraines. Among the more famous ones are Mount Reynolds, a glacial horn; Garden Wall, a towering arête that extends for miles; and the U-shaped St. Mary Valley.

Matterhorn, Switzerland

One of the most recognizable mountains in the world, the Matterhorn in the Pennine Alps on the border between Switzerland and Italy rises some 14,700 feet (4,480 meters). First successfully climbed in 1865, it is celebrated for its distinctive shape. The mountain is a classic example of a horn. Eroded by cirques, its steep sides meet in arêtes that lead to the hornlike, pointed peak.

The Alps mountain system in southern-central Europe curves in a great arc for approximately 500 miles (800 kilometers). It runs from the Mediterranean Sea up along the borders and adjacent regions of France, Italy, Switzerland, Germany, and Austria, before ending in Slovenia. The Alps was the first mountain system to be studied extensively by geologists. Many of the geologic terms associated with mountains and glaciers originated in those studies.

Walden Pond, Massachusetts

Walden Pond, the deepest lake in Massachusetts, lies in the northeast part of the state near the city of Concord. It is a kettle lake, created about ten thousand years ago when continental ice from the last ice age began to retreat. A huge block of that glacial ice broke off and remained behind, surrounded at it base by sand and gravel deposited by meltwater streams. The block melted over a period of about two hundred years, forming a steep-sided basin that filled with water. The current shape of the pond, with its steep sides, coves along its margins, and two deep areas, reflects the shape of the original block of ice. The current maximum depth of the pond is 103 feet (31 meters). The clear water that fills the lake comes from precipitation and groundwater (freshwater lying within the uppermost parts of Earth's crust, filling the pore spaces in soil and fractured rock).

The lake is famous because American writer Henry David Thoreau (1817–1862) lived along its shores between 1845 and 1847. While there, he wrote *Walden, or Life in the Woods* (published in 1854). In this work, a series of essays, Thoreau combined writing on transcendental philosophy with observations of aquatic ecology and aspects of limnology, the study of lakes. He also championed the value of living close to nature. Because of this highly influential work, many people consider Walden Pond and the area around it to be the birthplace of the American conservation movement.

In 1965, the U.S. National Park Service designated Walden Pond as a National Historic Landmark.

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Landslide and other gravity movements

Gravity is the physical force of attraction between any two objects in the universe. One of the four fundamental forces (the others are electromagnetism and the strong and weak forces), gravity affects all objects on Earth. From the largest mountains to the smallest grains of sand, gravity pulls everything in a direction toward the center of the planet. As long as material remains on a flat surface, one that is parallel to Earth's surface, gravity will not cause it to move. When material is on a slope and conditions are right, however, gravity will cause it to fall, slide, flow, slump, or creep downward.

That downhill movement of soil, rocks, mud, and other debris can be either slow or fast. Large amounts that move quickly are perhaps the most widespread geologic hazard. Each year in the United States, ground failures of various sorts cause between twenty-five and fifty deaths and roughly $1.5 billion in economic loss. In less-developed nations, where poorly constructed buildings house many people in areas prone to ground failures, the death tolls and amount of property damage are much higher.

The shape of the land

Geologists use the term mass wasting to describe the spontaneous movement of Earth material down a slope in response to gravity. This does not include material transported downward by streams, winds, or glaciers. Mass wasting plays an important role in the overall process of erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. Through mass wasting, material from higher elevations is moved to lower elevations where streams, glaciers, and wind pick it up and move it to even lower elevations. Mass wasting occurs continuously on all slopes. While some mass-wasting processes act very slowly, others occur very suddenly. The general term landslide is used to describe all relatively rapid forms of mass wasting.

Landslide in San Salvador, El Salvador, resulting from a powerful earthquake. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Mass wasting may be divided into two broad categories: slope failures and flows. Slope failures occur when debris moves downslope as the result of a sudden failure on a steep slope or cliff. Flows occur when a loose mixture of debris, water, and air move downslope in a fluidlike manner. Each of these categories may be further divided into various types: Slope failures include falls, slides, and slumps; flows include mudflows, debris flows, solifluction (pronounced so-lih-FLUK-shun), debris avalanches, earthflows, and creep. Flows may be grouped according to the amount of water present in the particular flow. Mudflows, debris flows, and solifluction are labeled slurry flows. These contain between 20 and 40 percent water. Debris avalanches, earthflows, and creep are granular or dry flows, which contain up to 20 percent water.

A fall is a sudden, steep drop of rock fragments or debris. A rockfall commonly occurs on a steep cliff and may involve a single rock or a mass of rocks. As a rock falls down, it may plummet freely through the air or may strike and loosen other rocks in the cliff face. At the base of the cliff, the rock fragments accumulate in a sloping pile known as a talus (pronounced TAY-less). The largest rocks in the pile tend to be located the farthest from the cliff face because of their greater size and momentum. Debris falls differ from rockfalls only in that they involve a mixture of soil, rocks, and vegetation.

In contrast to a fall, material in a slide maintains contact with the slope down which it moves. That material could be a mass of rocks or debris. Piles of talus are common where rock or debris slides end. A rock slide involving tons of material may reach a speed exceeding 100 miles (161 kilometers) per hour.

A slump is the downward movement of a block of material on a curved surface, one shaped like a spoon. Instead of sliding downward parallel to the surface of the slope, a slump block rotates backward toward the slope in a series of curving downward and outward movements, creating a series of steplike depressions. A bulge of material, known as a toe, develops at the base of the slope. At the head of the slump, a scalloped hollow is left in the slope. A slump generally does not travel far, unlike a fall or a slide, normally moving at a pace of 7 feet (2.1 meters) per day or slower.

The most common, the most liquid, and the fastest type of flow is a mudflow. A mixture primarily of the smallest silt and clay particles and water, a mudflow has the consistency of newly mixed concrete. It can travel down a slope as fast as 55 miles (88 kilometers) per hour and have enough force to pick up and carry along debris the size of boulders, cars, trees, and houses. Mudflows can travel for great distances over gently sloping terrain. When they reach valley floors, mudflows spread out, depositing a thin layer of mud mixed with boulders. A type of mudflow produced by a volcanic eruption is called a lahar (pronounced LAH-hahr). A mixture of volcanic ash, rocks,

Words to Know

Angle of repose: The steepest angle at which loose material on a slope remains motionless.

Bedrock: The general term for the solid rock that underlies the soil.

Chemical weathering: The process by which chemical reactions alter the chemical makeup of rocks and minerals.

Creep: The extremely slow, almost continuous movement of soil and other material downslope.

Debris avalanche: The extremely rapid downward movement of rocks, soil, mud, and other debris mixed with air and water.

Debris flow: A mixture of water and clay, silt, sand, and rock fragments that flows rapidly down steep slopes.

Earthflow: The downward movement of water-saturated, clay-rich soil on a moderate slope.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fall: A sudden, steep drop of rock fragments or debris.

Flow: The downward movement of a loose mixture of debris, water, and air that moves in a fluidlike manner.

Granular flow: A flow that contains up to 20 percent water.

Gravity: The physical force of attraction between any two objects in the universe.

Lahar: A mudflow composed of volcanic ash, rocks, and water produced by a volcanic eruption.

Landslide: A general term used to describe all relatively rapid forms of mass wasting.

Mass wasting: The spontaneous movement of material down a slope in response to gravity.

Mechanical weathering: The process by which a rock or mineral is broken down into smaller fragments without altering its chemical makeup.

Mudflow: A mixture primarily made of the smallest silt and clay particles and water that has the consistency of newly mixed concrete and that flows quickly down slopes.

Regolith: The layer of loose, uncemented rocks and rock fragments of various size that lies beneath the soil and above the bedrock.

Shear stress: The force of gravity acting on an object on a slope, pulling it downward in a direction parallel to the slope.

Slide: The movement of a mass of rocks or debris down a slope.

Slope failure: A type of mass wasting that occurs when debris moves downward as the result of a sudden failure on a steep slope or cliff.

Slump: The downward movement of blocks of material on a curved surface.

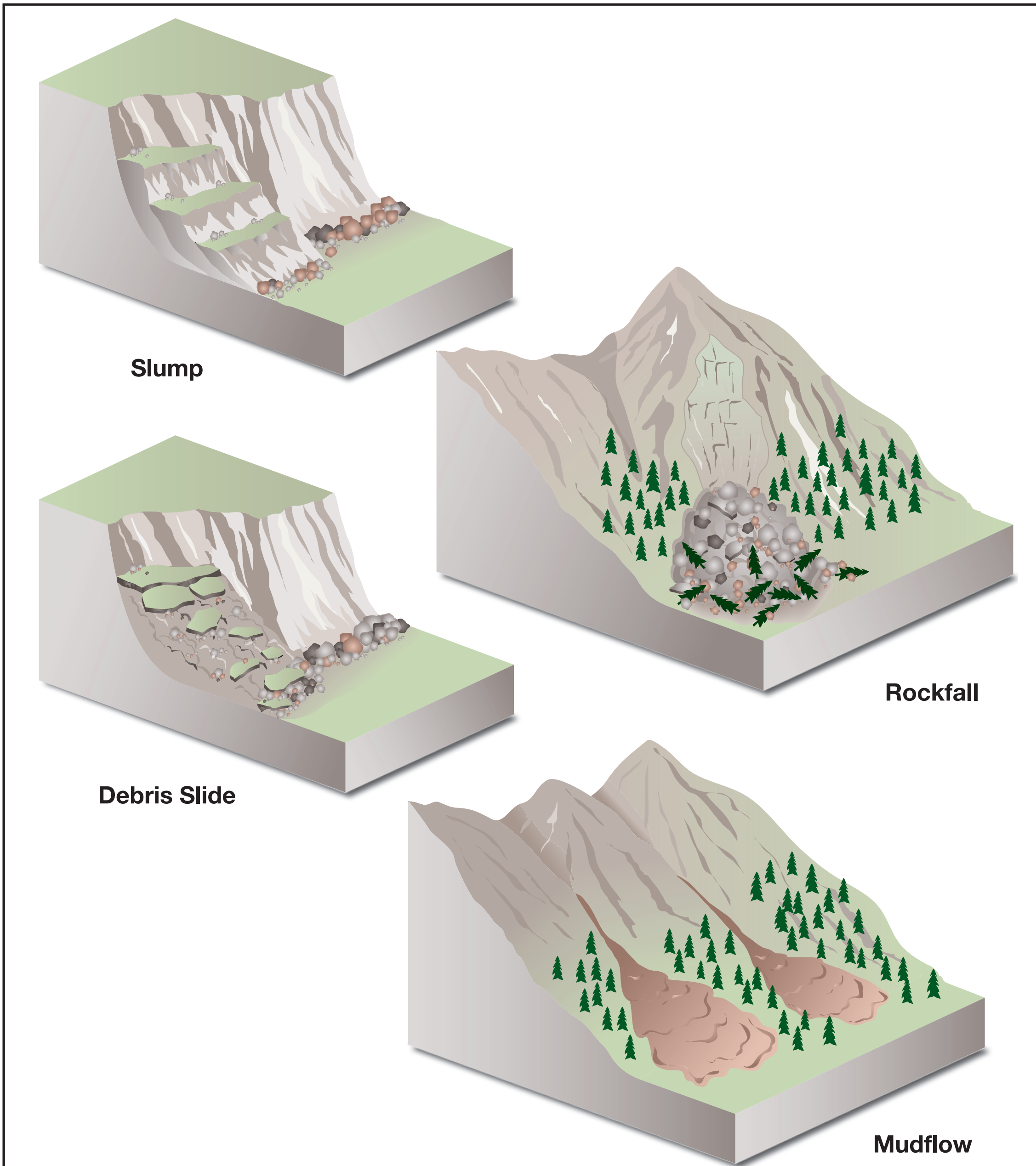
Slurry flow: A flow that contains between 20 and 40 percent water.

Solifluction: A form of mass wasting that occurs in relatively cold regions in which waterlogged soil flows very slowly down a slope.

Talus: A sloping pile of rock fragments lying at the base of the cliff or steep slope from which they have broken off; also known as scree.

Weathering: The process by which rocks and minerals are broken down at or near Earth's surface.

and water from melted snow and glaciers around the volcanic crater, a lahar may be very hot. Traveling down the steep side of a volcano at speeds approaching 200 miles (322 kilometers) per hour, a lahar can flow for great distances, burying everything it encounters.



Some of the major forms of mass wasting, or the spontaneous movement of material down a slope in response to gravity.

A mixture of water and clay, silt, sand, and rock fragments (more than half of the particles are larger than sand), a debris flow travels at a slower speed than a mudflow, usually up to about 25 miles (40 kilometers) per hour. At this velocity, a debris flow still has enough energy to pick up and transport large rocks, boulders, trees, and other material in its path. This type of flow generally occurs on steep slopes that have little or no vegetation. Traveling downward, the material in a debris flow tends to mix with more water and even air. Studies have shown that debris flows gain speed because they actually ride on a cushion of air as they flow downslope.

The slowest type of slurry flow is called solifluction. This form of mass wasting occurs in relatively cold regions where short summers thaw the uppermost layers of soil, generally the top 3 feet (1 meter). Below this remains a layer of permanently frozen soil called permafrost through which the water does not drain. Water-saturated and weak, the upper layers flow very slowly downslope at a rate of 0.2 to 5.9 inches (0.5 to 15 centimeters) per year, forming distinct lobes (rounded segments).

The fastest type of granular flow is the debris avalanche. The term avalanche is generally applied to any fast-moving downward flow of any type of material. Similar to an avalanche of snow, a debris avalanche is an extremely rapid downward movement of rocks, soil, mud, and other debris mixed with air and water. Common in areas with steep slopes, debris avalanches usually result from the complete collapse of a mountainous slope, often triggered by earthquakes and volcanic eruptions. They move downward through avalanche chutes (channel-like depressions along which an avalanche has moved), reaching speeds over 300 miles (480 kilometers) per hour. Debris avalanches can travel for considerable distances along relatively gentle slopes.

Another type of granular flow is an earthflow, which usually occurs when clay-rich soil has become saturated by heavy rains. The material in an earthflow is coarser and less fluid than that in a mudflow and finer and more fluid than that in a debris flow. Although it may move at a variety of speeds and over varying distances, an earthflow generally moves slower and travels a shorter distance than a mudflow. Slow earthflows move in starts and stops, covering only several feet per year. This type of flow normally has an hourglass shape. A bowl or depression forms at the head where the unstable material collects and flows downward. It narrows in its central area before widening once again at the base of the slope.

Creep is the extremely slow, almost continuous movement of soil and other material downslope. Most creep movement is less than 0.4 inch (1 centimeter) per year. Occurring on almost all slopes, it is the most widespread and costliest type of mass wasting in terms of total material moved and monetary damage caused. Although creep cannot be witnessed, evidence of the movement can be seen on hillslopes in curved tree trucks and leaning fence posts, telephone poles, and gravestones.

Submarine Flows

Storms or earthquakes may trigger flows of water and sediment down a continental slope, the steeply sloping region of the continental margin (the submerged outer edge of a continent) that extends downward to the ocean basin. As the material begins to move down the slope, it gathers speed and mixes with water to form turbidity currents. Because they are heavier than the surrounding water, the currents are pulled downward by gravity. Flowing at speeds of up to 50 miles (80 kilometers) per hour, the currents gather more sediment by scouring the slope as they travel downward. When they come to the base of the slope, the currents slow and the sediments settle on ocean basin, forming a fanlike deposit. (For more information on turbidity currents, see the **Continental margin** entry.)

Forces and changes: Construction and destruction

Mass wasting occurs throughout the world, continually sculpting the landscape. The areas at greatest risk for mass wasting events are in mountainous regions with relatively steep slopes. In the United States, those areas are found in the Appalachian Mountains, the Rocky Mountains, and along the Pacific Coast. However, the potential for mass wasting is not determined by slope angle alone. The highest peaks rise in western states, but the largest area at risk from landslides is in the eastern Appalachian states. Water, much more plentiful in the eastern than in the western part of the country (with the exception of the Pacific Northwest), plays a significant role in mass wasting. Other factors play other roles. Earthquakes and other natural disasters, the absence of vegetation, and human activities can also influence the potential for mass wasting.

Playing chief roles in the mass wasting process are weathering, gravity, and water.

Weathering

The process by which rocks and minerals are broken down at or near Earth's surface is called weathering. This encompasses all the processes that cause rocks and minerals to fragment, crack, crumble, or decay. There are two types of weathering: mechanical and chemical. Mechanical weathering is the process by which a rock or mineral is broken down into smaller fragments without altering its chemical makeup. Examples of this type of weathering include frost wedging, which takes place when water in a crack freezes and enlarges, forcing apart a rock. Rocks may also be forced apart in places like deserts by drastic temperature changes above freezing. The roots of trees and other plants may wedge into rocks,

Human Cost of Mass-Wasting Events

Event	Deaths	Location	Year
Loess flow	180,000	China	1920
Debris avalanche	70,000	Peru	1970
Mudflow	23,000	Columbia	1985
Debris avalanche	12,000–20,000	Soviet Union (present-day Russia)	1949
Debris avalanche	18,000	Peru	1970
Debris flow	10,000	Columbia	1999
Lahar	5,110	Indonesia	1919
Rock avalanche	4,000	Peru	1962
Rock slide	2,000	Italy	1963
Debris flow	1,000	Ecuador	1987

widening cracks. The other type of weathering, chemical weathering, is the process by which chemical reactions alter the chemical makeup of rocks and minerals. It involves the decomposition of rocks and minerals by atmospheric gases and water. Oxygen dissolved in water may oxidize minerals that contain iron. Carbon dioxide dissolved in water forms a weak carbonic acid that can dissolve limestone. Water alone may also dissolve some minerals or combine with others to form new by-products.

Rocks weather at different rates depending on the climate and their mineral composition and texture. Rocks weather rapidly in hot, moist climates, but slowly in cooler, drier climates. In general, weathering tends to produce rounded rocks. Weathering also produces regolith (pronounced REH-gah-lith). This is the layer of loose, uncemented rocks and rock fragments of various size that lies beneath the soil and above the bedrock (general term for the solid rock that underlies the soil). Over time, regolith itself can be further weathered to create soil. It is the movement of regolith downhill under the influence of gravity that defines mass wasting.

Gravity

The force of gravity acts in two ways on regolith and other material on a slope. As mentioned earlier, gravity is a constant force exerting a pull on everything on Earth's surface in a direction toward the center of the planet. Stated another way, the force of gravity pulls material straight down in a direction perpendicular to the surface. Material on a slope is thus pulled inward in a direction that is perpendicular to the slope. This helps prevent material from sliding downward. However, on a slope, gravity also exerts a force that acts to pull material down a slope, parallel to the surface of the slope. This second force of gravity is known as shear

Vehicles buried by a California mudslide that was triggered by heavy rains, 1982. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

stress. The amount of shear stress exerted is related directly to the steepness of the slope. Shear stress increases as the slope steepens. As shear stress increases, the perpendicular force of gravity decreases.

When shear stress becomes greater than the perpendicular force of gravity, material on a slope may still not move downward right away. It may be held in place by the frictional contact between the particles making up that material. Contact between the surfaces of the particles creates a certain amount of tension that holds the particles in place at an angle. The steepest angle at which loose material on a slope remains motionless is called the angle of repose. In general, that angle is about 35 degrees. It may vary slightly depending on certain factors, such as the size and shape of the particles. The angle of repose usually increases with increasing particle size. Particles that are irregularly shaped (with angled edges that catch on each other) also tend to have a higher angle of repose than those that have become rounded through weathering and that simply roll over each other.

Water

Water is an important agent in the process of mass wasting. Water will either help hold material together, increasing its angle of repose, or cause it to slide downward like a liquid. In mass wasting, water acts as either a glue or a lubricant. Small amounts of water can strengthen material. Slightly wet particles have a higher angle of repose because the thin film of water that exists between the particles increases the tension holding them together. An example of this action can be seen in sand. Dry sand does not stick together very well. A sand castle made of dry sand will not stand very high. Yet one made with slightly moist sand will. If too much water is added, though, the sand will become waterlogged and the castle will collapse. When material becomes saturated with water, the angle of repose is reduced to a small degree and the material tends to flow like a liquid. This occurs because the excess water completely surrounds the particles in the material, eliminating the frictional contact between the particles that holds them together.

Excess water also increases the mass of material on a slope. Mass is a measurement of how much matter is in an object, while weight is a measurement of how hard gravity is pulling on that object. The force of gravity is proportional to the mass of an object: the greater the mass, the greater the force of gravity. If the mass of the material on a slope increases, so will the force of gravity exerted on it. With low or even nonexistent frictional contact between its particles, waterlogged material is subject to high shear stress, and it will slide or flow down a slope under that force of gravity.

Triggering events

As long as material on a slope stays within its angle of repose, it will remain stationary. Good vegetative cover, a small amount of moisture, and a high amount of binding material such as clay will increase the strength and stability of a slope, preventing mass wasting. Once a slope becomes unstable, mass wasting can occur. In areas where there are alternating periods of freezing and thawing or of wetting and drying, particles of soil and regolith are lifted up and set back down, but not in the same place as before. Gravity always causes the rocks and soil to settle just a little farther downslope than from where they started. This is the slow movement that defines creep, where the slope is unstable all the time and the process is continuous.

But other times, triggering events can arise that cause a sudden instability in a slope. A sudden shock, such as shock waves from an earthquake, can alter the structure of a slope, causing the slipping of surface soil and rock and the collapse of cliffs. Volcanic eruptions produce shocks similar

A Blast of Rock

Temperature fluctuations, water freezing in cracks, and growing tree roots make rockfalls a common occurrence in Yosemite National Park in California. However, in July 1996, the ground at the park was shaken by a tremendous rockfall. An 80,000-ton (72,560-metric ton) block of granite broke free from a cliff high above Yosemite Valley near Glacier Point. It slid down a steep slope for the first 500 feet (152 meters), then took to the air and fell freely for over 1,700 feet (518 meters). The impact of the rock when it smashed into a rocky slope near the base of the cliff generated winds in excess of 160 miles (257 kilometers) per hour. The blast blew down 10 acres (4 hectares) of trees. The dust created by the impact hung in the air for several hours before settling over an area of about 50 acres (20 hectares). Places near the impact site were covered with up to 2 inches (5 centimeters) of dust.

to earthquakes. They can also cause snow and ice to melt, rapidly releasing large amounts of water that can mix with volcanic ash and regolith to produce debris flows, mudflows, and lahars. Sudden heavy rains and floods can saturate the soil and regolith, reducing frictional contact and the angle of repose.

The normal erosive action of streams and waves can undercut stream banks and cliffs along coasts. Since it is no longer at the angle of repose, the bank or cliff becomes unstable and material falls downward.

Human activities may dramatically increase mass-wasting events. Heavy trucks rumbling down a road can send shock waves through nearby unstable slopes. This is especially true in areas that have been altered by grading (leveling-off of an area) for road or building construction. When a portion of a mountainside or hillside is graded, material is cut out of the slope and removed. The slope directly above the graded area is greatly steepened, reducing support for material higher up the slope. Mining is another activity that weakens slopes and promotes mass wasting. The removal of coal, stone, and other natural resources from the area beneath a slope makes the slope unstable and vulnerable to collapse.

The removal of vegetation on a slope, such as through forest fire or the cutting down of trees, can also lead to mass wasting. The roots of trees and other plants absorb water from rain or snow and release it slowly into the soil. Roots also act as anchors, holding the soil together. Soil with no vegetative cover erodes quickly. Landslides on deforested slopes, once set in motion, have no natural barriers to slow or stop them.

Spotlight on famous forms

Frank Slide, Alberta, Canada

On April 29, 1903, in a glacier-modified valley near Alberta, Canada, the greatest landslide in recorded North American history took place. A wedge of the eastern slope of Turtle Mountain, measuring approximately 0.5 square mile (1.3 square kilometers) in area, gave way and hurtled 2,300 feet (700 meters) down the mountain. An estimated 100 million tons (91 million metric tons) of rock plowed through a portion of the nearby small coal-mining town of Frank, continued 2.5 miles (3.2 kilometers) across the valley floor, then climbed 400 feet (122 meters) up the opposite side. The fallen rock, which in places along the valley floor reached a height of 100 feet (30.5 meters), dammed the Crowsnest River and created a new lake. Seventy-six people were killed instantly in the rock slide that lasted less than two minutes. Only twelve bodies were ever recovered.

The main cause of the rock slide, which became known as the Frank Slide, was the mountain's unstable structure. Two years prior to the slide, mines had been dug in order to mine the massive deposits of coal beneath the eastern slope of the mountain. Already unstable because of the loss of rock structure underneath, the mountainside was put into further jeopardy when a sudden cold spell caused water from melting snow to freeze in cracks on its surface. As the water turned to ice, it expanded, widening the cracks and initiating the slide.

Gansu landslide, China

The Loess Plateau covers an area of about 247,100 square miles (640,000 square kilometers) in the north-central area of China. Loess (pronounced LUSS; a German word meaning "loose") is a deposit of fine, yellowish-gray, silty sediment. The loess covering the plateau was blown in from the Gobi Desert in Mongolia by windstorms over many, many years. Because it is so fine and loosely packed, loess is highly prone to erosion by wind and water.

In 1920, an earthquake struck the Loess Plateau region near Gansu (formerly Kansu) Province. Treeless and covered in loess, the hills and cliffs in the region were highly susceptible to loess flows. The shock of the earthquake caused the sides of 100-foot-high (30-meter-high) cliffs to collapse. Flowing material barricaded the entrances of mountainside caves, in which many peasants made their homes. The flows laid waste to ten cities and numerous villages in the region. An estimated 180,000 people died, more than the number who were killed at Hiroshima, Japan, on August 6, 1945, when the first atomic bomb was dropped.

Location of the Turtle Mountain landslide, which covered the town of Frank, Alberta, in 1903. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Mount Huascarán debris avalanche, Peru

Mount Huascarán (pronounced wass-ka-RON), the tallest mountain in Peru, is part of the Andes mountain system, the world's longest system on land, which runs for more than 5,000 miles (8,000 kilometers) along the western coast of South America. An extinct volcano, Mount Huascarán rises to a height of 22,205 feet (6,768 meters). Like other peaks in the area, it features many alpine glaciers.

In May 1970, a forty-five-second earthquake struck beneath the mountain, causing a mass of rock and glacial ice measuring 3,000 feet (914 meters) wide and 1 mile (1.6 kilometers) long to break off its west face and slide toward the valley below. Traveling at an average speed of 100 miles (161 kilometers) per hour, the debris avalanche quickly reached the village of Yungay, located 11 miles (18 kilometers) away from the mountain. Estimated to have consisted of almost 80 million cubic yards (61 cubic meters) of rock, ice, water, and other debris, the avalanche completely buried the village and others in its path, killing 18,000 people.

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Mesa and butte

Spanish explorers in the mid-sixteenth century ranged over the American Southwest. They had come north from Mexico, looking for gold and gems and the legendary Seven Cities of Cibola (pronounced SEE-bow-lah), allegedly filled with such treasures. In their quest, they found neither gold nor riches. They did, however, become the first Europeans to view the geological wonders of the area, and they were amazed at what they saw.

Among the canyons, plateaus, and rock towers and arches, the explorers saw landforms that appeared plateaulike, only smaller and isolated. They called these geologic features mesas (pronounced MAY-suz), which means table in Spanish, because the explorers thought the landforms resembled tables with their smooth, flat tops and sides that drop away steeply. Populating the spare, arid (dry) landscape of the area along with mesas were still smaller landforms that had a similar appearance. At the beginning of the nineteenth century, the word butte (pronounced BYOOT) was coined from the French word meaning mound or hillock to describe these solitary landforms.

The shape of the land

A mesa is an isolated, flat-topped hill or mountain with steep sides that is smaller in area than a plateau. A butte is also a flat-topped hill with steep sides, though smaller in area than a mesa. Definitions of the surface areas of mesas and buttes vary. One source states that a mesa has a surface area of less than 4 square miles (10 square kilometers), while a butte has a surface area less than 11,250 square feet (1,000 square meters). Another source states that the surface area of a mesa is larger than 1 square mile (2.59 square kilometers); the surface area of a butte is smaller than that dimension. Some simply define a mesa as a

Junction Butte in Canyonlands National Park, Utah. Part of the Colorado Plateau, the landscape of sedimentary sandstone in this area was eroded into countless canyons, mesas, and buttes by the Colorado River and its tributaries. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

landform that is wider than it is high and a butte as one that is higher than it is wide.

A mesa's and butte's characteristic shape—flat top and clifflike sides—is due to the layers of rock forming them. These landforms are most often composed of sedimentary rock, formed by the accumulation and compression of sediment (which may consist of rock fragments, remains of microscopic organisms, and minerals). This type of rock covers more than 75 percent of Earth's land surface. Most sedimentary rocks occur in layers, called strata, that are mostly horizontal or flat when first formed. Forces within Earth that rupture the surface to form volcanoes, mountains, plateaus, and many other topographical features (physical features on the planet's surface), may later cause these layers to tip, fold, warp, or fracture.

The top layer of a mesa and a butte is a hardened layer of rock that is resistant to erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. Sometimes this top layer, called the cap rock, is not sedimentary rock but is cooled and hardened lava that had spread out across the landscape in repeated flows from fissures or cracks in

Words to Know

Canyon: A narrow, deep, rocky, and steep-walled valley carved by a swift-moving river.

Cap rock: Erosion-resistant rock that overlies other layers of less-resistant rock.

Cliff: A high, steep face of rock.

Crust: The thin, solid, outermost layer of Earth.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Pinnacle: A tall, slender tower or spire of rock.

Plateau: A relatively level, large expanse of land that rises some 1,500 feet (457 meters) or more above its surroundings and has at least one steep side.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Sedimentary rock: Rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Strata: Layers in a series of sedimentary rocks.

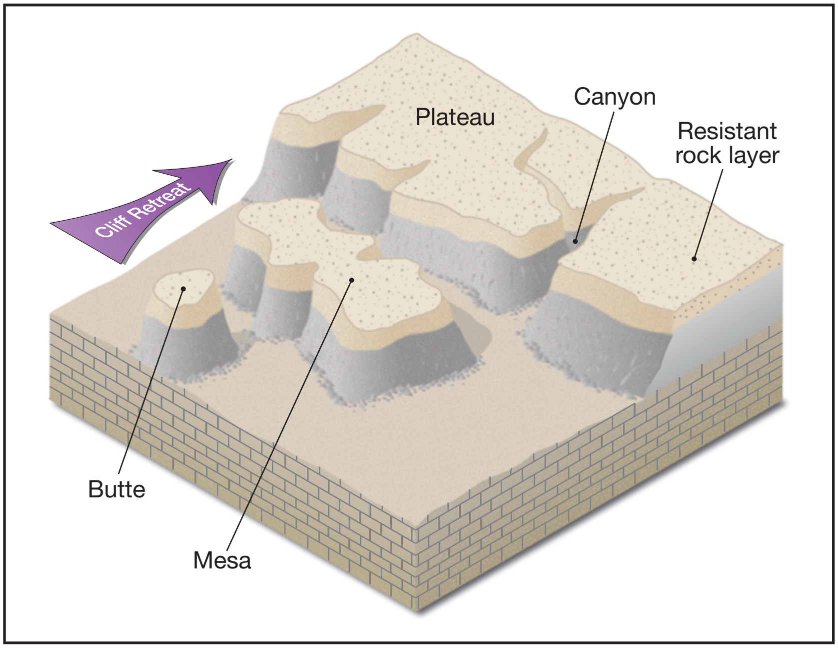
the ground. Beneath this flat protective cap of rock are horizontal layers of softer sedimentary rock. To varying degrees, these layers are not as resistant to erosion.

These landforms are found in arid and semiarid regions. Arid regions are defined as those that receive less than 10 inches (25 centimeters) of rain per year; semiarid regions receive 10 to 20 inches (25 to 50 centimeters) of rain per year. Precipitation in these regions often comes in the form of sudden, heavy rainfalls. Because water evaporates quickly in these normally dry environments, plants and other ground cover are scarce. Left exposed to the action of running water, the bare sides of the softer rock layers of mesas and buttes are eroded away over time. The base of these landforms is often gently sloped, contrasting with the almost-vertical sides leading down from the top. Rock material that has been eroded from the sides is carried downward, forming this sloping base.

Forces and changes: Construction and destruction

Mesas and buttes do not arise as completed landforms through sudden geological events. They have been shaped over millions of years by the slow, orderly process of erosion. They are part of a series of landforms that naturally erode into other landforms. That series begins with plateaus, which are relatively level, large expanses of land that rise some 1,500 feet (457 meters) or more above their surroundings and have at least one steep side.

A mesa is an isolated, flat-topped hill or mountain with steep sides that is smaller in area than a plateau. A butte is also a flat-topped hill with steep sides, though smaller in area than a mesa.



Plateaus develop in a few ways, all of which are directly related to the internal heat forces of Earth. These forces stirring beneath the crust (the outermost layer of the planet) are responsible for the physical features on the surface, from mountains to volcanoes to rift valleys and many others. Earth's internal forces have put pressure on the bottom of the crust, causing it to fracture into sections. As these sections, called plates, move about the surface in response to that pressure, they collide, slide past one another, or slide under each other. The interaction between the plates or the stress created within a plate as it has interacted with other plates have brought about the many landforms defining Earth's surface. The scientific theory explaining the plates and their movements and interactions is known as plate tectonics. (For further information on plateau formation and plate tectonics, see the **Plateau** chapter.)

Like all landforms elevated above their surrounding landscapes, a plateau is prone to erosion. Water, in the form of rain, snow, ice, rivers, runoff, and groundwater, is the primary force of that erosion. Wind also plays a part in this erosion, but to a far less degree. Rivers are the great cutting agents on plateaus. Whether raised with the plateau as it was elevated or formed afterward, a river will flow downward, seeking out the level of the body of water into which it drains. And it will do so as quickly as possible. It will seek out the path of least resistance, finding areas where rock is weak. Wearing away that rock, the river will cut downward deeper and deeper. Over millions of years, a river will form a valley, then a canyon, separating the plateau into sections. (For more information on canyon formation, see the **Canyon** chapter.)

On plateaus, areas of weak rock occur along faults, which are cracks or fractures in Earth's crust. Faults arise when pressure from underground forces pulls apart or compresses plates, creating stress within the plate. Faults are common in elevated regions. Rocks along a fault tend to be weak and broken, and a river or other flowing water easily cuts through the broken rock. Over time, valleys or canyons form, and a plateau is further dissected. (For more information on fault formation, see the **Fault** chapter.)

Rivers erode by picking up sediments (loose rock fragments) and transporting them to a new location. The speed or velocity at which a river flows determines the size of the material it can carry. A fast-moving river carries more sediment and larger material than a slow-moving one. The sediment acts as an abrasive as it is carried along, scouring and wearing away the banks and bed (sides and bottom) of the river. As new material is eroded, the river picks it up. In turn, this new sediment helps the river cut even deeper into its channel.

From plateaus to mesas to buttes to...

Geologically speaking, no landscape is ever "complete." The surface of the planet is in constant motion. As new landforms are built up, others are eroded away. As vast as it may seem, a plateau is relentlessly carved by erosion. The Colorado Plateau in the four corners region of the American Southwest is eroding at a rate of 500 vertical feet every 1 million years. Deep valleys and canyons form steep cliffs that retreat endlessly as water from storm runoff and streams and rivers washes away soft rock. Were it not for sections of resistant rock on the surface of a plateau, the entire landform would wear away over millions of years to a valley floor.

Those resistant sections allow a plateau to erode into mesas that rise above the ever-widening valley floor. Mesas maintain their shape because their cap rock offers protection to the layers of softer rock beneath. That protection, however, is short-lived. Again, water from storms washes over the sides of the mesa, wearing them away. As the sides retreat inward, the overhanging sections of cap rock weaken, fracture, and fall.

As the process of erosion continues, a mesa shrinks in size. Over time, it becomes a butte, taller than it is wide. Unrelenting, water erodes the butte as it had the mesa before it and the plateau before that. Capped by its resistant rock but ever shrinking, the butte may eventually erode into a pinnacle. This tall, slender tower or spire of rock will stand until it, too, succumbs to erosion and eventually crumbles to the valley floor.

The Face of Mars

In July 1976, the planetary probe *Viking 1* orbited Mars searching for a potential landing site for a sister probe, *Viking 2*. While photographing areas of the Cydonia region of the planet, the probe captured an image of a landform that resembled a face with darkened eyes, a narrow nose, and a frowning mouth. When the National Aeronautics and Space Administration (NASA) released the image to the public, it caused a sensation.

NASA scientists reasoned that sunlight on the landform created the apparent image, but many people thought otherwise. They believed that the face was artificially created. It was proof, they asserted, that intelligent life existed on Mars.

More than twenty years after the *Viking 1* probe was released, NASA sent another probe to Mars, the *Mars Global Surveyor.* In early 2001, after having taken tens of thousands of images of the planet, the *Surveyor* aimed its strong camera lens on the "Face of Mars." This time, the image clearly showed that the landform was simply another mesa in an area of mesas and buttes, very much like those that exist in the American Southwest.

Aerial photograph of a Martian mesa that resembles a human face. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

The Enchanted Mesa, in Acoma Pueblo, New Mexico, rises 430 feet from the desert valley. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Spotlight on famous forms

Enchanted Mesa, New Mexico

In west-central New Mexico stands a mesa made of sandstone, a type of rock composed of grains of sand bonded together by a mineral cement, like calcium carbonate. The mesa rises impressively 430 feet (131 meters) above the surrounding valley. Known as Enchanted Mesa, it was called Mesa Encantada by Spanish explorers and Katzimo by the Acoma (pronounced AK-ah-ma), the Native Americans who inhabit the area. The Acoma live in a pueblo (Native American village) on top of another sandstone mesa located a few miles away from Enchanted Mesa. The pueblo, believed to have been founded in the twelfth century, is the oldest continuously inhabited community in the United States.

According to Acoma legend, Enchanted Mesa is the ancestral home of the Acoma people. They lived on top of the mesa. One day, when the Acoma were tending their fields in the surrounding valley, a violent rainstorm arose. The rain washed away the stairway leading to the top of the mesa, leaving the elderly and the very young stranded on top. They eventually died from starvation. Another version of the legend states that only an old woman and her granddaughter were stranded on top. Rather than face certain starvation, they leapt to their deaths from the top of the mesa.

Mesa Verde, Colorado

Spanish for "green table," Mesa Verde (pronounced MAY-sah VURD or VUR-day) is a deeply carved mesa in southwest Colorado. The mesa is so-named because sagebrush, yucca, and other vegetation cover the area around it, while pinyon pine and juniper grow on its top. Unlike most mesas, the top of Mesa Verde is not completely horizontal, but tilts upward from south to north. Its north side rises nearly 2,000 feet (610 meters) above the valley below. Over millions of years, erosion has carved out the sides of the mesa. Overhangs and alcoves have developed where sections of softer sandstone layers have broken away.

Mesa Verde is perhaps more noted as a cultural landscape. Archaeologists estimate that twenty-four Native American cultures have had some connection to the area. Prominent among these were the Anasazi, who are believed to have been the ancestors of the modern Pueblo. For more than 700 years, from approximately 600 to 1300 C.E., their culture flourished at Mesa Verde. In the sheltered alcoves situated high on the mesa's sides, the Anasazi built their dwellings. Ruins of these elaborate stone structures survive to the present day. Archaeologists are not quite sure why the Anasazi abandoned their dwellings abruptly after so many centuries.

Monument Valley, Utah and Arizona

Lying entirely within the Navajo Indian Reservation on the border between southeastern Utah and northeastern Arizona is Monument Valley. Filled with striking mesas, buttes, and pinnacles, it is one of the most recognizable landscapes in the entire American Southwest. Countless Hollywood films have used the sandy region as a background, from *Stagecoach* (1939) to *Forrest Gump* (1993). More modern advertisements and television commercials are shot in Monument Valley than anywhere else on Earth.

Part of the Colorado Plateau, Monument Valley spans 2,000 square miles (5,180 square kilometers). In this flat, desolate landscape, red and orange landforms rise to heights of 1,000 feet (305 meters) or more. They are composed primarily of sandstone. Millions of years of erosion on the

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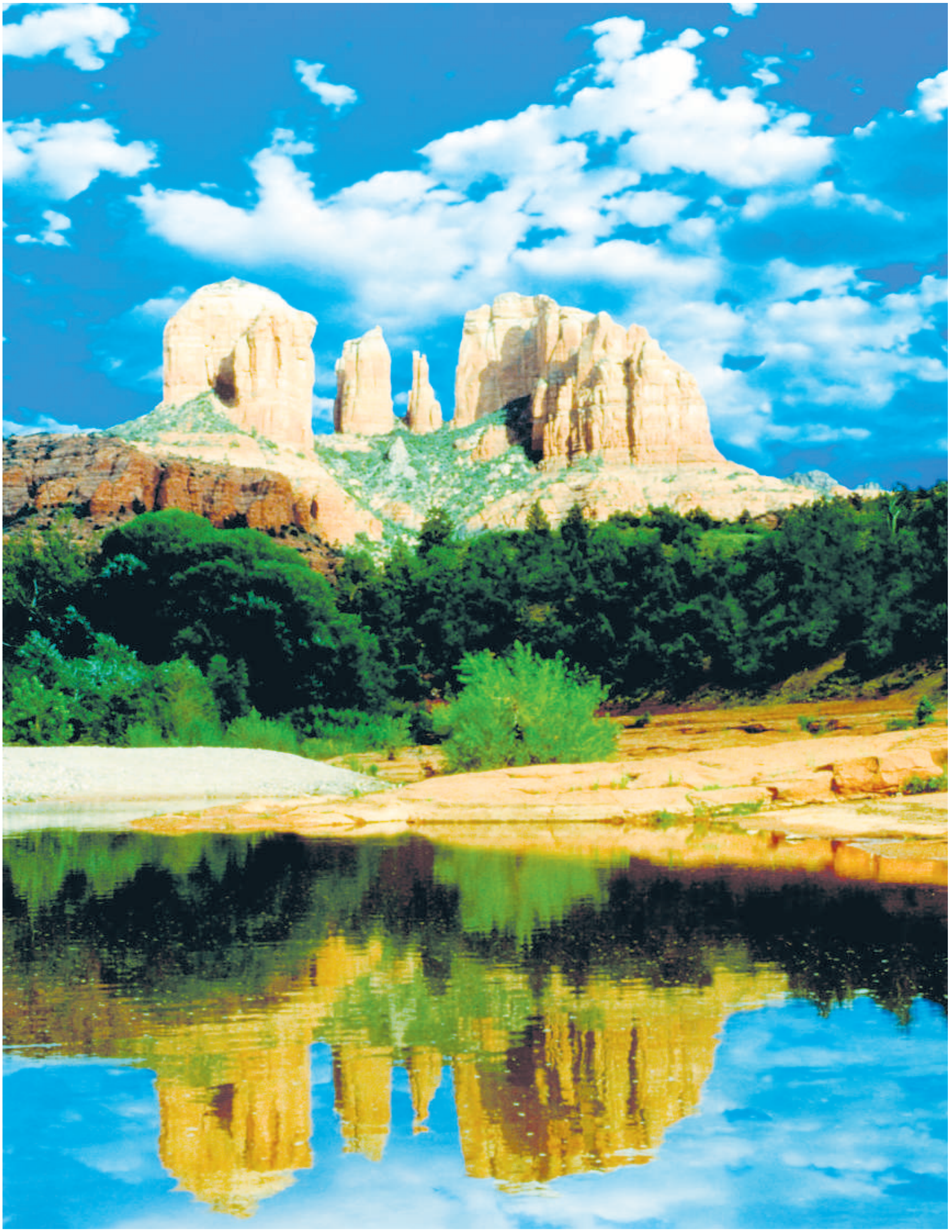
OPPOSITE Monument Valley, a 2,000-square-mile area on the border of Utah and Arizona, is filled with mesas, buttes, and canyons. Some of the freestanding rock formations rise as high 1,000 feet from the desert floor. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**



sedimentary rock layers of the plateau produced these isolated geological monuments.

Many of the rock formations in Monument Valley have been given names that describe their shape: East and West Mitten Buttes, Thunderbird Mesa, and Totem Pole (pinnacle), among others. The Navajo have occupied the area since the 1860s. Their history in the region, along with other Native American cultures, dates back centuries. Ancient ruins, petroglyphs (rock carvings), and pictographs (rock paintings) have been discovered throughout the area.

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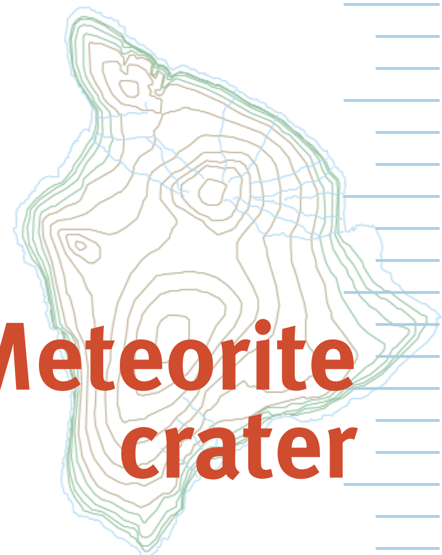


Meteorite crater

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

In July 1994, pieces of the comet Shoemaker-Levy 9 slammed into the southern hemisphere of the planet Jupiter at a speed of 37 miles (60 kilometers) per second. Professional and amateur astronomers around the world witnessed the spectacular and historic event. This marked the first time that scientists had an opportunity to witness the collision of two extraterrestrial bodies (those existing in space beyond Earth's atmosphere). Pictures taken of the impacts appeared on the Internet within hours of the event, captivating the public.

Afterward, while scientists studied data about the event, many in the public wondered if such a collision could happen to Earth and what would be the consequences. Science soon gave way to science fiction. By the end of the decade, popular movies like *Armageddon* (1998) and *Deep Impact* (1998) presented visions of Earth caught in the path of life-threatening asteroids and comets.

Although movies about planetary disasters often seem far-fetched, impacts between extraterrestrial bodies and Earth are not. In fact, an estimated 100 to 200 tons (91 to 181 metric tons) of extraterrestrial material bombards Earth's surface every day. Much of this material ranges in size from dust to pebbles and lands unnoticed. During the planet's history, though, thousands of impacts have produced craters, some of which have measured 100 miles (160 kilometers) or more in diameter. These landforms exist everywhere in our solar system except on the gaseous planets Jupiter, Saturn, Uranus, and Neptune.

The shape of the land

A meteorite is a fragment of extraterrestrial material that strikes the surface of Earth. When that material is floating in space before it hits Earth's surface, it is called a meteoroid. These terms are derived from the

Meteor Crater, also known as Barringer Crater, in Winslow, Arizona, measures nearly a mile wide and 570 feet in depth. There are more than 160 known meteorite craters on the surface of Earth. **PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.**

Greek word *meteoron,* which means "phenomenon in the sky." The vast majority of meteoroids are fragments of asteroids, which are small, irregularly shaped rocky bodies that orbit the Sun. Asteroids are planetesimals (pronounced plan-ne-TESS-i-mals) or minor planets. They are ancient chunks of matter that originated with the formation of our solar system, but never came together to form a planet. The remainder of meteoroids are fragments of comets. Sometimes called "dirty snowballs," comets are clumps of rocky material, dust, frozen methane, ammonia, and water. A comet's tail, which forms as the comet approaches the Sun, is made of vaporized ice. Solar winds sweep the tail back away from the Sun.

Once a meteoroid enters Earth's atmosphere, it becomes heated due to friction and begins to glow. The glowing fragments are known as a meteor, which is more commonly known as a shooting star. A meteor that is extremely bright is called a fireball. Large swarms of meteors entering Earth's atmosphere from approximately the same direction at certain times during the year are called meteor showers.

On Earth, a meteorite crater, also known as an impact crater, forms when a meteorite greater than 3 feet (0.9 meter) in diameter hits the surface. The size and depth of the crater depend upon the size and incoming speed of the meteorite. In general, a meteorite that hits Earth's surface

Words to Know

Asteroid: A small, irregularly shaped rocky body that orbits the Sun.

Breccia: A coarse-grained rock composed of angular, broken rock fragments held together by a mineral cement.

Comet: An icy extraterrestrial object that glows when it approaches the Sun, producing a long, wispy tail that points away from the Sun.

Ejecta blanket: The circular layer of rock and dust lying immediately around a meteorite crater.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Meteor: A glowing fragment of extraterrestrial material passing through Earth's atmosphere.

Meteorite: A fragment of extraterrestrial material that strikes the surface of Earth.

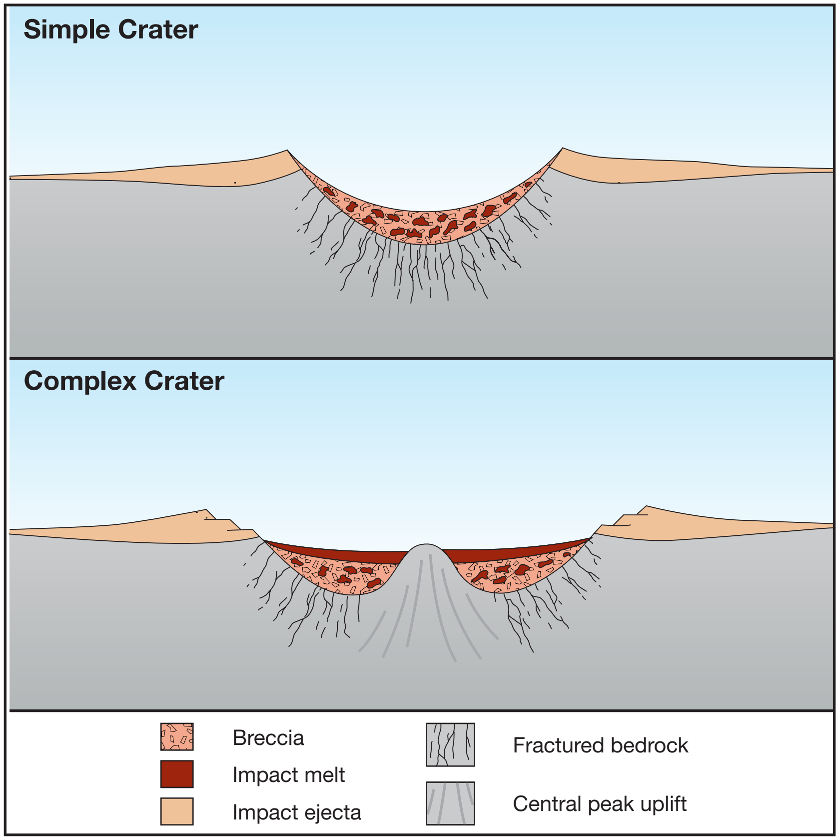
Meteoroid: A small solid body floating in space.

Shock wave: A wave of increased temperature and pressure formed by the sudden compression of the medium through which the wave moves.

creates a crater twelve to twenty times its size. When a meteorite slams into Earth, it forms one of two types of craters: simple or complex.

A relatively small meteorite forms a simple impact crater. Measuring typically less than 3 miles (5 kilometers) in diameter, this type of impact crater is relatively smooth, bowl-shaped, and nearly circular. The rim or upper edge of the crater is well-defined and raised above the surrounding landscape. The interior of the crater is steepest near the rim. The slope gradually decreases toward the center of the crater. Partially lining the interior of the crater is a layer of breccia (pronounced BREH-chee-ah; a coarse-grained rock composed of angular, broken rock fragments held together by a mineral cement). The energy of the impact typically causes some rocks to melt. In simple craters, this impact melt is often found as small blobs of material within the breccia layer. Surrounding the rim of the crater is a circular layer of rock and dust thrown out of the crater during its formation. Known as an ejecta blanket, this layer is deepest close to the rim. It becomes increasingly shallow outward from the crater.

A larger meteorite forms a complex impact crater, which generally measures more than 2 miles (3 kilometers) in diameter. While the interior of a complex crater may initially be smooth, it does not remain so for long. Gravity causes the steep walls to collapse downward and inward, forming terraced walls that may produce additional rims or rings within the crater. In the center of a complex crater lies a distinct central peak. The peak forms as the crater floor rebounds from the shock of the meteorite impact. The largest complex impact craters have several rings and several inner peaks. Breccia also partially fills complex craters, and its layer may contain



sheets of impact melt. An ejecta blanket surrounds a complex impact crater much as it does a simple impact crater.

Forces and changes: Construction and destruction

There are presently more than 160 known meteorite craters on the surface of Earth. Almost all have been recognized since 1950. New ones are discovered each year. The vast majority of recognized craters are found in North America, Europe, and Australia, where most exploration has taken place. Throughout the planet's history, countless other craters have existed. Like all other inner bodies in our solar system, Earth has been heavily impacted by meteorites. In fact, the planet has been impacted even more heavily than the Moon.

Yet most of these impact craters are no longer present. The geologic processes responsible for mountain building, volcanic eruptions, earthquakes, seafloor spreading, and many other physical features on the planet's surface have erased their mark. Chiefly, they have been worn

What Is a NEO?

A NEO or Near-Earth Object is an extraterrestrial body (an asteroid or a comet) whose orbit brings it within 28 million miles (45 million kilometers) of Earth's orbit. Those NEOs with orbits that actually intersect Earth's orbit are called ECOs or Earth-Crossing Objects. Scientists watch NEOs to determine which, if any, might one day strike Earth.

Any NEOs smaller than 164 feet (50 meters) in diameter would disintegrate in Earth's atmosphere. Scientists believe there are perhaps 1 million NEOs larger than this size. Although the vast majority of these measure less than 0.6 mile (1 kilometer) in diameter, they could pass through the atmosphere and cause tremendous damage if they hit the planet's surface. The largest NEOs yet discovered measure less than 15.5 miles (25 kilometers) in diameter. If one of these NEOs struck Earth, the result would be disastrous.

None of the known NEOs is currently a threat, but scientists have no way to predict the next impact from an unknown extraterrestrial object.

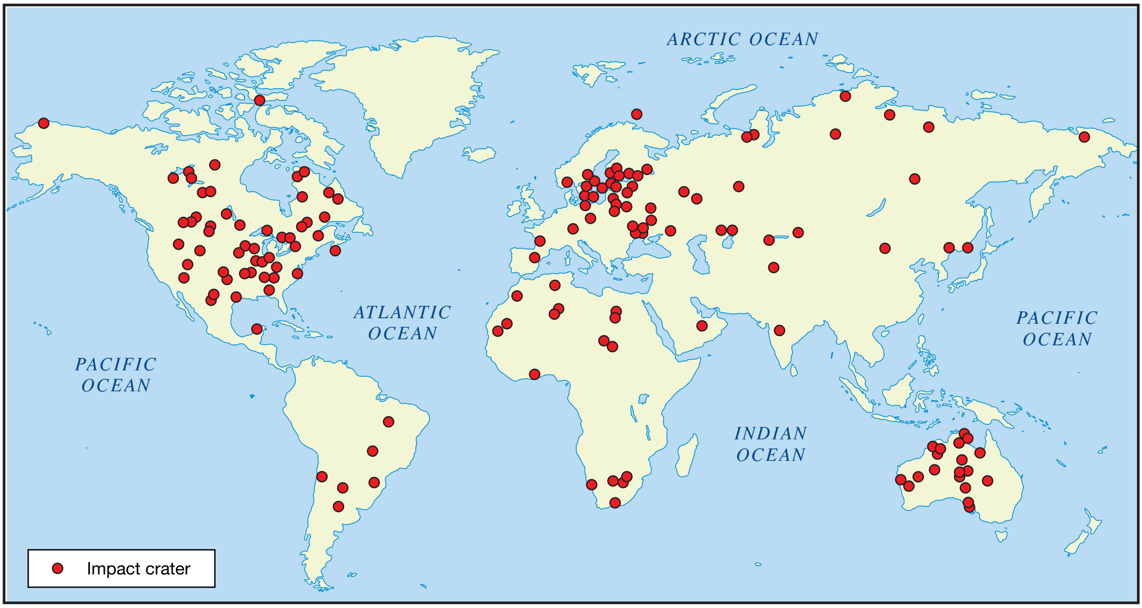
away by erosion, the gradual wearing away of Earth surfaces through the action of wind and water. The craters present on Earth today are either relatively recent, were caused by a relatively large meteorite, or are in a part of the world that experiences little geologic change (such as Antarctica or the Australian desert).

Scientists have never observed the formation of an impact crater in nature. They have, however, figured out the mechanics of such an event through laboratory experiments. Scientists know that an average meteoroid enters Earth's atmosphere at a velocity, or speed, between 6.2 and 43.5 miles (10 and 70 kilometers) per second. Because of friction caused by the atmosphere, all but the largest meteoroids quickly lose velocity. Most simply burn up and disintegrate before reaching Earth's surface.

Stages of impact crater formation

When a large meteorite strikes the planet's surface, enormous amounts of energy are released. Many of the characteristics of an impact crater are the result of the energy released almost instantaneously during the impact. This energy can be compared to that produced by geologic processes on Earth such as volcanic eruptions and earthquakes. The sequence of events that occurs when a meteorite strikes Earth can be divided into three stages: contact and compression, excavation, and modification.

A crater begins to form the instant a meteorite contacts Earth's surface. By the time the meteorite has penetrated the surface a distance less



Map highlighting the known meteorite craters around the world.

than twice its diameter, its energy is transferred as shock waves to the rocks in the crater. (Shock waves are waves of increased temperature and pressure formed by the sudden compression of the medium through which the waves move.) Shock waves also form in the meteorite, beginning at the edge that struck the ground and moving backward. The shock waves compress the rocks in Earth's surface and the material in the meteorite. The extremely high temperature and pressure created at the area of contact melts or even vaporizes much of the rock and meteorite material in that area. As the shock waves continue to move through Earth's surface, both downward and outward, they lose speed and pressure. Rocks no longer melt, but become cracked and fractured. Rock that had been compressed in the center of the crater may rebound, forming a peak.

At almost the same time, some of the shock-wave energy forces a stream of rock and dust (the ejecta) to be thrown away from the point of impact at high speeds and in all directions. The crater takes on its characteristic bowl shape with an uplifted rim because rocks near the upper levels of the crater move upward and outward while rocks in the lower levels move downward and outward. When the ejecta settles back to the ground, it forms the ejecta blanket around the crater rim.

Finally, after the shock waves have diminished to the point where they no longer have an effect and no more material is thrown from the crater, gravity takes over. Weak rocks in the walls of the crater may fall or slide down, and portions of the ejecta may also fall back into the crater.

The crater-forming process is very rapid. The entire sequence takes anywhere from a few seconds to one minute or so. In relation to other geologic processes on Earth, impact cratering releases the greatest amount of energy in the shortest amount of time.

Despite the tremendous forces that generate meteorite craters on Earth, those craters are not permanent. Like all other landforms on the planet, they are subject to erosion and Earth's ever-shifting surface. Water and wind quickly erode crater rims and ejecta blankets. They may also fill the crater with sediments and other rock debris, forever changing its form.

Inspired by a meteor shower?

The upper air burst into life!

And a hundred fire-flags sheen,

To and fro they were hurried about!

And to and fro, and in and out,

The wan stars danced between.

And the coming wind did roar more loud,

And the sails did sigh like sedge;

And the rain poured down from one black cloud;

The Moon was at its edge.

—Samuel Taylor Coleridge, *The Rime of the Ancient Mariner*

Spotlight on famous forms

Chicxulub Crater, Yucatan Peninsula

Scientists believe that approximately 65 million years ago, a meteorite measuring about 6.2 miles (10 kilometers) in diameter slammed into a prehistoric ocean near present-day Mexico's Yucatan Peninsula. The buried crater is presently known as Chicxulub (pronounced cheek-soo-LOOB; from the Mayan word roughly meaning "tail of the devil"). Initially, the crater measured nearly 62 miles (100 kilometers) in diameter and 9 miles (14 kilometers) in depth. The energy released by the impact was 6 million times more powerful than that released during the 1980 eruption of Mount St. Helens in Washington state. The walls of the complex impact crater were unstable and soon collapsed inward. The final diameter of the crater was enlarged to between 90 and 112 miles (145 and 180 kilometers).

During the crater's formation, clouds of water vapor and debris were thrown into the sky. Some of the 100 billion tons (91 billion metric tons) of vaporized material solidified into glassy spheres and rained back down on Earth. The rest of the material rose into the atmosphere where winds carried it around the planet. The material blocked sunlight from reaching Earth's surface, reducing temperatures worldwide.

As the meteorite passed through Earth's atmosphere, the air friction generated searing heat, which ignited widespread wildfires. In turn, these fires produced tremendous amounts of soot, carbon dioxide, and sulfur dioxide. The sulfur dioxide reacted with moisture in the blackened air to

A Rain of Asteroids

Some 4 billion years ago, roughly the same time life was forming on the planet, a flurry of asteroids rained down on Earth and the Moon. Scientists estimate that the barrage lasted from 20 million to 200 million years. It melted rocks, blasted out craters, and reshaped the surface of both Earth and the Moon. On the Moon, the bombardment produced the great basins that are clearly visible from Earth. On Earth, the huge asteroids produced craters rim-to-rim the size of present-day continents, vaporized the oceans, and filled the atmosphere with life-choking fog. Some scientists believe the impacts may have even affected the evolution of life on the planet. The asteroids may have forced life to begin anew or may have brought minerals, water, or even the building blocks of life to Earth.

form sulfuric acid, which fell to Earth in the form of acid rain. The lack of sunlight, combined with the air pollution and acid rain, soon killed off most of the plants on the planet. This led to the starvation of many animals, both plant-eating and meat-eating. Included were the dinosaurs. It is estimated that 70 percent of all plant and animal life perished within a few months of the meteorite's impact.

Supporting the theory that this meteorite caused worldwide destruction is a layer of iridium found in Earth's crust at a depth marking that time period. Iridium is an element commonly found in meteorites, but is exceedingly rare in the planet's crust. Iridium, at thirty times the normal amount, has been found at this depth around the world, from New Zealand to Italy. Soot has also been found with the iridium, providing evidence of widespread forest fires.

Meteor Crater, Arizona

Located in the desert near Winslow, Arizona, is Meteor Crater, the first impact crater to be so recognized. The arid (dry) conditions in the area have helped preserve this classic simple impact crater. Measuring 0.8 mile (1.3 kilometers) in diameter and 570 feet (174 meters) in depth, the crater was formed roughly 50,000 years ago by a meteorite measuring 100 feet (30.5 meters) in diameter and weighing 60,000 pounds (27,240 kilograms). The rim of the crater rises 150 feet (46 meters) above the level of the surrounding desert plain. Scientists estimate that the meteorite, a solid mixture of nickel and iron, was traveling at almost 45,000 miles (72,405 kilometers) per hour when it hit Earth's surface.

Meteor Crater is also known as Barringer Crater, after Daniel Moreau Barringer (1860–1929). A mining engineer, Barringer was the first to suggest the crater was the result of a meteorite impact. Before his assertion in 1905, many geologists believed it was a volcanic crater. Barringer spent many years trying to find the iron he believed would have been left over from the meteorite. He failed to realize, however, that most of the meteorite vaporized on impact. Nonetheless, his assertion behind the crater's formation was finally, and correctly, accepted by most scientists by the 1920s.

Vredefort Crater, South Africa

The Vredefort Crater in South Africa is the world's oldest and largest recognized impact crater. Scientists believe the highly eroded complex crater formed just over 2 billion years ago when a meteorite measuring over 6.2 miles (10 kilometers) in diameter hit the area. Some 16.8 cubic miles (70 cubic kilometers) would have been vaporized in the impact. The crater, which is estimated to have measured approximately 90 by 200 miles (140 by 300 kilometers), was long thought to be of volcanic origin. It encompasses the entire extent of the present-day Witwatersrand Basin. Located within the center of the impact structure is a ring of hills called the Vredefort Dome. Measuring 43.5 miles (70 kilometers) in diameter, the ring is the eroded remains of a peak created by the rebound of rock below the impact site after the meteorite hit.

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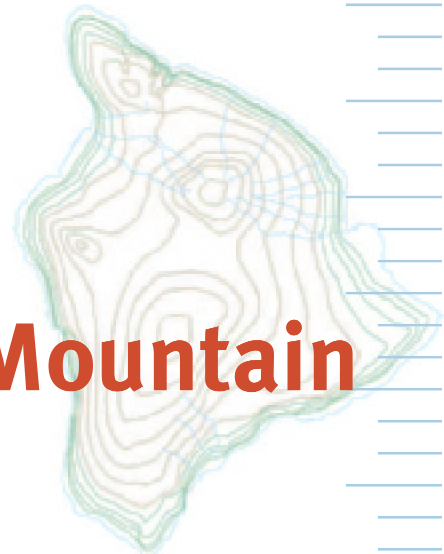


Mountain

Mountains loom large on the face of the planet. These rocky landforms, which tower over all others on Earth, are places of extreme temperatures and winds. Reaching high into the atmosphere, mountains form a barrier against moving air, robbing it of any precipitation. The tops of many mountains are laden with glossy caps of snow and ice. The summits of the highest mountains are often shrouded in mists and clouds.

Mountains also loom large in people's imaginations. Throughout human history, many people have regarded these mysterious places as the domain or home of supernatural beings or gods. Others have seen them as the ultimate in human adventure. Mountain climbing is viewed as an extreme test of human endurance and desire. Many climbers have succeeded in scaling the summits of the world's highest mountains; others have died trying.

The shape of the land

A mountain is any landmass on Earth's surface that rises abruptly to a great height in comparison to its surrounding landscape. By definition, a mountain rises 1,000 feet (305 meters) or more above its surroundings and has steep sides meeting in a summit that is much narrower in width than the mountain's base. Any highland that rises no higher than 1,000 feet (305 meters) above its surroundings, has a rounded top, and is less rugged in outline than a mountain is considered a hill. High hills at the base of mountains are known as foothills.

Mountains cover approximately one-fifth of Earth's land surface. Although rare, a mountain can exist singly, such as Mount Kilimanjaro in northeast Tanzania. Most mountains, however, occur as a group, called a mountain range. An example of a mountain range is the Sierra Nevada,

The highest mountain in the world is Mount Everest, located on the border of Tibet and Nepal. Its frozen summit stands 29,035 feet above sea level. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

which extends for about 400 miles (643 kilometers) in eastern California. A group of mountain ranges that share a common origin and form is known as a mountain system. The Sierra Madre, which arises just south of the U.S. border and extends south, is Mexico's chief mountain system. A group of mountain systems is called a mountain chain. The Pyrenees forms a mountain chain in southwest Europe between Spain and France. Finally, a complex group of mountain ranges, systems, and chains is called a mountain belt or cordillera (pronounced kor-dee-YARE-ah). The North American Cordillera runs from Alaska to Guatemala and includes all of the mountains and elevated plateaus in that vast region.

Like everything else in the natural world, mountains go though a life cycle. They rise from a variety of causes and wear down over time at various rates. The building up of mountains takes millions of years, and the process has been occurring since Earth's beginning over 4.5 billion years ago. Yet as soon as their rocks are exposed to the erosive actions of water and wind, mountains begin to fracture and dissolve. This explains the high and rugged appearance of young mountains and the lower and smoother appearance of older mountains. Some mountains that once existed on the planet hundred of millions of years ago have long since eroded away.

Words to Know

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Anticline: An upward-curving (convex) fold in rock that resembles an arch.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Cordillera: A complex group of mountain ranges, systems, and chains.

Crust: The thin, solid outermost layer of Earth.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Foothill: A high hill at the base of a mountain.

Graben: A block of Earth's crust dropped downward between faults.

Hill: A highland that rises up to 1,000 feet (305 meters) above its surroundings, has a rounded top, and is less rugged in outline than a mountain.

Horst: A block of Earth's crust forced upward between faults.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Magma: Molten rock containing particles of mineral grains and dissolved gas that forms deep within Earth.

Magma chamber: A reservoir or cavity beneath Earth's surface containing magma that feeds a volcano.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

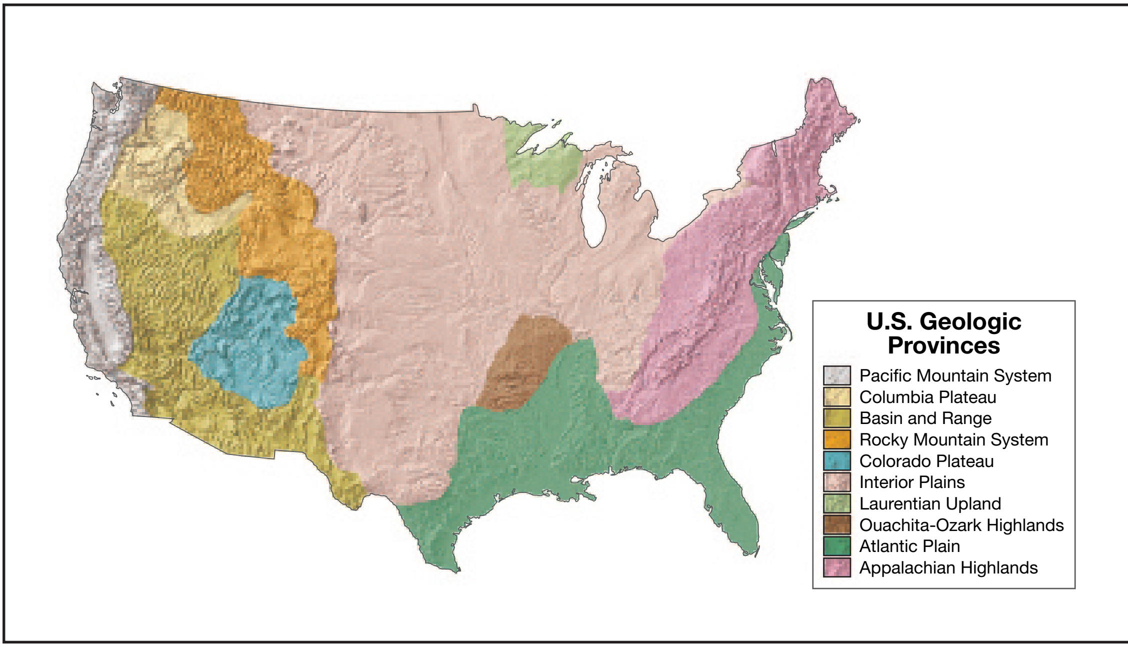
Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Syncline: A downward-curving (concave) fold in rock that resembles a trough.

Uplift: In geology, the slow upward movement of large parts of stable areas of Earth's crust.

Orogeny (pronounced o-RAH-je-nee) is the word scientists use to describe the process of mountain building. (Orogeny comes from the Greek words *oro*, meaning "mountain," and *geneia*, meaning "born.") There are several distinct types of mountains, each having formed through varying causes: volcanic mountains, upwarped mountains, folded mountains, and fault-block mountains.

Technically, a volcano is a vent or hole in Earth's surface through which magma and other molten matter escapes from underground. Many volcanoes are classified as mountains because the magma (called lava once it reaches Earth's surface) ejected through the vent often accumulates to form a cone around the vent reaching thousands of feet in height. The shape of the accumulated landform (also known as a volcano), with a summit much narrower than its base, also fits the definition of a mountain. (For further information on volcanic landforms, see the **Volcano** chapter.)



An example of a volcanic mountain in North America is Mount Rainier in the state of Washington. Part of the Cascade Range mountain chain, it rises 14,410 feet (4,392 meters) in elevation. Mauna Loa on the island of Hawaii is the world's largest volcano, rising 13,680 feet (4,170 meters) above sea level. Since it also extends more than 18,000 feet (5,544 meters) to the floor of the Pacific Ocean, Mauna Loa measures about 32,000 feet (9,754 meters) from its base to its summit. This makes it the tallest mountain on the planet (Mount Everest in the Himalayan Mountains is the tallest on land).

Most of the world's volcanic mountains lie not on land but underwater. The global mid-ocean ridge system is an undersea mountain system that snakes its way between the continents, encircling the planet like the seams on a baseball. It extends more than 40,000 miles (64,000 kilometers) in length. At the mid-ocean ridge, the seafloor splits apart and lava from below wells up into the crack or rift, solidifying and forming new seafloor. On either side of the rift lie tall volcanic mountains. The peaks of some of these mountains rise above the surface of the ocean to form islands, such as Iceland and the Azores. (For further information on oceanic landforms, see the **Ocean basin** chapter.)

Upwarped mountains are also formed by the action of rising magma. In this process, instead of passing through Earth's surface, such as it does in the formation of a volcanic mountain, magma remains underground, exerting pressure on the crust (the thin, solid outermost layer of Earth). This pressure gently uplifts a broad area of the crust, sometimes in the shape of a blisterlike dome. As the crust is uplifted, softer material on top may also be eroded or worn away by rivers or other flowing water, leaving sharp peaks and ridges. Examples of upwarped mountains in North America include the Adirondack Mountains in northeast New York and the Black Hills in western South Dakota and northeast Wyoming.

Fault-block and folded mountains are formed when stresses on Earth's crust cause it to crack and uplift or buckle and fold. As its name indicates, a fault-block mountain forms along a fault. A fault is a crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other. (For further information on faults, see the **Fault** chapter.) In the formation of a fault-block mountain, a section of the crust on one side of the fault is forced upward. The resulting mountains in the range may have steep clifflike faces on one side and gentler inclines on the other. The Teton Range of Wyoming is an example of fault-block mountains.

The Literary Landscape

"Straddling the top of the world, one foot in China and the other in Nepal, I cleared the ice from my oxygen mask, hunched a shoulder against the wind, and stared absently down at the vastness of Tibet. I understood on some dim, detached level that the sweep of earth beneath my feet was a spectacular sight. I'd been fantasizing about this moment, and the release of emotion that would accompany it, for many months. But now that I was finally here, actually standing on the summit of Mount Everest, I just couldn't summon the energy to care."

—Jon Krakauer, *Into Thin Air,* 1997.

Folded mountains are the most common type on land. They are created when forces within Earth push adjacent sections of the crust into each other. When the sections collide, their edges along the line of collision buckle and fold in a wavelike pattern like a wrinkled rug. As the sections continue to push into each other, their leading edges are thrust higher and higher. This process has created some of the world's highest, and most famous, mountain ranges and systems. Folded mountains include those of the Appalachian Mountain system in eastern North America, the Alps mountain system in southern-central Europe, and the Himalayan mountain system in southwest Asia.

Forces and changes: Construction and destruction

Mountains form mainly as a result of movements of sections of Earth's crust in response to heat and pressure within the planet. Prior to the 1960s, geologists lacked a clear scientific explanation as to what moved continents and other sections of crust across the surface of the planet. The theory of plate

Folded mountains are the most common type on land. They are created when forces within Earth push adjacent sections of the crust into each other. When the sections collide, their edges along the line of collision buckle and fold in a wavelike pattern. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

tectonics, developed at that time, provided the answer. It explains not only how mountains are built, but also how and why volcanoes erupt, why earthquakes occur, why the seafloor spreads, and how many other topographic features (physical features on Earth's surface) are formed. Like the theory of evolution in biology, plate tectonics is the unifying concept of geology.

Earth's heated interior

At Earth's center, the inner core spins at a rate slightly faster than the planet. A blisteringly hot mass of iron, the inner core has a temperature exceeding 9,900°F (5,482°C). Around this solid inner portion is a molten, or melted, outer portion. Above the two-layered core is a large section of very dense rock called the mantle that extends upward to the crust.

The mantle itself is separated into two distinct layers: a rigid upper layer and a partially melted lower layer. The crust and the uppermost layer together make up what geologists call the lithosphere (pronounced LITH-uh-sfeer). The part of the mantle immediately beneath the lithosphere is called the asthenosphere (pronounced as-THEN-uh-sfeer). This layer is composed of partially melted rock that has the consistency of soft putty. The lithosphere is broken into many large slabs or plates that "float" on the soft asthenosphere. In constant contact with each other, these plates fit together like a jigsaw puzzle.

It is the intense heat energy created by the extreme temperatures in the core that cause the lithospheric plates to move back and forth across the surface of the planet. If this heat energy were not carried upward to Earth's surface, where it can be released in some manner, the interior of the planet would melt. This does not happen because circular currents, called convection currents, carry the energy from the core upward through the mantle.

Circulating currents

Convection takes place when material at a deeper level is heated to the point where it expands and becomes less dense (lighter) than the material above it. Once this occurs, the heated material rises. This process is similar to what happens in a pot of boiling water. As it begins to boil, water in a pot turns over and over. Heated water at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense. Once at the surface, the heated water cools and becomes dense (heavier), then sinks back down to the bottom to become reheated. This continuous motion of heated material rising, cooling, and sinking within the pot forms the circular convection currents.

Convection currents form in the planet's interior when rock surrounding the core heats up. Expanding and becoming less dense, the heated rock slowly rises through cooler, denser rock that surrounds it in the mantle. When it reaches the lithosphere, the heated rock moves along the lithosphere's base, losing heat. Cooling and becoming denser, the rock then sinks back toward the core, only to be heated once again.

The pressure exerted by the convection currents underneath the lithosphere causes the plates to move. The plates, which vary in size and shape, are in constant contact with each other. When one plate moves, other plates move in response. This movement and interaction of the plates either directly or indirectly creates the major geologic features on Earth's surface, including mountains.

Plate movement and mountain building

The boundaries where plates meet and interact are known as plate margins. It is here where mountain building primarily occurs. The type of mountain that develops is dependent on the nature of the plate interaction. Plates interact by moving toward each other (converge), moving away from each other (diverge), or sliding past each other (transform). Most mountains are formed when plates converge.

When continental plates (those under the continents or landmasses) converge, the rocks in the collision area are compressed, shattered, and folded. Although normally brittle, rocks in Earth's crust can bend and fold like warm toffee when placed under great pressure and heat for long periods of time (thousands to millions of years). As the plates continue to push into each other, the rock layers are folded into a wavelike series of high points and low points. Geologists call the upfold on a curve (the peak) the anticline and the troughlike downfold (the valley) the syncline. Since tectonic plates move only a few inches per year (about as fast as fingernails grow), the process forming folded mountains takes millions of years. Folded mountains stand high because the crust beneath them is thickened as the two plates pile on each other in the collision process.

The situation is different when a continental plate and an oceanic plate converge. The crust under the oceans is made primarily of basalt, a type of rock that is denser (heavier) than the granite rocks that make up the crust under the continents. Because of this difference in density, the oceanic plate subducts or slides under the continental plate where they are pushed together. As the oceanic plate sinks deeper and deeper into Earth, intense pressure and heat in the mantle melts the leading edge of rock on the plate. This molten rock (magma) is less dense than the rock that surrounds it underground. As a result, it begins to rise toward Earth's surface through weakened layers of rock, collecting in underground reservoirs called magma chambers. When pressure from the expanding magma exceeds that of the overlying rocks, the magma is forced through cracks or vents in the planet's surface, forming volcanic mountains. Lines of volcanic mountains are usually formed on the forward edge of the continental plate.

The Andes mountain system, the world's longest system on land, runs for more than 5,000 miles (8,000 kilometers) along the western coast of South America. It features many volcanic mountains. They have formed on the edge of the continental South American Plate where the leading edge of the oceanic Nazca Plate is subducting below it. As it sinks, some crust on the top layer of the Nazca Plate is also scraped off at the base of the Andes, adding height to the system.

Volcanic mountains may also form where tectonic pressure is stretching continental crust beyond its limits. As the crust splits apart, magma rises and squeezes through the widening cracks or faults. The rising magma, whether it erupts, puts more pressure on the crust, producing

Highest Points on Land Around the World

Location	Name	Elevation
Africa (Tanzania)	Kilimanjaro	19,340 feet (5,895 meters)
Antarctica	Vinson Massif	16,860 feet (5,139 meters)
Asia (Tibet/Nepal)	Everest	29,035 feet (8,850 meters)
Australia	Kosciusko	7,316 feet (2,230 meters)
Europe, Eastern (Georgia)	Elbrus	18,481 feet (5,633 meters)
Europe, Western (France)	Mont Blanc	15,771 feet (4,870 meters)
North America (Alaska)	McKinley	20,320 feet (6,194 meters)
Oceania (New Guinea)	Jaya Peak	16,503 feet (5,030 meters)
South America (Argentina)	Aconcagua	22,835 feet (6,960 meters)

additional fractures. Ultimately, sections of the crust drop down between the faults, forming a rift valley. Volcanic mountains may then arise in or along the valley. Mount Kilimanjaro is an extinct volcano that stands along the East African Rift Valley in northeast Tanzania. It is the largest of many volcanoes in the area. Geologists believe that if the spreading of the rift valley continues, the edge of the present-day African continent will separate completely. The Indian Ocean will then flood the area, making the easternmost corner of Africa a large island.

Stress from the movement of tectonic plates can fracture continental crust. This stress or unequal pressure may be in different forms: tensional stress, which stretches or pulls rock; compressional stress, which squeezes and squashes rock; and shear stress, which changes the shape of rock by causing adjacent parts to slide past one another. When sudden stress near Earth's surface fractures brittle rock, it creates a fault in the crust.

Fault-block mountains form when tensional stress fractures the crust, separating it into blocks between faults. Pressure from magma moving underneath the surface can move the large blocks of rock (called fault blocks) either up or down. A block that is uplifted between faults is known as a horst; one that sinks is a graben (pronounced GRAH-bin). A large horst that is uplifted high between two parallel normal faults can form a fault-block mountain. More often, a fault-block mountain is created when one edge of a fault block is tilted upward at the fault a great distance in relation to the block on the other side. Sometimes these resulting landforms are referred to as tilted fault-block mountains.

Magma welling up beneath continental crust may not be able to reach Earth's surface through vents or move blocks of the crust located alongside faults. Instead, its high temperature and pressure may simply cause the overlying crust to fold and bubble gently outward into a dome shape. Over

The Black Hills stretch across 6,000 square miles of southwestern South Dakota and northeastern Wyoming. The region is home to many minerals, such as uranium and silver, and the largest gold mine in the United States is located there. PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.

millions of years, the magma beneath the dome cools and hardens into a solid core. During the same period, erosion wears away the softer materials on top, leaving the rugged, harder material beneath exposed as an upwarped mountain.

Spotlight on famous forms

Black Hills, South Dakota and Wyoming

Some 65 million years ago, an upwelling of magma under Earth's crust in the present-day Great Plains region formed the Black Hills. These rugged mountains, which rise some 2,500 feet (760 meters), cover an area of approximately 6,000 square miles (15,540 square kilometers). The highest point in the Black Hills is Harney Peak, which stands 7,242 feet (2,207 meters) in elevation.

The Black Hills region contains large amounts of many minerals, including a few rare ones. Uranium, feldspar, mica, and silver are among the important minerals found in the area. Gold was discovered in the Black Hills in 1874. The Homestake Mine, the largest gold mine in the United States, produced more than $200 million worth of gold between 1876 and 2002.

The discovery of gold led to an invasion of white settlers into the Black Hills, forcing out local Native Americans from the area. The Lakota, Northern Cheyenne, and Omaha tribes believe the mountainous region is a sacred landscape. Two landforms the Native Americans consider particularly sacred in the Black Hills are Bear Butte and Devils Tower. Bear Butte, which rises 1,253 feet (382 meters) above the surrounding plain, is made of magma that rose, deformed the crust, then cooled and solidified. Devils Tower, standing 1,267 feet (386 meters), is a volcanic neck, the inner remains of an ancient volcano.

Cascade Range, Pacific Northwestern United States

The largest collection of volcanic mountains in the contiguous United States (connected forty-eight states) is the Cascade Range. This mountain chain extends about 700 miles (1,125 kilometers) in length. It runs south from British Columbia, Canada, through the U.S. states of Washington and Oregon before it becomes the Sierra Nevada mountain range in northeastern California. It parallels the edge of the Pacific Ocean, lying 100 to 150 miles (161 to 241 kilometers) inland from the West Coast of the United States.

The Cascade Range formed more than 30 million years ago when the oceanic Juan de Fuca Plate sunk beneath the continental North American Plate as the two plates converged. Rising magma from the leading edge of the oceanic plate created an arc of volcanic mountains. Many of these form the range's highest peaks. Mount Rainier, at 14,410 feet (4,392 meters) is the highest point in the Cascades. Other notable volcanic mountains in the range include Lassen Peak, Mount Hood, Mount Shasta, and Mount St. Helens, which last erupted in 1980. Since the Juan de Fuca Plate continues to sink beneath the North American Plate at a rate of about 1.6 inches (4 centimeters) per year, many of the volcanoes in the range are still active.

Mount Everest, on the border of Tibet and Nepal

The collision between the Indian Plate and the Eurasian Plate some 40 to 50 million years ago led to the formation of the Himalayan Mountains. The highest mountain system in the world, it features thirty mountains that rise above 25,000 feet (7,620 meters). The highest mountain in the system, and the highest on land anywhere in the world, is Mount Everest. Its frozen summit stands 29,035 feet (8,850 meters) above sea level.

Geologists estimate that when the Indian Plate moved into the Eurasian Plate, it did so at rates of up to 6 inches (15 centimeters) per year. Most plates move at rates one-fourth as fast. At present, the Indian Plate

Farthest from the Center of Earth

Although the summit of Mount Everest in the Himalayan Mountains is the highest elevation on land, it is not the farthest point from the center of Earth. That distinction goes to the volcanic mountain Chimborazo (pronounced cheem-bor-AH–so) in the Andes mountain system in central Ecuador. The highest mountain in Ecuador, Mount Chimborazo rises to a height of 20,703 feet (6,310 meters). While it is 8,832 feet (2,540 meters) lower than that of Mount Everest, its summit is actually farther away from the center of Earth because of the equatorial bulge caused by the rotation of the planet.

Earth is not a perfectly round sphere or ball; it bulges around the equator (a shape scientists call an oblate spheroid). As it revolves around the Sun, Earth also rotates or spins on its axis like a top. At the equator, the rate of this motion is slightly more than 1,000 miles (1,609 kilometers) per hour. This constant circular motion of Earth creates centrifugal force, which is the tendency of an object traveling around a central point to fly away from that point. Riders on a merry-go-round experience this same force. The centrifugal force created by Earth's rotation causes the middle of the planet to bulge slightly and the north and south poles to flatten slightly. The diameter of Earth from the North Pole to the South Pole is 7,900 miles (12,711 kilometers), but through the equator it is 7,926 miles (12,753 kilometers).

Mount Chimborazo lies very near the equator; Mount Everest lies farther north. Because of the equatorial bulge, the summit of Mount Chimborazo is 7,153 feet (2,180 meters) farther away from the center of Earth than the summit of Mount Everest.

is still inching northward, and the Himalayan Mountains are rising by as much as 0.4 inch (1 centimeter) per year.

In 1865, Mount Everest was given its English name in honor of George Everest (1790–1866), who had served as the English surveyor general of India. Tibetans call the mountain Chomolongma, meaning Mother Goddess of the World. Nepalese call it Sagarmatha, meaning Goddess of the Sky. Both hold the mountain to be sacred.

The first mountain climbers to reach the summit of Mount Everest were Edmund Hillary (1919–) of New Zealand and Tenzing Norgay (1914–1986) of Nepal on May 28, 1953. Since that time, more than 1,600 climbers have reached the summit of the world's tallest mountain. A record-breaking 54 climbers reached the peak on May 16, 2002. Not everyone who attempts to reach the top of Mount Everest is successful or even returns from the incredibly dangerous feat. The bodies of more than 160 climbers remain on the mountain.

The snow-capped peak of Mount Chimborazo stands 20,703 feet high. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Sierra Nevadas, California

The Sierra Nevada mountain range is the largest fault-block mountain formation in the United States. It runs mainly along California's eastern border for about 400 miles (643 kilometers). Its width varies from 40 to 80 miles (64 to 129 kilometers). The highest and most rugged mountains in the range occur in its southern portion. Here, 11 peaks rise more than 14,000 feet in elevation. The summits of many of these high mountains are continuously covered with snow. The highest peak in the range, Mount Whitney, rises to 14,495 feet (4,418 meters). It is the tallest mountain in the contiguous United States (connected forty-eight states).

The blocks of crust that formed the range tilted upward along its eastern side. As a result, its eastern slope rises steeply while its western slope descends gradually to the hills in California's central valley. Forests filled with aspen, cedar, fir, pine, and sequoia trees dominate the western slope.

Cultural Landforms

To followers of the religions of Buddhism and Hinduism, Mount Kailas is a sacred place. Part of the Himalayan mountain system, Mount Kailas rises some 22,280 feet (6,790 meters) above the Tibetan Plateau. What is unique about the mountain is that it sits on the highest part of the plateau, and it stands isolated: Over the course of several days, an individual may walk completely around the mountain at its base. Four of Asia's largest rivers also have their sources within 62 miles (100 kilometers) of the mountain. They flow away from the mountain in four different directions, like spokes from the hub of wheel: the Indus to the north, the Karnali to the south, the Yarlung Zangbo to the east, and the Sutlej to the west.

Hindus believe Mount Kailas is the dwelling place of Shiva, one of the greatest gods of Hinduism. Along with the gods Brahma and Vishnu, Shiva forms the Hindu Supreme Being. Although difficult to define simply, Hinduism is based on the concept that all living things in the universe are in a constant cycle of creation, preservation, and destruction. Shiva is the god of destruction.

Tibetan Buddhists believe that Mount Kailas is the earthly form of mythical Mount Sumeru, the cosmic axis or center of the universe. This is the place where all planes, or realms of existence—spiritual and physical—are united.

Tibetan pilgrims at the base of Mount Kailas. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

The beauty of the Sierra Nevadas is immeasurable. Two of the nation's most-scenic national parks, Sequoia National Park and Yosemite National Park, are located within the range.

OPPOSITE The 400-mile-long Sierra Nevada mountain range, which runs along California's eastern border, was formed when the North American and Pacific plates converged many millions of years ago. Glaciers later shaped the mountains. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

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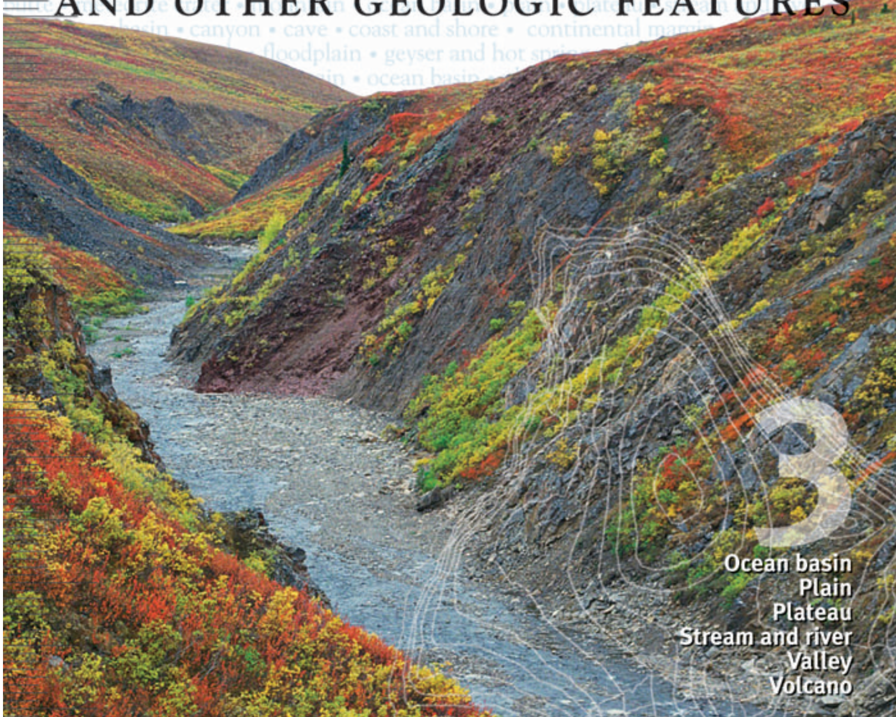

3

Ocean basin
Plain
Plateau
Stream and river
Valley
Volcano

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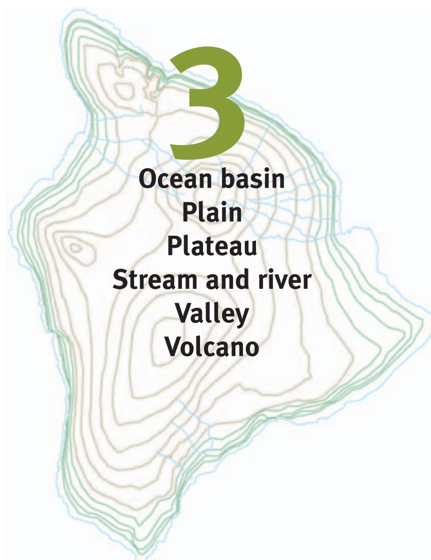

3

Ocean basin
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Rob Nagel

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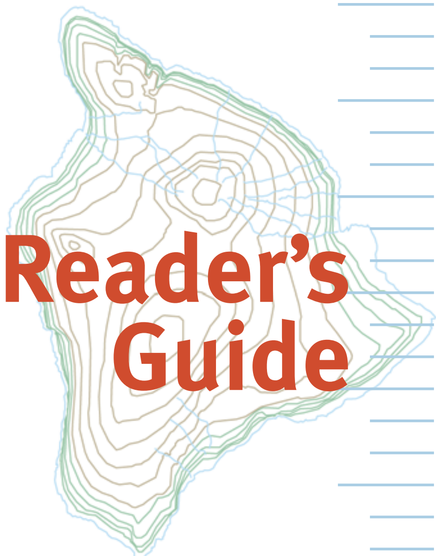

Reader's Guide

From the perspective of human time, very little changes on the surface of Earth. From the perspective of geologic time, the period from Earth's beginning more than 4.5 billion years ago to the present day, however, the surface of the planet is in constant motion, being reshaped over and over. The constructive and destructive forces at play in this reshaping have helped create landforms, specific geomorphic features on Earth's land surface. Mountains and canyons, plains and plateaus, faults and basins: These are but a few of the varied and spectacular features that define the landscape of the planet.

U•X•L Encyclopedia of Landforms and Other Geologic Features explores twenty-two of these landforms: what they are, how they look, how they were created, how they change over time, and major geological events associated with them.

Scope and Format

In three volumes, *U•X•L Encyclopedia of Landforms and Other Geologic Features* is organized alphabetically into the following chapters:

Basin
Canyon
Cave
Coast and shore
Continental margin
Coral reef
Delta
Dune and other desert features
Fault
Floodplain
Geyser and hot spring
Glacial landforms and features
Landslide and other gravity movements
Mesa and butte

Meteorite crater	Mountain
Ocean basin	Plain
Plateau	Stream and river
Valley	Volcano

Each chapter begins with an overview of that specific landform. The remaining information in the chapter is broken into four sections:

- **The shape of the land** describes the physical aspects of the landform, including its general size, shape, and location on the surface of the planet, if applicable. A standard definition of the landform opens the discussion. If the landform exists as various types, those types are defined and further described.
- **Forces and changes: Construction and destruction** describes in detail the forces and agents responsible for the construction, evolution, and destruction of the landform. The erosional actions of wind and water, the dynamic movement of crustal plates, the influence of gravity, and the changes in climate both across regions and time are explained in this section, depending on their relation to the specific landform.
- **Spotlight on famous forms** describes specific examples of the landform in question. Many of these examples are well-known; others may not be. The biggest, the highest, and the deepest were not the sole criteria for selection, although many of the featured landforms meet these superlatives. While almost all chapters include examples found in the United States, they also contain examples of landforms found throughout the world.
- **For More Information** offers students further sources for research—books or Web sites—about that particular landform.

Other features include more than 120 color photos and illustrations, "Words to Know" boxes providing definitions of terms used in each chapter, sidebar boxes highlighting interesting facts relating to particular landforms, a general bibliography, and a cumulative index offering easy access to all of the subjects discussed in *U•X•L Encyclopedia of Landforms and Other Geologic Features*.

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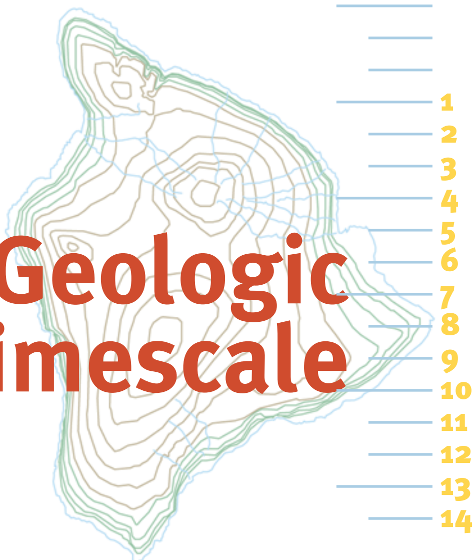
Comments and Suggestions

We welcome your comments on *U•X•L Encyclopedia of Landforms and Other Geologic Features*. Please write: Editors, *U•X•L Encyclopedia of Landforms and Other Geologic Features*, U•X•L, 27500 Drake Rd., Farmington Hills, MI 48331; call toll-free: 1-800-877-4253; fax: 248-699-8097; or send e-mail via http://www.gale.com.

Geologic Timescale



Era	Period		Epoch	Started (millions of years ago)
Cenozoic: 66.4 millions of years ago–present time	**Quaternary**		Holocene	0.01
			Pleistocene	1.6
	Tertiary	**Neogene**	Pliocene	5.3
			Miocene	23.7
		Paleogene	Oligocene	36.6
			Eocene	57.8
			Paleocene	66.4
Mesozoic: 245–66.4 millions of years ago	**Cretaceous**		Late	97.5
			Early	144
	Jurassic		Late	163
			Middle	187
			Early	208
	Triassic		Late	230
			Middle	240
			Early	245
Paleozoic: 570–245 millions of years ago	**Permian**		Late	258
			Early	286
	Carboniferous	**Pennsylvanian**	Late	320
		Mississippian	Early	360
	Devonian		Late	374
			Middle	387
			Early	408
	Silurian		Late	421
			Early	438
	Ordovician		Late	458
			Middle	478
			Early	505
	Cambrian		Late	523
			Middle	540
			Early	570
Precambrian time: 4500-570 millions of years ago				4500

Words to Know

A

Ablation zone: The area of a glacier where mass is lost through melting or evaporation at a greater rate than snow and ice accumulate.

Abrasion: The erosion or wearing away of bedrock by continuous friction caused by sand or rock fragments in water, wind, and ice.

Abyssal hill: A gently sloping, small hill, typically of volcanic origin, found on an abyssal plain.

Abyssal plain: The relatively flat area of an ocean basin between a continental margin and a mid-ocean ridge.

Accretionary wedge: A mass of sediment and oceanic rock that is transferred from an oceanic plate to the edge of the less dense plate under which it is subducting.

Accumulation zone: The area of a glacier where mass is increased through snowfall at a greater rate than snow and ice is lost through ablation.

Active continental margin: A continental margin that has a very narrow, or even nonexistent, continental shelf and a narrow and steep continental slope that ends in a deep trench instead of a continental rise; it is marked by earthquake and volcanic activity.

Alluvial fan: A fanlike deposit of sediment that forms where an intermittent, yet rapidly flowing canyon or mountain stream spills out onto a plain or relatively flat valley.

Alluvium: A general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Alpine glacier: A relatively small glacier that forms in high elevations near the tops of mountains.

Angle of repose: The steepest angle at which loose material on a slope remains motionless.

Anticline: An upward-curving (convex) fold in rock that resembles an arch.

Arête: A sharp-edged ridge of rock formed between adjacent cirque glaciers.

Arroyo: A steep-sided and flat-bottomed gully in a dry region that is filled with water for a short time only after occasional rains.

Asteroid: A small, irregularly shaped rocky body that orbits the Sun.

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Atmospheric pressure: The pressure exerted by the weight of air over a given area of Earth's surface.

Atoll: A ring-shaped collection of coral reefs that nearly or entirely enclose a lagoon.

B

Back reef: The landward side of a reef between the reefcrest and the land.

Backshore zone: The area of a beach normally affected by waves only during a storm at high tide.

Backswamp: The lower, poorly drained area of a floodplain that retains water.

Backwash: The return flow of water to the ocean following the swash of a wave.

Bajada: Several alluvial fans that have joined together.

Bar: A ridge or mound of sand or gravel that lies underwater a short distance from and parallel to a beach; also commonly known as a sand bar.

Barrier island: A bar that has been built up so that it rises above the normal high tide level.

Barrier reef: A long, narrow ridge of coral relatively near and parallel to a shoreline, separated from it by a lagoon.

Basal sliding: The sliding of a glacier over the ground on a layer of water.

Basalt: A dark, dense volcanic rock, about 50 percent of which is silica.

Base level: The level below which a stream cannot erode.

Basin: A hollow or depression in Earth's surface with no outlet for water.

Bay: A body of water in a curved inlet between headlands.

Beach: A deposit of loose material on shores that is moved by waves, tides, and, sometimes, winds.

Beach drift: The downwind movement of sand along a beach as a result of the zigzag pattern created by swash and backwash.

Bed load: The coarse sediment rolled along the bottom of a river or stream.

Bedrock: The general term for the solid rock that underlies the soil.

Berm: A distinct mound of sand or gravel running parallel to the shoreline that divides the foreshore zone from the backshore zone of a beach.

Blowout: A depression or low spot made in sand or light soil by strong wind.

Bottomset bed: A fine, horizontal layer of clay and silt deposited beyond the edge of a delta.

Breccia: A coarse-grained rock composed of angular, broken rock fragments held together by a mineral cement.

Butte: A flat-topped hill with steep sides that is smaller in area than a mesa.

C

Caldera: Large, usually circular, steep-walled basin at the summit of a volcano.

Canyon: A narrow, deep, rocky, and steep-walled valley carved by a swift-moving river.

Cap rock: Erosion-resistant rock that overlies other layers of less-resistant rock.

Cave: A naturally formed cavity or hollow beneath the surface of Earth that is beyond the zone of light and is large enough to be entered by humans.

Cavern: A large chamber within a cave.

Cave system: A series of caves connected by passages.

Channel: The depression where a stream flows or may flow.

Chemical weathering: The process by which chemical reactions alter the chemical makeup of rocks and minerals.

Cirque: A bowl-shaped depression carved out of a mountain by an alpine glacier.

Cliff: A high, steep face of rock.

Coast: A strip of land that extends landward from the coastline to the first major change in terrain features.

Coastal plain: A low, generally broad plain that lies between an oceanic shore and a higher landform such as a plateau or a mountain range.

Coastline: The boundary between the coast and the shore.

Comet: An icy extraterrestrial object that glows when it approaches the Sun, producing a long, wispy tail that points away from the Sun.

Compression: The reduction in the mass or volume of something by applying pressure.

Continental drift: The hypothesis proposed by Alfred Wegener that the continents are not stationary, but have moved across the surface of Earth over time.

Continental glacier: A glacier that forms over large areas of continents close to the poles.

Continental margin: The submerged outer edge of a continent, composed of the continental shelf and the continental slope.

Continental rise: The gently sloping, smooth-surfaced, thick accumulation of sediment at the base of certain continental slopes.

Continental shelf: The gently sloping region of the continental margin that extends seaward from the shoreline to the continental shelf break.

Continental shelf break: The outer edge of the continental shelf at which there is a sharp drop-off to the steeper continental slope.

Continental slope: The steeply sloping region of the continental margin that extends from the continental shelf break downward to the ocean basin.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Coral polyp: A small, invertebrate marine animal with tentacles that lives within a hard, cuplike skeleton that it secretes around itself.

Coral reef: A wave-resistant limestone structure produced by living organisms, found principally in shallow, tropical marine waters.

Cordillera: A complex group of mountain ranges, systems, and chains.

Creep: The extremely slow, almost continuous movement of soil and other material downslope.

Crest: The highest point or level; summit.

Crevasse: A deep, nearly vertical crack that develops in the upper portion of glacier ice.

Crust: The thin, solid outermost layer of Earth.

Curtain: A thin, wavy or folded sheetlike mineral deposit that hangs from the ceiling of a cave.

Cut bank: A steep, bare slope formed on the outside of a meander.

D

Debris avalanche: The extremely rapid downward movement of rocks, soil, mud, and other debris mixed with air and water.

Debris flow: A mixture of water and clay, silt, sand, and rock fragments that flows rapidly down steep slopes.

Deflation: The lowering of the land surface due to the removal of fine-grained particles by the wind.

Delta: A body of sediment deposited at the mouth of a river or stream where it enters an ocean or lake.

Desert pavement: Surface of flat desert lands covered with a layer of closely packed coarse pebbles and gravel.

Dip: The measured angle from the horizontal plane (Earth's surface) to a fault plane or bed of rock.

Dissolved load: Dissolved substances, the result of the chemical weathering of rock, that are carried along in a river or stream.

Distributaries: The channels that branch off of the main river in a delta, carrying water and sediment to the delta's edges.

Dune: A mound or ridge of loose, wind-blown sand.

E

Earthflow: The downward movement of water-saturated, clay-rich soil on a moderate slope.

Ecosystem: A system formed by the interaction of a community of plants, animals, and microorganisms with their environment.

Ejecta blanket: The circular layer of rock and dust lying immediately around a meteorite crater.

Emergent coast: A coast in which land formerly under water has gradually risen above sea level through geologic uplift of the land or has been exposed because of a drop in sea level.

Eolian: Formed or deposited by the action of the wind.

Erg: A vast area deeply covered with sand and topped with dunes.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Erratic: A large boulder that a glacier deposits on a surface made of different rock.

Esker: A long, snakelike ridge of sediment deposited by a stream that ran under or within a glacier.

F

Fall: A sudden, steep drop of rock fragments or debris.

Fall line: The imaginary line that marks the sharp upward slope of land along a coastal plain's inland edge where waterfalls and rapids occur as rivers cross the zone from harder to softer rocks.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Fault creep: The slow, continuous movement of crustal blocks along a fault.

Fault line: The line on Earth's surface defining a fault; also known as a fault trace.

Fault plane: The area where crustal blocks meet and move along a fault from the fault line down into the crust.

Fault scarp: A steep-sided ledge or cliff generated as a result of fault movement.

Fault system: A network of connected faults.

Flash flood: A flood that occurs after a period of heavy rain, usually within six hours of the rain event.

Firn: The granular ice formed by the recrystallization of snow; also known as névé.

Fjord: A deep glacial trough submerged with seawater.

Floodplain: An area of nearly flat land bordering a stream or river that is naturally subject to periodic flooding.

Flow: A type of mass wasting that occurs when a loose mixture of debris, water, and air moves down a slope in a fluidlike manner.

Flowstone: The general term for a sheetlike mineral deposit on a wall or floor of a cave.

Fold: A bend or warp in a layered rock.

Foothill: A high hill at the base of a mountain.

Footwall: The crustal block that lies beneath an inclined fault plane.

Fore reef: The seaward edge of a reef that is fairly steep and slopes down to deeper water.

Foreset bed: An inclined layer of sand and gravel deposited along the edge of a delta.

Foreshore zone: The area of a beach between the ordinary low tide mark and the high tide mark.

Fracture zone: The area where faults occur at right angles to a main feature, such as a mid-ocean ridge.

Fringing reef: A coral reef formed close to a shoreline.

Fumarole: A small hole or vent in Earth's surface through which volcanic gases escape from underground.

G

Geyser: A hot spring that periodically erupts through an opening in Earth's surface, spewing hot water and steam.

Geyserite: A white or grayish silica-based deposit formed around hot springs.

Glacial drift: A general term for all material transported and deposited directly by or from glacial ice.

Glacial polish: The smooth and shiny surfaces produced on rocks underneath a glacier by material carried in the base of that glacier.

Glacial surge: The rapid forward movement of a glacier.

Glacial trough: A U-shaped valley carved out of a V-shaped stream valley by a valley glacier.

Glaciation: The transformation of the landscape through the action of glaciers.

Glacier: A large body of ice that formed on land by the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity.

Graben: A block of Earth's crust dropped downward between faults.

Graded stream: A stream that is maintaining a balance between the processes of erosion and deposition.

Granular flow: A flow that contains up to 20 percent water.

Gravity: The physical force of attraction between any two objects in the universe.

Ground moraine: A continuous layer of till deposited beneath a steadily retreating glacier.

Groundwater: Freshwater lying within the uppermost parts of Earth's crust, filling the pore spaces in soil and fractured rock.

Gully: A channel cut into Earth's surface by running water, especially after a heavy rain.

Guyot: An undersea, flat-topped seamount.

H

Hanging valley: A shallow glacial trough that leads into the side of a larger, main glacial trough.

Hanging wall: The crustal block that lies above an inclined fault plane.

Headland: An elevated area of hard rock that projects out into an ocean or other large body of water.

Hill: A highland that rises up to 1,000 feet (305 meters) above its surroundings, has a rounded top, and is less rugged in outline than a mountain.

Horn: A high mountain peak that forms when the walls of three or more glacial cirques intersect.

Horst: A block of Earth's crust forced upward between faults.

Hot spot: An area beneath Earth's crust where magma currents rise.

Hot spring: A pool of hot water that has seeped through an opening in Earth's surface.

I

Igneous rock: Rock formed by the cooling and hardening of magma, molten rock that is underground (called lava once it reaches Earth's surface).

Internal flow: The movement of ice inside a glacier through the deformation and realignment of ice crystals; also known as creep.

Invertebrates: Animals without backbones.

K

Kame: A steep-sided, conical mound or hill formed of glacial drift that is created when sediment is washed into a depression on the top surface of

a glacier and is then deposited on the ground below when the glacier melts away.

Karst topography: A landscape characterized by the presence of sinkholes, caves, springs, and losing streams.

Kettle: A shallow, bowl-shaped depression formed when a large block of glacial ice breaks away from the main glacier and is buried beneath glacial till, then melts. If the depression fills with water, it is known as a kettle lake.

L

Lagoon: A quiet, shallow stretch of water separated from the open sea by an offshore reef or other type of landform.

Lahar: A mudflow composed of volcanic ash, rocks, and water produced by a volcanic eruption.

Landslide: A general term used to describe all relatively rapid forms of mass wasting.

Lateral moraine: A moraine deposited along the side of a valley glacier.

Lava: Magma that has reached Earth's surface.

Lava dome: Mass of lava, created by many individual flows, that forms in the crater of a volcano after a major eruption.

Leeward: On or toward the side facing away from the wind.

Levee (natural): A low ridge or mound along a stream bank, formed by deposits left when floodwater slows down on leaving the channel.

Limestone: A sedimentary rock composed primarily of the mineral calcite (calcium carbonate).

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Longshore current: An ocean current that flows close and almost parallel to the shoreline and is caused by the angled rush of waves toward the shore.

Longshore drift: The movement of sand and other material along a shoreline in the longshore current.

Losing stream: A stream on Earth's surface that is diverted underground through a sinkhole or a cave.

M

Magma: Molten rock containing particles of mineral grains and dissolved gas that forms deep within Earth.

Magma chamber: A reservoir or cavity beneath Earth's surface containing magma that feeds a volcano.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Mass wasting: The spontaneous movement of material down a slope in response to gravity.

Meander: A bend or loop in a stream's course.

Mechanical weathering: The process by which a rock or mineral is broken down into smaller fragments without altering its chemical makeup.

Medial moraine: A moraine formed when two adjacent glaciers flow into each other and their lateral moraines are caught in the middle of the joined glacier.

Meltwater: The water from melted snow or ice.

Mesa: A flat-topped hill or mountain with steep sides that is smaller in area than a plateau.

Metamorphic rock: Rock whose texture or composition has been changed by extreme heat and pressure.

Meteor: A glowing fragment of extraterrestrial material passing through Earth's atmosphere.

Meteorite: A fragment of extraterrestrial material that strikes the surface of Earth.

Meteorite crater: A crater or depression in the surface of a celestial body caused by the impact of a meteorite; also known as an impact crater.

Meteoroid: A small, solid body floating in space.

Mid-ocean ridge: A long, continuous volcanic mountain range found on the basins of all oceans.

Moraine: The general term for a ridge or mound of till deposited by a glacier.

Mountain: A landmass that rises 1,000 feet (305 meters) or more above its surroundings and has steep sides meeting in a summit that is much narrower in width than the base of the landmass.

Mudflow: A mixture primarily of the smallest silt and clay particles and water that has the consistency of newly mixed concrete and flows quickly down slopes.

Mud pot: A hot spring that contains thick, muddy clay.

O

Oasis: A fertile area in a desert or other dry region where groundwater reaches the surface through springs or wells.

Ocean basin: That part of Earth's surface that extends seaward from a continental margin.

Oxbow lake: A crescent-shaped body of water formed from a single loop that was cut off from a meandering stream.

P

Paleomagnetism: The study of changes in the intensity and direction of Earth's magnetic field through time.

Passive continental margin: A continental margin that has a broad continental shelf, a gentle continental slope, and a pronounced continental rise; it is marked by a lack of earthquake and volcanic activity.

Peneplain: A broad, low, almost featureless surface allegedly created by long-continued erosion.

Photosynthesis: The process by which plants use energy from sunlight to change water and carbon dioxide into sugars and starches.

Piedmont glacier: A valley glacier that flows out of a mountainous area onto a gentle slope or plain and spreads out over the surrounding terrain.

Pinnacle: A tall, slender tower or spire of rock.

Plateau: A relatively level, large expanse of land that rises some 1,500 feet (457 meters) or more above its surroundings and has at least one steep side.

Plates: Large sections of Earth's lithosphere separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Playa: A shallow, short-lived lake that forms where water drains into a basin and quickly evaporates, leaving a flat surface of clay, silt, and minerals.

Point bar: The low, crescent-shaped deposit of sediment on the inside of a meander.

Pyroclastic material: Rock fragments, crystals, ash, pumice, and glass shards formed by a volcanic explosion or ejection from a volcanic vent.

R

Rapids: The section of a stream where water flows fast over hard rocks.

Reef crest: The high point of a coral reef that is almost always exposed at low tide.

Regolith: The layer of loose, uncemented rocks and rock fragments of various size that lies beneath the soil and above the bedrock.

Rhyolite: A fine-grained type of volcanic rock that has a high silica content.

Rift valley: The deep central crevice in a mid-ocean ridge; also, a valley or trough formed between two normal faults.

Ring of Fire: The name given to the geographically active belt around the Pacific Ocean that is home to more than 75 percent of the planet's volcanoes.

River: A large stream.

Rock flour: Fine-grained rock material produced when a glacier abrades or scrapes rock beneath it.

S

Saltation: The jumping movement of sand caused by the wind.

Sea arch: An arch created by the erosion of weak rock in a sea cliff through wave action.

Seafloor spreading: The process by which new oceanic crust is formed by the upwelling of magma at mid-ocean ridges, resulting in the continuous lateral movement of existing oceanic crust.

Seamount: An isolated volcanic mountain that often rises 3,280 feet (1,000 meters) or more above the surrounding ocean floor.

Sea stack: An isolated column of rock, the eroded remnant of a sea arch, located in the ocean a short distance from the shoreline.

Sediment: Rock debris such as gravel, sand, silt, and clay.

Sedimentary rock: Rock that is formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Shear stress: The force of gravity acting on an object on a slope, pulling it downward in a direction parallel to the slope.

Shock wave: Wave of increased temperature and pressure formed by the sudden compression of the medium through which the wave moves.

Shore: The strip of ground bordering a body of water that is alternately covered or exposed by waves or tides.

Shoreline: The fluctuating line between water and the shore.

Silica: An oxide (a compound of an element and oxygen) found in magma that, when cooled, crystallizes to become the mineral quartz, which is one of the most common compounds found in Earth's crust.

Silt: Fine earthy particles smaller than sand carried by moving water and deposited as a sediment.

Sinkhole: A bowl-like depression that develops on Earth's surface above a cave ceiling that has collapsed or on an area where the underlying sedimentary rock has been eroded away.

Slide: The movement of a mass of rocks or debris down a slope.

Slip face: The steeply sloped side of a dune that faces away from the wind.

Slope failure: A type of mass wasting that occurs when debris moves downward as the result of a sudden failure on a steep slope or cliff.

Slump: The downward movement of blocks of material on a curved surface.

Slurry flow: A flow that contains between 20 and 40 percent water.

Snow line: The elevation above which snow can form and remain all year.

Solifluction: A form of mass wasting that occurs in relatively cold regions in which waterlogged soil flows very slowly down a slope.

Speleothem: A mineral deposit formed in a cave.

Spit: A long, narrow deposit of sand or gravel that projects from land into open water.

Stalactite: An icicle-shaped mineral deposit hanging from the roof of a cave.

Stalagmite: A cone-shaped mineral deposit projecting upward from the floor of a cave.

Strain: The change in a rock's shape or volume (or both) in response to stress.

Strata: The layers in a series of sedimentary rocks.

Stream: Any body of running water that moves downslope under the influence of gravity in a narrow and defined channel on Earth's surface.

Stress: The force acting on an object (per unit of area).

Striations: The long, parallel scratches and grooves produced in rocks underneath a glacier as it moves over them.

Strike: The compass direction of a fault line.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Submarine canyon: A steep-walled, V-shaped canyon that is cut into the rocks and sediments of the continental slope and, sometimes, the outer continental shelf.

Submergent coast: A coast in which formerly dry land has been gradually flooded, either by land sinking or by sea level rising.

Surface creep: The rolling and pushing of sand and slightly larger particles by the wind.

Suspended load: The fine-grained sediment that is suspended in the flow of water in a river or stream.

Swash: The rush of water up the shore after the breaking of a wave.

Symbiosis: The close, long-term association between two organisms of different species, which may or may not be beneficial for both organisms.

Syncline: A downward-curving (concave) fold in rock that resembles a trough.

T

Talus: A sloping pile of rock fragments lying at the base of the cliff or steep slope from which they have broken off; also known as scree.

Tarn: A small lake that fills the central depression in a cirque.

Terminal moraine: A moraine found near the terminus of a glacier; also known as an end moraine.

Terminus: The leading edge of a glacier; also known as the glacier snout.

Terrace: The exposed portion of a former floodplain that stands like a flat bench above the outer edges of the new floodplain.

Tide: The periodic rising and falling of water in oceans and other large bodies of water that results from the gravitational attraction of the Moon and the Sun upon Earth.

Till: A random mixture of finely crushed rock, sand, pebbles, and boulders deposited by a glacier.

Tombolo: A mound of sand or other beach material that rises above the water to connect an offshore island to the shore or to another island.

Topset bed: A horizontal layer of coarse sand and gravel deposited on top of a delta.

Travertine: A dense, white deposit formed from calcium carbonate that creates rock formations around hot springs.

Trench: A long, deep, narrow depression on the ocean basin with relatively steep sides.

Turbidity current: A turbulent mixture of water and sediment that flows down a continental slope under the influence of gravity.

U

Uplift: In geology, the slow upward movement of large parts of stable areas of Earth's crust.

U-shaped valley: A valley created by glacial erosion that has a profile suggesting the form of the letter "U," characterized by steep sides that may curve inwards at their base and a broad, nearly flat floor.

V

Valley glacier: An alpine glacier flowing downward through a preexisting stream valley.

Ventifact: A stone or bedrock surface that has been shaped or eroded by the wind.

Viscosity: The measure of a fluid's resistance to flow.

Volcano: A vent or hole in Earth's surface through which magma, hot gases, ash, and rock fragments escape from deep inside the planet; the term is also used to describe the cone of erupted material that builds up around that opening.

V-shaped valley: A narrow valley created by the downcutting action of a stream that has a profile suggesting the form of the letter "V," characterized by steeply sloping sides.

W

Waterfall: An often steep drop in a stream bed causing the water in a stream channel to fall vertically or nearly vertically.

Wave crest: The highest part of a wave.

Wave-cut notch: An indentation produced by wave erosion at the base of a sea cliff.

Wave-cut platform: A horizontal bench of rock formed beneath the waves at the base of a sea cliff as it retreats because of wave erosion.

Wave height: The vertical distance between the wave crest and the wave trough.

Wavelength: The horizontal distance between two wave crests or troughs.

Wave trough: The lowest part of a wave form between two crests.

Weathering: The process by which rocks and minerals are broken down at or near Earth's surface.

Windward: On or toward the side facing into the wind.

Y

Yardang: Wind-sculpted, streamlined ridge that lies parallel to the prevailing winds.

Yazoo stream: A small stream that enters a floodplain and flows alongside a larger stream or river for quite a distance before eventually flowing into the larger waterway.

Z

Zooxanthellae: Microscopic algae that live symbiotically within the cells of some marine invertebrates, especially coral.

Ocean basin

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

The features of continental landscapes are mirrored by similar features on the ocean basins. Plateaus, plains, valleys, rolling hills, and volcanic cones and mountains are found beneath the waters of the oceans, just as they are on dry land. Yet the largest underwater mountains are higher than those on the continents, and underwater plains are flatter and more extensive than their dry counterparts. These "oceanscapes," at one time unseen and unknown, may resemble familiar landscapes, but on a much grander scale.

The shape of the land

Ocean basins are that part of Earth's surface that extends seaward from the continental margins (the submerged outer edges of continents, each composed of a continental shelf and a continental slope). Basins lie at an average water depth of about 12,450 feet (3,795 meters). From there they drop steeply down into the deepest trenches. The oceans and seas of the planet form a layer of water that covers approximately 71 percent of Earth's surface. Ocean basins occupy more than 76 percent of the total ocean area.

Many sources include the continental margins as part of the ocean basins, but the margins are the drowned edges of the continents. They are part of the same crust (thin, solid outermost layer of Earth) that forms the continents. The transition between continental crust and oceanic crust occurs in the continental slope. Continental crust is composed mostly of granite, whereas oceanic crust is mostly basalt. Although they differ in composition, both are types of igneous rock that forms when magma cools and solidifies. Granite forms when magma with a high silica content cools slowly deep beneath Earth's surface; basalt forms when magma with a low silica content cools quickly outside of or very near Earth's surface. (For

Canning Basin, western Australia. Ocean basins are that part of Earth's surface that extends seaward from the continental margins. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

further information on continental margins, see the **Continental margin** chapter.)

By ocean basins, this discussion is referring to what may be termed the deep-ocean basins: those areas of the ocean floor lying more than 10,500 feet (3,200 meters) beneath the surface of the oceans. The four main ocean basins are those of the Pacific, Atlantic, Indian, and Arctic Oceans. The Pacific Ocean, which occupies about one-third of Earth's surface, has the largest basin. Its basin also has the greatest average depth at approximately 14,000 feet (4,300 meters). The Atlantic Ocean basin is half the size of that of the Pacific Ocean and is not quite as deep, averaging about 12,000 feet (3,660 meters). While slightly smaller in size than the Atlantic Ocean basin, the Indian Ocean basin sits at a lower average depth, 12,750 feet (3,885 meters). The Arctic Ocean basin is less than 10 percent the size of the Pacific Ocean basin and lies at an average depth of 3,900 feet (1,190 meters).

All ocean basins contain certain primary features: mid-ocean ridges, abyssal (pronounced ah-BISS-ul) plains, trenches, and seamounts.

Perhaps the most impressive features found on all ocean basins are long, continuous volcanic mountain ranges called mid-ocean ridges. These elevated ridges mark the area where sections of oceanic crust are pulling apart from each other. As they do, hot magma (liquid rock) emerges from beneath the crust and seeps forth as lava to fill the crack continuously created by the separation. The lava cools and attaches to the trailing edge of each section, forming new ocean floor crust in a process known as seafloor spreading. Additional lava is deposited by the thousands of volcanoes that periodically erupt along the ridges.

The large depression that is created between the spreading sections is known as a rift valley. Mid-ocean ridges are divided into three groups depending on their spreading rates: slow, medium, and fast. Ridges that spread slowly, from 0.4 to 2 inches (1 to 5 centimeters) per year, have a wide and deep central rift valley. The valley may be 6 miles (10 kilometers) wide and 2 miles (3 kilometers) deep below the crests, or tops, of the ridges that surround it on either side. Ridges that are classified as medium spread at a rate of 2 to 4 inches (5 to 10 centimeters) per year. The valleys of these ridges may be up to 3 miles (5 kilometers) across and range in depth from 165 to 655 feet (50 to 200 meters). Finally, fast-spreading ridges open up at a rate of 4 to 8 inches (10 to 20 centimeters) per year. Their rift valleys are much smoother in appearance. On average, these small valleys are only 330 feet (100 meters) wide and 33 to 66 feet (10 to 20 meters) deep.

In most locations, mid-ocean ridges are 6,500 feet (1,980 meters) or more below the surface of the oceans. In a few places, however, they actually extend above sea level and form islands. Iceland (in the North Atlantic), the Azores (west of the coast of Portugal), and Tristan de Cunha (in the south Atlantic midway between southern Africa and South America) are examples of such islands.

The most-studied mid-ocean ridge in the world is the Mid-Atlantic Ridge. It begins at the tip of Greenland and runs down the center of the Atlantic Ocean between the Americas on the west and Europe and Africa on the east. It ends its course at the southern tip of the African continent. At that point, the ridge continues around the eastern edge of Africa as the Southwest Indian Ridge. That ridge then divides near the center of the Indian Ocean basin into the Central Indian Ridge that runs north into the African continent and the Southeast Indian Ridge that runs east below the Australian continent. The ridge continues eastward along the southern portion of the Pacific Ocean basin as the Pacific Antarctic Ridge. It eventually heads northward along the western coastline of South and Central America as the East Pacific Rise.

These mid-ocean ridges combine to form a global undersea mountain system known as the mid-ocean ridge system. Extending more than 40,000 miles (64,000 kilometers), it is the longest topographic or surface feature on Earth. Snaking its way between the continents, the ridge system encircles the planet like the seams on a baseball. Whereas the seams form a continuous loop, the mid-ocean ridge system is offset in many places. The offsets are called fracture zones. These breaks in the ridge line are caused by faults, cracks or fractures in Earth's crust along which rock on one side has moved relative to rock on the other. Ocean crust on either side of a fault in a fracture zone slides in opposite directions. This helps relieve tension created when different sections of a mid-ocean ridge spread at different rates. The faults form deep, linear gouges almost perpendicular to the ridges. Crust in a fracture zone looks like it has been sliced up by a giant knife. The largest fracture zone occurs along the Mid-Atlantic Ridge, offsetting it by 590 miles (950 kilometers).

The relatively flat areas of ocean basins between continental margins and mid-ocean ridges are called abyssal plains. They are generally found at depths of 13,000 to 16,000 feet (3,960 to 4,875 meters). Likely the most level places on Earth, they are far flatter than any plain on dry land. They have gentle slopes of less than 1 foot (0.3 meter) of elevation difference for each 1,000 feet (305 meters) of distance.

The flatness of abyssal plains is due to an accumulation of layers of sediments formed from the remains of marine life and rock debris such as gravel, sand, silt, and clay. Much of this rock debris has been washed off the surface of the continents for hundreds of thousands of years. It is carried down continental slopes by turbidity currents, turbulent mixtures of water and sediment. Pulled by gravity, these currents may surge downward like an avalanche at up to 50 miles (80 kilometers) per hour. When the currents reach the ocean basin, they slow and the sediment they carry falls on the abyssal plains. In many areas, these sediment layers measure up to 3 miles (5 kilometers) thick. The sediments cover many of the irregularities that may exist in the basaltic rock of the ocean floor. In places where the layers of sediment are thinner, gently sloping hills may rise from the abyssal plains to heights less than 3,280 feet (1,000 meters). Known as abyssal hills, these low, oval-shaped hills are typically volcanic in origin.

The deepest parts of ocean basins are trenches, which may descend over 36,000 feet (11,000 meters) beneath the surface of an ocean. These long, narrow, canyonlike structures are formed where sections of oceanic crust are moving and sliding under sections of continental crust. Thus, trenches are often found parallel to continental margins and the seaward

Words to Know

Abyssal hill: A gently sloping, small hill, typically of volcanic origin, found on an abyssal plain.

Abyssal plain: The relatively flat area of an ocean basin between a continental margin and a mid-ocean ridge.

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Continental drift: The hypothesis proposed by Alfred Wegener that the continents are not stationary, but have moved across the surface of Earth over time.

Continental margin: The submerged outer edge of a continent, composed of the continental shelf and the continental slope.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid outermost layer of Earth.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Fracture zone: An area where faults occur at right angles to a main feature, such as a mid-ocean ridge.

Guyot: An undersea, flat-topped seamount.

Hot spot: An area beneath Earth's crust where magma currents rise.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Mid-ocean ridge: A long, continuous volcanic mountain range found on the basins of all oceans.

Paleomagnetism: The study of changes in the intensity and direction of Earth's magnetic field through time.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Rift valley: The deep central crevice in a mid-ocean ridge; also, a valley or trough formed between two normal faults.

Seafloor spreading: The process by which new oceanic crust is formed by the upwelling of magma at mid-ocean ridges, resulting in the continuous lateral movement of existing oceanic crust.

Seamount: An isolated volcanic mountain that often rises 3,280 feet (1,000 meters) or more above the surrounding ocean floor.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Trench: A long, deep, narrow depression on the ocean basin with relatively steep sides.

Turbidity current: A turbulent mixture of water and sediment that flows down a continental slope under the influence of gravity.

edge of volcanic island arcs like Japan, the Philippines, and the Aleutian Islands. Of the twenty-two trenches that have been identified around the world, eighteen are located in the Pacific Ocean basin, three in the Atlantic Ocean basin, and one in the Indian Ocean basin.

Glomar Challenger

In 1968, the oceanographic drilling and coring vessel *Glomar Challenger* was launched on a voyage to study the geological evolution of Earth. From its platform, it was possible to lower up to 20,000 feet (6,096 meters) of pipe into the open ocean, bore into the seafloor to a depth of 2,500 feet (762 meters), and then bring up samples (or cores) of the crust beneath the ocean.

During her fifteen years of operation, the *Glomar Challenger* operated in all the major oceans and seas of the world. For the geologic community, each of her voyages was the equivalent of a moon shot. The core samples the vessel retrieved were from a remote and largely unexplored portion of Earth's surface. From those samples, geologists were able to establish that Alfred Wegener's hypothesis of continental drift was correct. They were also able to prove the theory of seafloor spreading and determine that the oldest oceanic crust was far younger than the oldest continental crust. From samples taken during later voyages, geologists were able to prove that Earth's magnetic poles have reversed themselves over time.

Seamounts are isolated volcanic mountains that often rise 3,280 feet (1,000 meters) or more above the surrounding ocean floor. Sometimes seamounts rise above sea level to create islands. Geologists estimate that there may be as many as 85 million seamounts on the floors of the world's oceans. Seamounts usually form near mid-ocean ridges or above hot spots, areas where magma plumes melt through Earth's crust to form volcanoes. Hot spot plumes may exist for millions of years. As a section of oceanic crust moves over the hot spot, a chain of volcanoes may be produced. The Hawaiian Islands are an example of such activity.

When volcanic activity ceases, a seamount begins to erode and collapse back into an ocean. If wave action and weathering continue long enough while the seamount is still above sea level, its top may be eroded flat. An undersea, flat-topped seamount is called a guyot (pronounced GHEE-oh). These types of seamounts are common in the western Pacific Ocean.

Forces and changes: Construction and destruction

Prior to World War II (1939–45), the floors of the oceans had been a part of Earth that had received little scientific study. During the war, the U.S. military employed geologists to carry out studies of the sea floors to find hiding places that might be used by both friendly and enemy submarines. The studies, which involved measuring the depth of ocean floors, revealed two important surface features on the floors: mid-ocean ridges and trenches. The geologists also made another important discovery. While using an underwater instrument that measured magnetic materials in order to detect submarines, they found alternating magnetic differences on the ocean floors.

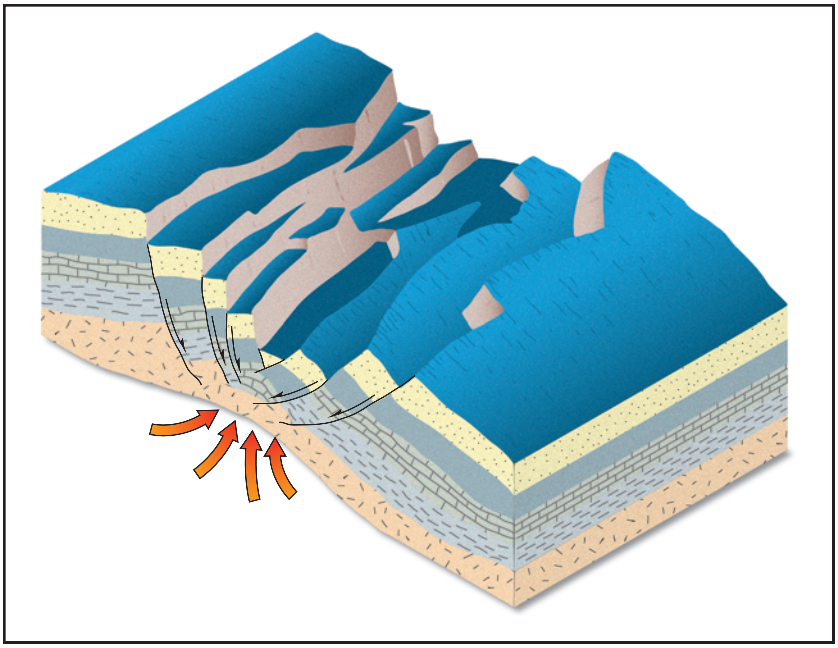
Scientists believe the magnetic field that exists around the planet is generated by Earth's core. The very center of the planet, Earth's core begins some 1,800 miles (2,900 kilometers) beneath the planet's surface and extends to a depth of 3,960 miles (6,370 kilometers). Composed of the metal elements iron and nickel, the core has a solid inner portion and a liquid outer portion. As Earth rotates, so does that iron-bearing core, creating the magnetic field that may be detected with a compass.

Puzzled by the magnetic anomalies found on the ocean floors, geologists in the 1950s began to explore the possible reasons through the study of paleomagnetism (pronounced pay-lee-oh-MAG-nuh-ti-zum; the study of changes in the intensity and direction of Earth's magnetic field through geologic time). They discovered that almost all rocks contain some type of magnetic material. After a rock has formed and begins to cool, the grain or grains of magnetic material in the rock become aligned with the polarity (north-south directionality) of Earth's magnetic field at that time. In effect, a permanent record of Earth's magnetic field at the time the rock cooled and solidified is locked into its magnetic grains.

Studying the magnetic properties of rocks from different locations around the planet, geologists found that Earth's magnetic poles appeared to have wandered around the globe for at least the past several million years. Since this seemed unlikely, geologists concluded that the continents themselves must have moved across the surface of the planet, carrying the magnetic rocks with them. This brought new attention to the hypothesis of continental drift. (A hypothesis is an educated guess, while a theory is a principle supported by extensive scientific evidence and testing.)

Continental drift

In 1910, German geophysicist Alfred Wegener (1880–1930) had begun arguing that Earth's continents do not remain in a fixed position on the planet's surface. He believed instead that they are mobile and over vast amounts of time have drifted across the surface. Wegener called his hypothesis continental drift. He based his hypothesis on the idea that the coastlines of several of the world's continents fit remarkably together. From this, he proposed that the continents had once been joined together in one large continental mass. He called this supercontinent Pangaea (pronounced pan-JEE-ah; from the Greek words meaning "all lands"). What Wegener lacked, however, was a convincing explanation as to what moved the continents along the surface.



Seafloor spreading is the theory that explains how the floors of oceans had split apart and rocks on either side of the ridges are moving away from each other.

Seafloor spreading

A little more than fifty years after Wegener first proposed his hypothesis, American geologist Harry H. Hess (1906–69) offered up his own hypothesis: seafloor spreading. Hess proposed that mid-ocean ridges were areas where the floors of oceans had split apart and where rocks on either side of the ridges were moving away from each other. At the center of the ridges, lava from below welled up and solidified into new volcanic rock on the ocean floors. Like a giant conveyer belt, the spreading ocean floor carried rock away from the ridges in either direction. The youngest rocks were located along the ridges where new lava rose up. The farther the rocks had moved from the ridges, the older they were.

Within a few years of Hess's proposal, geologists discovered that over short time scales, Earth's magnetic field undergoes polarity reversals (the north magnetic pole becomes the south magnetic pole and vice versa). Although not entirely sure of the reasons, geologists know this occurs every 500,000 years or so. As these magnetic reversals occurred in the past, the changing polarities—normal, reversed, normal, reversed—were recorded in newly forming rocks along mid-ocean ridges. When tied with the idea of seafloor spreading, this helped explain the magnetic differences geologists had found on the ocean floors during World War II.

Combining continental drift and seafloor spreading, geologists were able to develop a unifying theory that helped explain how landforms and other geologic features are created and how Earth's surface changes over time. That revolutionary theory is known as plate tectonics.

Plate tectonics

The processes occurring in Earth, from the core to the crust, have put the surface of the planet in motion, constantly changing its shape. Geologists divide the surface and the interior of Earth into layers. As mentioned, the core is at the very center of the planet. Above the core is the mantle, which extends up to about 31 miles (50 kilometers) below the surface of the planet. The mantle accounts for approximately 80 percent of the volume of Earth. Above the mantle lies the brittle crust, the thin shell of rock that covers Earth.

The upper portion of the mantle is rigid. Geologists combine this section of the mantle with the overlying crust, calling it the lithosphere (pronounced LITH-uh-sfeer). The lithosphere measures roughly 60 miles (100 kilometers) thick. The part of the mantle immediately beneath the lithosphere is called the asthenosphere (pronounced as-THEN-uh-sfeer). This layer is composed of partially melted rock that has the consistency of putty and extends to a depth of about 155 miles (250 kilometers).

The lithosphere is broken into many pieces called tectonic or crustal plates, which vary in size and shape. They are in constant contact with each other, fitting together like pieces in a jigsaw puzzle. They float on the semi-molten asthenosphere, and because they are interconnected, no plate can move without affecting those around it. What causes the plates to move are convection currents, which originate at the base of the mantle where it surrounds the core.

With estimated temperatures in the core exceeding 9,900°F (5,482°C), tremendous heat energy is generated there. If that energy were not released in some manner, the interior of the planet would melt. This is prevented by the convection currents, which carry the energy to the surface of the planet where it is released.

Convection currents act similar to the currents produced in a pot of boiling liquid on a hot stove. When a liquid in a pot begins to boil, it turns over and over. Liquid heated at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense (lighter). Once at the surface, the heated material cools and becomes dense once more. It then sinks back down to the bottom to become reheated. This continuous motion of heated material rising, cooling, and sinking forms the circular-moving convection currents.

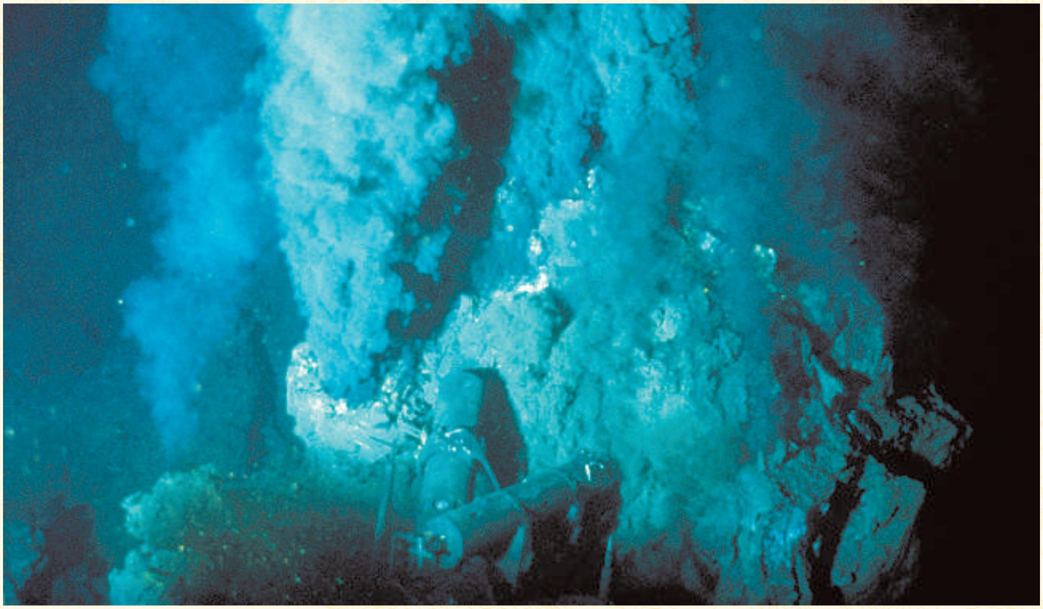
Like an enormous stove, the core heats the mantle rock that immediately surrounds it. Expanding and becoming less dense, the heated rock slowly rises through cooler, denser mantle rock above it. When it reaches

Hydrothermal Vents

Hydrothermal vents are cracks in the ocean floor or chimneylike structures extending from the ocean floor generally up to 150 feet (45 meters) high. Some are much higher. They are usually found at mid-ocean ridges where volcanic activity is present. Using deep-sea submersible vessels, scientists first discovered hydrothermal vents in the Pacific Ocean in 1977.

These vents release hot mineral-laden water into the surrounding ocean. Temperature of this fluid is typically around 660°F (350°C). Because of the high pressure exerted by water at ocean floor depths, hydrothermal fluids can exceed 212°F (100°C) without boiling. Often, the fluid released is black due to the presence of very fine sulfide mineral particles that contain iron, copper, zinc, and other metals. As a result, these deep-ocean hot springs are called black smokers.

Hydrothermal vents are surrounded by unusual forms of sea life, including giant clams, tube worms, and unique types of fish. These organisms live off bacteria that thrive on the energy-rich chemical compounds transported by hydrothermal fluids. This is the only environment on Earth supported by a food chain that does not depend on the energy of the Sun or photosynthesis. The energy source is chemical, not solar, and is called chemosynthesis.



Hydrothermal vents in the Gulf of California's Guaymas Basin. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

the lithosphere, the heated rock moves along the base of the lithosphere, exerting dragging forces on the tectonic plates. This causes the plates to move. In the process, the heated rock begins to lose heat. Cooling and becoming denser, the rock then sinks back toward the core, where it will be heated once more. Scientists estimate that it takes mantle rock 200 million years to make the circular trip from the core to the lithosphere and back again.

On average, a plate inches its way across the surface of Earth at a rate no faster than human fingernails grow, which is roughly 2 inches (5 centimeters) per year. As it moves, a plate can transform or slide along another, converge or move into another, or diverge or move away from another. The boundaries where plates meet and interact are known as plate margins.

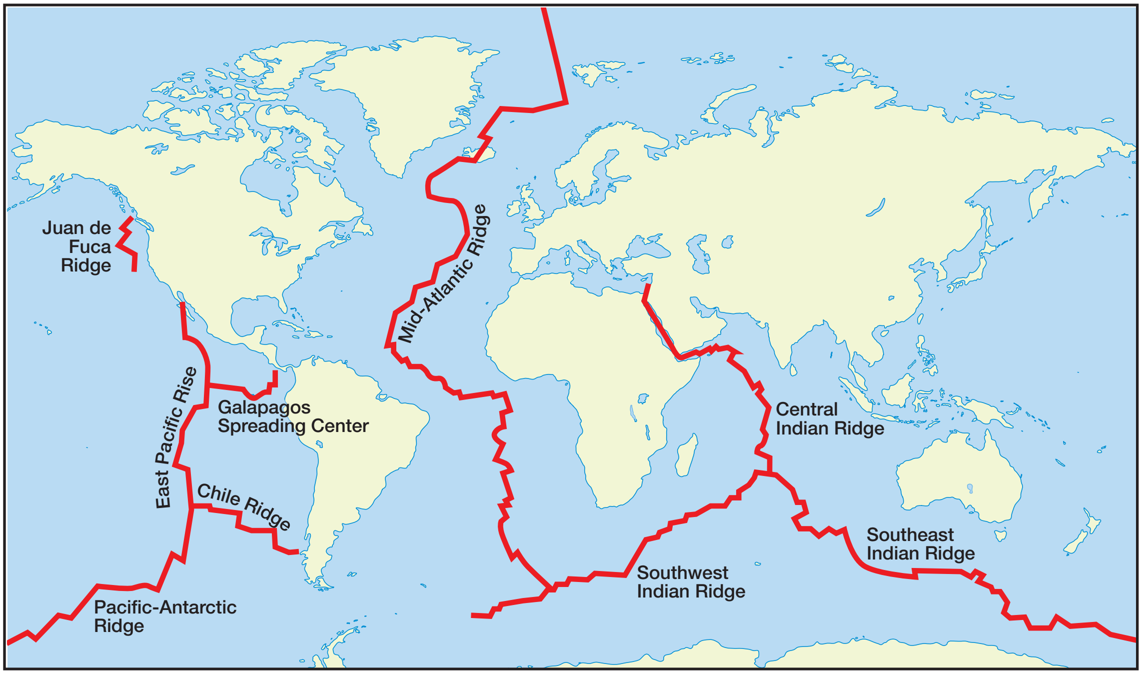
When two continental plates converge, they will crumple up and compress, forming complex mountain ranges. When an oceanic plate converges with a continental plate or another oceanic plate, it will sink beneath the other plate. This is because oceanic crust is made of basalt, which is denser (heavier) than the granite rocks that compose continental crust. The process of one tectonic plate sinking beneath another is known as subduction, and the region where it occurs is known as a subduction zone.

When a tectonic plate subducts beneath another, the leading edge of the subducting plate is pushed farther and farther beneath the surface. When it reaches about 70 miles (112 kilometers) into the mantle, high temperature and pressure melt the rock at the edge of the plate, forming thick, flowing magma. Since it is less dense than the rock that typically surrounds it deep underground, magma tends to rise toward Earth's surface, forcing its way through weakened layers of rock. Most often, magma collects in underground reservoirs called magma chambers where it remains until it is ejected onto the planet's surface through vents called volcanoes. (For further information, see the **Volcano** chapter.)

Mid-ocean ridges and diverging plates

A mid-ocean ridge is a plate margin where two tectonic plates are diverging. Molten rocks emerge from beneath the crest of the ridge. Geologists estimate that 75 percent of the molten rocks or magma reaching Earth's surface does so through mid-ocean ridges. Coming in contact with seawater, the magma solidifies, forming new ocean crust at the trailing ends of the diverging plates. Rocks solidifying at the ridge crest record the current polarity of Earth's magnetic field.

Fast-spreading ridges have more magma beneath them and more volcanic eruptions occur along the ridges. These ridges seem to spread



The system of mid-ocean ridges, or submarine volcanic mountain ranges, around the world. Geologists estimate that 75 percent of the molten rocks or magma reaching Earth's surface does so through mid-ocean ridges.

somewhat smoothly like hot taffy being pulled apart. Slower-spreading ridges have less magma, and the ocean crust in these areas cracks and breaks as it is pulled apart. The age of rocks in ocean basins increases the farther away they are from ridges. They are also more deeply buried by sediments because those sediments have had a longer time to collect.

Because Earth is in a constant dynamic state, creation and expansion of the crust in one area requires the destruction of the crust elsewhere. On the planet, new crust is formed at diverging plate margins and destroyed at subduction zones. Continental crust may be more than 3 billion years old, but oceanic crust is less than 200 million years old. The recycling of oceanic crust takes place between mid-ocean ridges (where it is created) and huge ocean trenches (where it is destroyed). The Pacific Ocean basin, containing the vast majority of the world's trenches, is currently shrinking as the other ocean basins are expanding.

In a subduction zone, an oceanic plate folds downward, plunging steeply under the adjacent plate and descending into the mantle where it is reabsorbed and returned to a molten state, beginning the cycle all over again. Part of that molten material may rise to the surface again through fractures in the crust. As a consequence, numerous volcanoes are formed parallel to the trenches on the side opposite to that of the subducting oceanic plate. Where the trenches are located in the ocean, as in the

Western Pacific, these volcanoes form arcs or chains of volcanic islands. Where the trenches run along the margins of continents, chains of volcanic mountains are formed near the edges of the continents, such as the Andes Mountains in South America.

Spotlight on famous forms

Loihi Seamount, Pacific Ocean

Loihi (pronounced low-EE-hee) is the youngest volcano associated with the Hawaiian Islands chain. It is located about 20 miles (32 kilometers) off the southeastern shore of the island of Hawaii. The basin-shaped summit of the volcano lies 3,178 feet (969 meters) below sea level.

Prior to 1970, geologists believed the seamount was inactive and similar to the other seamounts that surround the Hawaiian Islands. Many of these other seamounts are 80 to 100 million years old. Geologists soon discovered repeated, intense earthquake activity (called swarms) at Loihi. In 1996, the volcano erupted and has been intermittently active since then. If Loihi erupts at rates comparable to other active volcanoes in the Hawaiian Islands, geologists believe it will reach sea level in a few tens of thousands of years.

Mariana Trench, Pacific Ocean

The deepest point on the surface of Earth is found in the Mariana Trench, which is located in the basin of the Pacific Ocean southeast of the Mariana Islands. The trench marks the location where the Pacific Plate is subducting beneath the Philippine Plate. Measuring 1,580 miles (2,542 kilometers) long and 43 miles (69 kilometers) wide, the arc-shaped trench plunges to a maximum depth of 36,201 feet (11,034 meters). The pressure at that great depth is more than 16,000 pounds per square inch (1,125 kilograms per square centimeter). If Mount Everest, the highest point on land, were set into the trench at its deepest point, more than 7,000 feet (2,134 meters) of water would still cover the mountain's peak.

The trench's deepest point, located near its southern extremity, is called the Challenger Deep. It was named after *Challenger II*, the British naval research vessel that discovered it in 1951. In 1960, the *Trieste*, a deep-sea research vessel owned by the U.S. Navy, descended to a depth of 35,802 feet (10,912 meters) in the Mariana Trench, setting a record.

Mid-Atlantic Ridge, Atlantic Ocean

The Mid-Atlantic Ridge is a divergent boundary that divides the floor of the Atlantic Ocean. It separates the North American Plate from the Eurasian Plate in its northern section and the South American Plate and the African Plate in its southern section. The submarine mountain range, which extends for about 10,000 miles (16,100 kilometers), is the longest mountain range on Earth. It lies about 10,000 feet (3,048 meters) below water level, except in a few areas where it surfaces as islands.

A slow-spreading mid-ocean ridge, it has a broad and deep central rift valley. The ridge, which ranges in width from 300 to 600 miles (483 to 965 kilometers), features many earthquakes and much volcanic activity. In a 500-mile (805-kilometer) segment of the ridge, geologists recorded a minimum of 481 seamounts.

The Mid-Atlantic Ridge began to develop almost 200 million years ago when the tectonic plates holding the present-day Americas, Europe, and Africa started to move away from each other. The Atlantic Ocean basin formed as a result, and it continues to widen.

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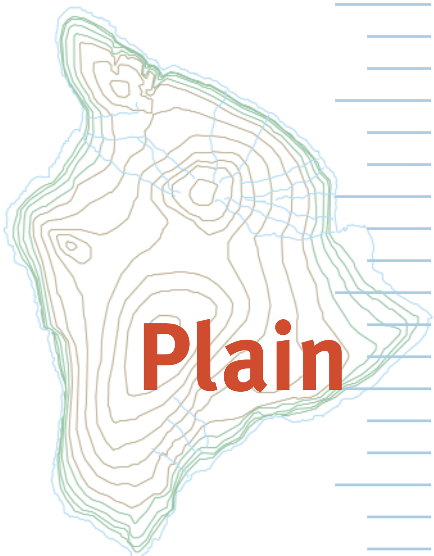

Plain

The topography or surface area of the world's continents varies greatly, with features ranging from mountains and other highland areas to plunging canyons and low-lying basins. Despite this diversity of landforms, certain large-scale features are common to all continents. Generally, the continents contain vast interior plains that make up over 50 percent of their landscape. Plains are also found along certain coasts of continents and on the ocean floor.

Plains may seem common and unremarkable, lacking the grand character of mountains or the mysteriousness of caves. Yet these normally flat landforms have a rich geological history, offering an insight into the forces that have helped shape the surface of the planet.

The shape of the land

A plain may be defined broadly as any lowland area that is level or gently sloping or rolling. It normally has few, if any, prominent hills or valleys, but may have considerable slope. A plain may be forested or bare of trees. Many plains around the world are covered in grasses. A plain may be as small as several hundred square feet or as large as hundreds of thousands of square miles.

A plateau is another landform that is relatively level, and some sources claim that a plateau is an elevated plain. A plateau has at least one steep, clifflike side. It forms as a result of geologic uplift (the slow upward movement of large parts of stable areas of Earth's crust due to heat forces within the planet) or as a result of many lava flows that spread out over hundreds of thousands of square miles. These flows, which build up the land surface, form plateaus known as lava or basalt plateaus because basalt is the dark, dense volcanic rock that forms these particular lava flows. (For further information, see the **Plateau** chapter.)

A plain may be defined as any lowland area that is level or gently sloping or rolling. Many plains around the world are covered in grasses. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

There are significant differences between a plateau and a plain. A plain has no steep sides, but sits at a low elevation relative to its surrounding landscape. It experiences no uplift. In fact, the heat forces within Earth, the actions of which have led to the formation of mountains, volcanoes, and plateaus, have played no direct role in the formation of plains. Those forces have broken Earth's crust (the thin, solid, outermost layer of the planet) and uppermost mantle (the region of the planet just below the crust) into sections or plates. The movement of the plates across the surface of the planet in response to the pressure exerted by those heat forces is known as tectonic activity (pronounced tek-TAH-nik; from the Greek word *tekton,* meaning "builder"). In contrast, plains are areas that are not tectonically active, but are quite stable.

Plains are formed primarily by erosion and the deposition of sediment. Erosion is the gradual wearing away of Earth surfaces through the action of wind and water. Sediment is rock debris such as clay, silt, sand, and gravel (or even larger material) that is being carried from its place of origin or has already been deposited on Earth's surface by wind, water, or ice.

Plains found on the interior of continents are known generally as interior or continental plains; those found along coasts are coastal plains.

Words to Know

Abyssal plain: The relatively flat area of an ocean basin between a continental margin and a mid-ocean ridge.

Alluvial fan: A fanlike deposit of sediment that forms where an intermittent, yet rapidly flowing canyon or mountain stream spills out onto a plain or relatively flat valley.

Alluvium: The general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Coastal plain: A low, generally broad plain that lies between an oceanic shore and a higher landform such as a plateau or a mountain range.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fall line: The imaginary line that marks the sharp upward slope of land along a coastal plain's inland edge where waterfalls and rapids occur as rivers cross the zone from harder to softer rocks.

Floodplain: An area of nearly flat land bordering a stream or river that is naturally subject to periodic flooding.

Glacier: A large body of ice that formed on land from the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity.

Peneplain: A broad, low, almost featureless surface allegedly created by long-continued erosion.

Sedimentary rock: Rock that is formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals.

Interior plains are frequently bounded on one or more sides by mountain ranges. Coastal plains, which cover less than 1 percent of the planet's total land area, generally rise from sea level until they meet higher landforms such as plateaus or mountain ranges. Some form narrow strips along coasts; others extend hundreds of miles inland. The imaginary line that marks the sharp upward slope of land along a coastal plain's inland edge where waterfalls and rapids occur as rivers cross the zone from harder to softer rocks is called the fall line. Some geologists now consider that term to be obsolete because materials that compose coastal plains are often found inland beyond that point.

Smaller-scale, level features formed by erosion and deposition are also labeled as plains. Glaciers, large bodies of ice that formed on land from the compaction and recrystallization of snow and survive year to year, deposit large amounts of sediment at their leading edges. This sediment forms broad, sweeping plains called outwash plains. (For further information on glaciers and their actions, see the **Glacial landforms and features** chapter.) Streams and rivers that periodically overflow the banks of their channels deposit sediment they are carrying on the surrounding landscape, creating floodplains. The general term for sediment deposited by running water is alluvium (pronounced ah-LOO-vee-em). Because floodplains are covered with alluvium, they are often called alluvial plains. Some sources use the term alluvial plain to describe any plain built up by sediments deposited by streams or sheets of running water. (For further information, see the **Floodplain** chapter.)

Abyssal (pronounced ah-BISS-ul) plains are relatively flat areas of ocean basins, which are that part of Earth's surface that extends seaward from the continental margins, the submerged outer edges of the continents. With gentle slopes of less than 1 foot (0.3 meter) of elevation difference for each 1,000 feet (305 meters) of distance, abyssal plains are far flatter than any plains on dry land. (For further information, see the **Ocean basin** chapter.)

A peneplain (pronounced PEE-nah-plane) is a broad, low, almost featureless surface allegedly created by long-continued erosion, which may include the action of glaciers or streams. Some sources state that peneplains descended from landforms that were originally rugged or much higher, such as plateaus or ancient mountains. These relatively flat surfaces are end products of the land surface after, supposedly, millions of years of erosion. This concept is troubling to many geologists, and the idea behind the formation of peneplains remains hotly debated.

Some sources incorrectly state that tundras, steppes, prairies, pampas, savannas, and llanos (pronounced YAH-nos) are plains. A plain is a landform; all of the others are biomes, which are distinct, natural communities chiefly distinguished by their plant life and climate. The confusion may be due to the fact that these biomes commonly cover plains.

Forces and changes: Construction and destruction

Fluvius is the Latin word meaning "river." Fluvial (pronounced FLEW-vee-ul) landforms are those shaped and created by running water. Because streams and other forms of running water are present in almost all landscapes, even if only occasionally, fluvial landforms dominate Earth's land surface. A highly effective means of erosion and transportation, running water carries billions of tons of sediment across the surface of the planet. Over a 1,000-year period, this is enough to lower land surfaces by an average of 1.3 inches (3.3 centimeters). It is a rate ample enough to level all continental land surfaces to a flat, featureless landscape in 25 million years.

The action of running water

Surging over a landscape, water picks up and transports as much material from the surface as it can carry. Gravity and steep slopes aid rushing water in carrying increasingly larger and heavier objects. Erosion by water begins as soon as raindrops hit the ground and loosen small particles. During heavy rains, sheets of water flow over the ground, loosening and picking up even more particles. This water quickly concentrates into channels, which then become streams that flow into rivers.

The amount and size of the material that running water can transport depends on the velocity or speed of that water. A fast-moving stream, for example, carries more sediment and larger material than a slow-moving one. A stream that is turbulent or agitated can also lift and carry more rocks and sediment than one that flows gently.

Running water will continue to carry its load of sediment as long as its velocity remains constant or increases (if it increases, it can carry an even larger load). Any change in the geography of the landscape that causes a water channel to bend or rise will slow the flow of the water. If running water loses speed, it loses the ability to carry its entire load and a portion will be deposited, depending on how much it slows down. Particles will be deposited by size with the largest settling out first and the finest deposited last.

The Literary Landscape

"On this continent and in the psyche of its peoples the plains have always been a staggering presence, a place of myth and cliche, a place for transformation, bafflement, or heartbreak. From the east they are release from the clawing of swamp and tangle and human density. From the west they are a drop and a straightening after the kinks and strains of mountains. Entered from any direction they are new air, a joy to behold, a combination of large-scale intimidation and primordial inner acoustics.

—Merrill Gilfillan, *Magpie Rising: Sketches from the Great Plains*, 1988.

This is what occurs when streams and rivers overflow their banks to form floodplains. The water immediately loses velocity, and its load of sediment is deposited. As is always the case, larger particles drop out first, while finer-grained silts and clays are carried farther away from the stream or river channel.

Running water in high elevation areas, such as mountain ranges, flows rapidly down to lower-lying areas through canyons, valleys, and other narrow, confined channels. If the surface over which the water flows lacks plants and other ground cover, the rushing water easily picks up any loose material in its path.

When it finally reaches a lowland area, the running water loses power since gravity is no longer helping it flow down a steep slope. Slowing, the water is unable to carry the sediment it picked up on its way downhill. No longer confined to a narrow channel, the water spreads out the farther it moves away from the base of the mountain range. Large rocks and other heavy material are deposited first, followed by other material in decreasing size to form a fanlike deposit on the floor of the lowland. This deposit is known as an alluvial (pronounced ah-LOO-vee-al) fan.

Given time, as more water flows out, more sediment is deposited, and fans begin to merge with other fans. Over spans of millions of years, layer upon layer of sediment forms, spreading to cover thousands or hundreds of thousands of square miles, filling valleys, covering low hills, and leveling the land to form vast interior plains.

It is important to note that many interior plains, such as the Great Plains in the central United States, were once covered by ancient oceans and seas. As marine life perished, the remains settled to the bottom, where, over millions of years, they formed sedimentary rock (rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals). When the waters receded, flat-lying layers of sedimentary rock remained, providing a somewhat level base for the further accumulation of sediment from nearby highland areas.

Coastal plains

Coastal plains are similarly covered by layers of sediment, these laid down by seaward-flowing streams from inland highland areas. Many coastal plains have a terraced landscape that stair-steps down to the coast. These gradually rising stairs are former shorelines and portions of sea bottom that emerged to become land. This landscape was formed over the last few million years as sea levels rose and fell in response to the repeated melting and growth of large continental glaciers. The weight of these immense glaciers also depressed land along coasts below sea level. When global temperatures rose and glaciers retreated, the land "rebounded," rising once again above sea level.

As continental glaciers lumbered across the landscape, they scoured away material underneath them, eroding and leveling the surface. They also plucked up rocks and other material, some of which were house-sized boulders. When the glaciers began to melt and retreat, they produced meltwater that flowed on top, within, and underneath the glaciers through channels. This meltwater moved large quantities of sediment from the glaciers. At the leading edges of the glaciers, the meltwater emerged in rapidly flowing, broad streams that surged away from the glaciers. The sediment in the meltwater was then deposited, forming outwash plains. Characteristically flat or gently rolling, outwash plains consist of layers of sand and other finely crushed sediments.

Spotlight on famous forms

Atlantic-Gulf Coastal Plain, United States

The Atlantic-Gulf Coastal Plain stretches over 3,200 miles (5,150 kilometers) in length from Cape Cod to Mexico. It is the world's largest

The Great Plains cover an area of about 450,000 square miles in central North America. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

coastal plain, and it covers approximately 583,000 square miles (1,509,970 square kilometers). The coastal plain is divided into two regions in the United States. The Atlantic Coastal Plain stretches south from Cape Cod and the islands off southeast Massachusetts through New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, and Florida. Rounding Florida, it becomes the Gulf Coastal Plain, which continues through Alabama, Mississippi, Louisiana, Texas, and into Mexico.

The plain is narrow in New England but reaches a maximum width of about 200 miles (322 kilometers) farther south. While its terrain is mostly flat, it does slope gently seaward from the inland highlands in a series of terraces or ridges and low hills. This gentle slope continues far into the Atlantic Ocean and the Gulf of Mexico, forming the upper region of the continental margin, the submerged outer edge of the continent.

Great Plains, United States

The Great Plains form an extensive grassland region in central North America. They stretch from the Canadian provinces of Alberta, Saskatchewan, and Manitoba south into Montana, North Dakota, South Dakota, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, New Mexico, and northern Texas. They cover an area of about 450,000 square miles (1,165,500 square kilometers).

More than 65 million years ago, much of the present-day Great Plains was covered by a vast inland sea. Marine sediments that were deposited make up the nearly horizontal rock structure that underlies the area. When the Rocky Mountains began rising and the sea retreated, streams and rivers began to wash enormous amounts of sediment from the mountains over the plains. Currently, the plains slope gently eastward from that great mountain system at an elevation of 6,000 feet (1,829 meters). Where they merge into the interior lowlands, they stand at an elevation of approximately 1,500 feet (457 meters). The average eastward slope is roughly 10 feet per mile (1.9 meters per kilometer).

Glaciers from the last Ice Age left thick layers of sediment and other features that mark the landscape in the northern section of the Great Plains. In some places, the sediment measures to depths of hundreds of feet.

Although much of the terrain of the Great Plains is flat or gently rolling, several topographical features rise significantly above the plains. Prominent among these are the Black Hills of South Dakota and Wyoming, formed by an upwelling of magma under Earth's crust. They are one of the few indications of tectonic activity in this entire region.

West Siberian Plain, Russia

One of the world's largest regions of continuous flatland is found in central Russia. The West Siberian Plain lies between the Ural Mountains in the west and the Yenisey River Valley in the east. The Kara Sea bounds it in the north, while the Torghay Plateau, the Kazak Uplands, and the Altai Mountains mark its southern border. It stretches over a region nearly 1,100 miles (1,770 kilometers) wide, covering approximately 1.2 million square miles (3.1 million square kilometers).

Formed by glacial deposits after the last Ice Age, which ended approximately 10,000 years ago, the plain is exceedingly flat and featureless. Only occasional low hills and ridges, the remains of glacial action, punctuate the landscape. The plain has very poor drainage, resulting in vast swampy areas. The Vasyugan Swamp, in the center of the plain, covers 18,500 square miles (47,915 square kilometers). The northern section of the plain is mostly barren tundra.

The West Siberian Plain, which covers an area of about 1.2 million square miles, was formed by glacial deposits after the last Ice Age. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

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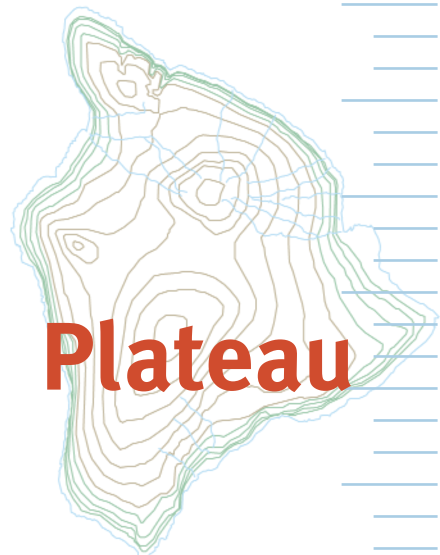

Plateau

Plateaus, known variously as tablelands or flat-topped mountains, are regions elevated thousands of feet above their surroundings. They are found on continents around the world, in countries ranging from Algeria to Mexico, from Mongolia to Zimbabwe. In Antarctica, which has a greater average elevation than any other continent, most of the land outside of the mountain ranges can be considered plateaus. Covered by thick ice, many of these areas have no names.

Some plateaus around the world exist at such great heights that their climate is harsh and living conditions are bleak. Others, at much lower elevations, offer more favorable conditions. The terrain of some plateaus is unbroken and flat. The terrain of many others has been eroded away by water and wind over millions of years to create distinct and unusual landforms. As such, many plateaus are landforms filled with landforms.

The shape of the land

By definition, a plateau is a relatively level, large expanse of land that rises some 1,500 feet (457 meters) or more above its surroundings and has at least one steep side. A plateau may cover an area as small as several square miles or as large as half the size of the lower forty-eight United States. Some plateaus formed as a result of geologic uplift, or the slow upward movement of large parts of stable areas of Earth's crust. Others lie between mountains, formed in response to the collision of sections of Earth's crust. Still others formed as a result of many lava flows that spread out over hundreds of thousands of square miles, building up the land surface. These latter plateaus are known as lava or basalt plateaus (basalt is the dark, dense volcanic rock that forms these particular lava flows). Some plateaus can form simply when the side of a land region is weathered away

The Colorado Plateau, which spans some 130,000 square miles, is actually made up of many plateaus. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

through erosion (the gradual wearing away of Earth surface features through the action of wind and water).

Plateaus are widespread, covering about 45 percent of Earth's land surface. In Australia, approximately two-thirds of the land area is covered by the Western Plateau. This plateau continues unbroken across much of the central portion of the country, with only occasional rock outcroppings. Much of the plateau has existed as a landmass for more than 500 million years. About 25 percent of China's total land area may be characterized as plateau. The Tibetan Plateau in China's southwest region is the highest and most extensive plateau in the world.

As with all elevated areas, plateaus are continuously carved by erosion, the gradual wearing away of Earth's surfaces through the action of wind and water. Plateaus that contain rivers also contain canyons that have been cut by the rivers as they have sought to reach the level of the lake or ocean into which they flow. Finding the path of least resistance, a river winds across a plateau's surface, cutting through the rock layers. Over millions of years, a river will erode through and expose the rock layers of a plateau, creating a canyon. (For further information, see the **Canyon** chapter.)

Words to Know

Basalt: A dark, dense volcanic rock, about 50 percent of which is silica.

Continental drift: The hypothesis proposed by Alfred Wegener that the continents are not stationary, but have moved across the surface of Earth over time.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid, outermost layer of Earth.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fault: A crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Uplift: In geology, the slow upward movement of large parts of stable areas of Earth's crust.

Plateaus may contain thousands of other landforms. Water is the primary sculpting force for most of these. In various forms (rain, groundwater, runoff, and rivers), water has carved mesas, buttes, domes, towers, hoodoos, goblins, temples, and natural rock arches and bridges across plateau landscapes (these landforms also appear elsewhere across the surface of Earth). In general, the relative hardness of the rock making up a plateau determines the type of landforms created there. If the plateau is built on sedimentary rock (rock formed by the accumulation and compression of sediment, which may consist of rock fragments, remains of microscopic organisms, and minerals), its layers will tend to be horizontal, and the landforms on it will have level or flat tops. If the plateau is built on different types of rock of varying hardness, its landforms may be flat or pointed.

Although a plateau is usually considered a single landmass, some plateaus may be composed of numerous smaller plateaus. Such is the case with the Colorado Plateau in the four-corners region (where the boundaries of the four states of Utah, Colorado, Arizona, and New Mexico meet) of the American Southwest. This plateau is actually a series of plateaus separated by north-south trending faults. A fault is a crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other. Unequal pressure beneath the Colorado Plateau, due to the heat forces contained within Earth, created stress in its surface. This resulted in faults. Separated by the faults, sections of the plateau moved upward by different degrees, creating differences in elevation across the plateau.

Forces and changes: Construction and destruction

The same internal forces of Earth responsible for mountain building, volcanic eruptions, earthquakes, seafloor spreading, and many other topographic features (physical features on the planet's surface) are also responsible for the creation of plateaus. To a lesser degree, so are external forces such as erosion, which helps define the steep sides of a plateau.

Earth is dynamic. As the planet revolves around the Sun and rotates on its axis, its surface and interior are also in motion. Landmasses are in a constant, though slow, state of change. They move, collide, and break apart due to the heat energy stirring beneath the surface of the planet. The giant furnace at Earth's core moves land no more than a few inches per year, but that is enough to have profound consequences on the shape of the landscape.

In the early twentieth century, German geophysicist Alfred Wegener (1880–1930) contended that Earth's continents do not remain in a fixed position on the planet's surface. He believed instead that they are mobile and over vast amounts of time have drifted across the surface. Wegener called his hypothesis continental drift. (A hypothesis is an educated guess, while a theory is a principle supported by extensive scientific evidence and testing.)

Wegener based his hypothesis on the idea that the coastlines of several of the world's continents fit remarkably together. From this, he proposed that the continents had once been joined together in one large continental mass. He called this supercontinent Pangaea (pronounced pan-JEE-ah; from the Greek words meaning "all lands"; see the box on page 255). What Wegener lacked, however, was a convincing explanation as to what moved the continents along the surface. Evidence to support his hypothesis did not come until the early 1960s when geologists developed the theory of plate tectonics.

Earth's layered interior

Geologists divide the surface and the interior of the planet into layers (see the illustration in Volume 1, page 63 of this set). The crust is the thin shell of rock that covers Earth. It is separated into two types: continental crust (which underlies the continents) and oceanic crust (which underlies the oceans). Varying in thickness from 3 to 31 miles (5 to 50 kilometers), the crust is thickest below land and thinnest below the oceans. Underneath the crust lies the mantle, which extends down roughly 1,800 miles (2,900 kilometers) beneath the planet's surface.

Pangaea: The Ancient Supercontinent

Throughout Earth's history, fragments of continental crust have floated across the planet's surface, pushed and pulled by plate tectonic motion. At times in the geologic past, these fragments (what we may now call continents) came together to form one large supercontinent, only to be broken apart once again by tectonic forces. The cycle of supercontinent construction and destruction took hundreds of millions of years.

The most recently created supercontinent was Pangaea (pronounced pan-JEE-ah), which came into being about 300 million years ago. Panthalassa, a giant ocean, surrounded it. In just 100 million years, though, Pangaea began to break apart. Tectonic forces created a north-south rift in the supercontinent, separating it into two new continents, Laurasia and Gondwanaland. As the new continents separated, the rift filled in with water, eventually becoming the present-day Atlantic Ocean. Laurasia, composed of the present-day continents of Asia, Europe, and North America (Greenland), occupied the northern hemisphere. Gondwanaland, composed of the present-day continents of Africa, Antarctica, Australia, and South America, occupied the southern hemisphere. The subcontinent of India was also part of Gondwanaland. By 135 million years ago, the breakup of Laurasia and Gondwanaland was underway, leading to the present-day locations of the continents.

The forces that formed Pangaea, then broke it apart, are still at work. North America, South America, and Greenland are all moving westward. Australia, India, and the western part of Africa are all moving northward. Europe and Asia are moving eastward. The Atlantic Ocean is becoming larger, and the Pacific Ocean is becoming smaller. Although impossible to know when, at some point in the future, millions of years from now, the continents may well come together to form yet another supercontinent.

The mantle itself is separated into two distinct layers. The uppermost layer is cold and rigid. Geologists combine this section of the mantle with the overlying crust, calling it the lithosphere (pronounced LITH-uh-sfeer). The lithosphere measures roughly 60 miles (100 kilometers) thick. The part of the mantle immediately beneath the lithosphere is called the asthenosphere (pronounced as-THEN-uh-sfeer). This layer is composed of partially melted rock that has the consistency of putty and extends to a depth of about 155 miles (250 kilometers).

Beginning some 1,800 miles (2,900 kilometers) beneath the surface and extending to a depth of 3,960 miles (6,370 kilometers), the very center of the planet, is Earth's core. Composed of the metal elements iron and

Cultural Landforms

Above the floor of a deep sandstone canyon on the Rainbow Plateau in Utah, surrounded by cliffs that rise 1,000 feet (305 meters), spans the Rainbow Bridge. This natural sandstone bridge, 32 feet (10 meters) thick at its narrowest, arches 290 feet (88 meters) above the streambed of the Bridge Creek. Covering a distance of 270 feet (82 meters), Rainbow Bridge is the largest and most symmetrical natural bridge in the world.

Salmon-pink in color, the bridge is composed entirely of Navajo sandstone. Sandstone is a type of rock made up of grains of sand bonded together by a mineral cement, like calcium carbonate. Water easily dissolves this bond, washing away portions of the sand to form fascinating shapes. Million of years ago, water flowing off nearby Navajo Mountain washed over the area, cutting a canyon in the soft sandstone. As water continued to course through the canyon, it cut a hole in a curve in the canyon's side, eventually leading to the formation of the Rainbow Bridge.

For centuries, the Dine, Hopi, Paiute, and other Native American tribes have held the bridge and the area around it sacred. Present-day Navajo consider it a symbol of rainfall and fertility. In 1910, U.S. President William Howard Taft (1857–1930) designated the bridge and its immediate area a national monument. Currently, Rainbow Bridge is threatened by rising water from nearby Lake Powell Reservoir and by tourism.

nickel, the core has a solid inner portion and a liquid outer portion. Scientists estimate that temperatures in the core exceed 9,900°F (5,482°C), creating extreme heat energy. Were this energy not released in some manner, Earth's interior would melt. Circulating currents, called convection currents, carry the energy to the surface of the planet, where it is released. It is the release of this energy underneath the lithosphere that leads to the formation of the major geologic features on the surface of the planet.

Convection currents

Convection is the driving force behind the motion of Earth's interior. The process is similar to what occurs in a pot of boiling water. When the water reaches boiling temperature, normally 212°F (100°C) at sea level, it turns over and over. Heated water at the bottom of the pot rises to the surface because heating has caused it to expand and become less dense (lighter). Once at the surface, the heated material cools and becomes more dense (heavier), then sinks back down to the bottom to be reheated. This continuous motion of heated material rising, cooling, and sinking creates circular currents known as convection currents.

Rainbow Bridge National Monument, Utah. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Convection currents form in the planet's interior when rock surrounding the core heats up. Expanding and becoming less dense, the heated rock slowly rises through cooler, denser rock that surrounds it in the mantle. When it reaches the lithosphere, the heated rock moves sideways along the bottom of the lithosphere, losing heat. As the rock cools and becomes denser, it sinks back toward the core, only to be heated once again. Scientists estimate that it takes about 200 million years for heated rock to make a circular trip from the core to the lithosphere and back again.

The slowly moving convection currents are able to release their heat energy near the surface of the planet because the lithosphere is not solid. It is broken into many large slabs or plates that "float" on the soft asthenosphere. In constant contact with each other, these plates fit together like a jigsaw puzzle. When one plate moves, other plates move in response. The pressure exerted by the convection currents underneath the lithosphere causes the plates to move toward or away from each other. Plate tectonics is the scientific theory explaining the plates and their movements and interactions.

Hoodoos on the Plateau

Hoodoo is a word used to refer to various forms of African-based folk magic and spiritual healing. It is also used to describe the strange and mystical rock shapes found in the western United States and Canada. The most remarkable hoodoos are found in Bryce Canyon in Utah, where erosion has shaped an enormous array of oddly shaped columns of rock tinted with countless subtle colors.

Water, ice, and gravity are the forces that formed Bryce Canyon and its unusual landforms. Yearly, the plateau area of the canyon receives about 19 inches (48 centimeters) of rain, which often falls in fierce thunderstorms. Unable to be absorbed by the normally dry soil, the water washes off in sheets and flash floods, eroding much of the soil and rock in its path. Water in the form of ice, however, is the greater erosive force in the canyon.

In addition to rain, approximately 100 inches (254 centimeters) of snow falls on the canyon per year. Water from the snow runs into cracks and joints in the canyon's rocks, then freezes at night. As water freezes into ice, it expands. The expanding ice in the cracks eventually breaks off portions of the rock, leaving behind a changed rock shape. This process is known as frost wedging.

The composition of the rocks of the hoodoos plays a further part in their bizarre-looking form. The hoodoos are composed of four different types of rock, each of which varies in hardness and erodes at a different rate. As different parts of the hoodoos erode at different times, the rock columns take on their wavy and pockmarked shape.

Plate tectonics and plateau formation

The plates making up the lithosphere have many different shapes and sizes. There are seven large plates, eight medium-sized plates, and a number of smaller plates. When the plates move, they interact with each other in one of three ways: they converge or move toward each other, they diverge or move away from each other, or they transform or slide past each other. Plate margins are the boundaries or areas where the plates meet and interact.

When two continental (land) plates converge, they crumple up and compress, forming complex mountain ranges and very high plateaus. This is the history of the Tibetan Plateau, created as a result of the collision between the Indian Plate and the Eurasian Plate. While the Himalayan Mountains formed along the edge of the collision, the plateau rose unbroken behind them.

When a continental plate and an oceanic plate converge, the oceanic plate (which is denser) slides beneath the continental plate in

Limestone hoodoos in Bryce Canyon National Park, Utah. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

a process known as subduction. As a plate subducts beneath another, its leading edge begins to melt because of high temperature and pressure in the mantle. This forms thick, flowing magma (molten rock beneath the planet's surface). Less dense than the rock that surrounds it deep underground, the magma rises toward Earth's surface, forcing its way through weakened layers of rock. In most instances, the magma collects in underground reservoirs called magma chambers. It remains there until enough pressure builds up to eject it onto the planet's surface through vents called volcanoes. (For further information, see the **Volcano** chapter.)

Sometimes the magma does not collect in a chamber, but rises beneath a large, stable landmass. Unable to break through any cracks or vents, the magma exerts pressure on the land, causing it to rise upward in one piece. Geologists believe this uplifting process formed the Colorado Plateau about five million years ago.

Lava plateaus

A lava plateau (also called a basalt plateau or flood basalt) is a special type of plateau, formed neither by the collision of continental plates nor by uplift. Instead, this layered plateau is built up over millions of years by lava repeatedly pouring forth through fissures, or long narrow cracks in the ground. (Lava is what magma is called once it reaches Earth's surface.) The cracks could be where tectonic plates are separating or where pressure from magma underneath the crust has created cracks in it.

The most abundant element found in magma is silicon, in the form of the oxide silica. (An oxide is a compound of an element and oxygen. As magma cools, the silica crystallizes to become the mineral quartz.) The amount of silica in magma determines how easily the magma flows. The higher the silica content, the slower the magma (lava) flows. Temperature also affects the flow rate of magma: the higher the magma's temperature, the more readily it flows.

The lava that floods the landscape to create a lava plateau is composed primarily of basalt, a hard, often glassy, black volcanic rock. Basalt has low silica content, and the lava it creates has a high temperature. These two properties combine to produce lava that flows quite rapidly. Erupting from cracks in the ground in thin sheets, basalt lava floods over the landscape, building up to form deposits thousands of feet thick.

The most famous example of a lava plateau in the United States is the Columbia Plateau. It covers most of southern Washington from its border with Idaho west to the Pacific Ocean and south into Oregon. The lava flows that accumulated to form the plateau occurred within the last seventeen million years. More than 40,700 square miles (170,000 square kilometers) of lava covers the plateau. In places, it measures 5,000 feet (1,524 meters) thick.

Spotlight on famous forms

Colorado Plateau, United States

Roughly circular, the Colorado Plateau sprawls across southeastern Utah, northern Arizona, northwestern New Mexico, and western Colorado. It covers a land area of 130,000 square miles (336,700 square kilometers). Only the states of Alaska, California, Montana, and Texas cover a larger area. While tectonic forces thrust the nearby Rocky Mountains into existence some forty to eighty million years ago, the Colorado Plateau remained structurally stable. Originally close to sea level, the plateau was slowly uplifted as a single mass approximately five million years ago.

Elevations on the plateau range from 3,000 to 14,000 feet (915 to 4,270 meters). The average elevation is 5,200 feet (1,585 meters).

Average yearly precipitation on the plateau is about 10 inches (25 centimeters). Because of the plateau's elevation and arid (dry) climate, there is limited plant cover. Erosion by wind and water has resulted in the creation of many dramatic landforms. Rivers have cut thousands of miles of canyons within the plateau. Among these many canyons is the Grand Canyon, sculpted by the Colorado River. The pinnacles and spires of red rock in southwestern Utah's Bryce Canyon are among the most remarkable sights in the country.

An area of the state of Tamil Nadu in the western portion of the Deccan Plateau. The Deccan Plateau, which is largely made up of basalt lava, covers some 300,000 square miles in west-central India. **PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.**

Deccan Plateau, India

The Deccan Plateau of west-central India is the oldest and most stable area of land in India. It is a lava plateau that formed over a period of one million or more years. Deccan comes from the Sanskrit work *dakshina*, meaning "south." The name is applied loosely to all elevated lands of southern India.

The relatively flat plateau covers some 300,000 square miles (770,000 square kilometers), encompassing the states of Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu. Two mountain ranges, the Western and Eastern Ghats, flank it. In spots, the basalt lava flows that created it accumulated to a thickness of 6,000 feet (1,829 meters). In its western regions, the plateau averages about 2,500 feet (762 meters) in elevation; in its eastern parts, it averages 1,000 feet (305 meters). As a result of this difference in elevation from one side to the other, almost all rivers on the plateau flow from west to east and drain into the Bay of Bengal.

Siberian Traps, Russia

The largest volcanic eruptions in Earth's history occurred about 250 million years ago in present-day central Russia. In these eruptions, which scientists believe lasted for 200,000 to 1 million years, basalt lava flowed out of cracks in the ground, forming what is now known as the Siberian Traps. An enormous stretch of rolling land, it covers about 750,000 square miles (1,942,500 square kilometers). Heights on this vast plateau range from 1,600 to 2,300 feet (500 to 700 meters). The lava that created the Siberian Traps would form a layer 10 feet (3 meters) thick if spread out evenly across the planet.

Scientists speculate that the lava on the plateau came from magma that originated some 1,860 miles (3,000 kilometers) beneath Earth's crust. Some scientists have even argued that the rapid volcanic event behind the plateau's formation also brought about the largest extinction of animals in Earth's history. As many as 95 percent of all animal species on the planet were wiped out in an extinction that occurred around the same time period. The scientists point out that the dust and ash released by the lava flows could have blocked out the Sun's light, killing off plant life around the world, a necessary food source for animals. Or great amounts of carbon dioxide released by the flows could have encircled the planet, trapping the Sun's heat and raising temperatures worldwide, killing many life forms.

Tibetan Plateau, Tibet

The Tibetan Plateau is the highest and most widespread plateau in the world. Many believe it is probably the largest and highest area ever to exist in Earth's history. The plateau covers some 888,000 square miles (2.3

million square kilometers), an area roughly half that of the contiguous United States (connected forty-eight states). It is bounded on the north by the deserts of the Tarim and Qaidam (pronounced CHIE-dahm)Basins and on the south by the Himalayan Mountains.

The Tibetan Plateau is the highest and most widespread plateau in the world, with an average altitude of 16,400 feet. It also contains the two highest peaks in the world, Mount Everest and Mount K2, and has the deepest canyon in the world, the Yarlung Zangbo. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Referred to as the "roof of the world," the plateau has an average elevation over 16,400 feet (5,000 meters). It contains fourteen mountains that rise higher than 26,248 feet (8,000 meters) and hundreds that rise more than 22,967 feet (7,000 meters). The Yarlung Zangbo River, which runs across the plateau, has cut the Yarlung Zangbo Grand Canyon, the deepest canyon in the world. The plateau itself is still geologically active and continues to rise, gaining an average of 0.04 inch (0.1 centimeter) per year in elevation.

Approximately forty to fifty million years ago, the northward-moving Indian Plate rammed into the Eurasian Plate, creating what would eventually become the Himalayan Mountains and the Tibetan Plateau. Geologists have long known that the crust beneath the plateau measures approximately 40 miles (65 kilometers) in depth, roughly twice that of the average continental crust. Only recently have scientists discovered that the plateau is supported by a bed of hot magma (molten rock). Since magma is less dense (lighter) than cold, crustal rock, this bed of magma has helped raise the plateau as a single mass to such a great height.

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Stream and river

Flowing water, in streams and rivers or across the land in sheets, is the dominant erosional process in shaping Earth's landscape. Streams and rivers are not merely systems for moving surface water to the world's oceans and seas. They are also systems for moving weathered rocks and other sediment to those large bodies of water. In fact, it is estimated that streams and rivers move about 1.65 billion tons (1.5 billion metric tons) of sediment from land to the oceans each year. By shifting such great masses of sediment, streams and rivers become sculptors of the land.

Streams and rivers erode, transport sediment, change course, and flood their banks in natural and recurring patterns. It is true that most of the erosional work done by surface water is not done by streams or rivers but instead by falling raindrops and by the resulting unorganized runoff down slopes. Yet streams and rivers are able to create both erosional landforms (their own channels, canyons, and valleys) and depositional landforms (floodplains, alluvial fans, and deltas) as they flow over Earth's surface.

The shape of the land

Geologists define a stream as any body of running water that moves downslope under the influence of gravity in a narrow and defined channel on Earth's surface. Streams are also found on the ground surface in caves and underneath and inside glaciers (large bodies of ice that formed on land by the compaction and recrystallization of snow and that survive year to year). Rivers, creeks, brooks, and runs are all streams. Most sources define a river simply as a large stream; creeks, brooks, and runs are simply small streams. For this discussion, stream will be used to refer to all of these bodies of running water.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

The waters of almost half a continent flow through the Mississippi River. About 159 million tons of sediment—70 percent of which consists of clay, silt, and fine sand—are carried by the river annually. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

When water flows down a slope, it tends to gather in small depressions on the surface along the way. This concentration of moving water stimulates the process of erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. As the water erodes rock and other material in the depression, it forms a channel. The stream channel is the landform, not the water carried in it. The sides of the channel are known as the stream's banks. The bottom is the stream bed.

A stream's velocity, or speed, determines its ability to erode, transport, and deposit sediment. Sediment is rock debris such as clay, silt, sand, gravel, or even larger material. Alluvium (pronounced ah-LOO-vee-em) is the general term for sediment deposited by running water. A fast-moving stream carries more sediment and larger material than a slow-moving one. A stream that is turbulent, with water whirling through the channel and not flowing in a steady and straight manner, can also lift and carry

Words to Know

Alluvial fan: A fanlike deposit of sediment that forms where an intermittent, yet rapidly flowing, canyon or mountain stream spills out onto a plain or relatively flat valley.

Alluvium: The general term for sediment (rock debris such as gravel, sand, silt, and clay) deposited by running water.

Base level: The level below which a stream cannot erode.

Bed load: The coarse sediment rolled along the bottom of a stream.

Channel: The depression where a stream flows or may flow.

Cut bank: A steep, bare slope formed on the outside of a meander.

Delta: A body of sediment deposited at the mouth of a stream where it enters an ocean or a lake.

Dissolved load: Dissolved substances, the result of the chemical weathering of rock, that are carried along in a stream.

Distributaries: The channels that branch off of the main stream in a delta, carrying water and sediment to the delta's edges.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Floodplain: An area of nearly flat land bordering a stream that is naturally subject to periodic flooding.

Graded stream: A stream that is maintaining a balance between the processes of erosion and deposition.

Groundwater: Freshwater lying within the uppermost parts of Earth's crust, filling the pore spaces in soil and fractured rock.

Levee (natural): A low ridge or mound along a stream bank, formed by deposits left when floodwater slows down on leaving the channel.

Meander: A bend or loop in a stream's course.

Oxbow lake: A crescent-shaped body of water formed from a single loop that was cut off from a meandering stream.

Point bar: The low, crescent-shaped deposit of sediment on the inside of a meander.

Rapids: The section of a stream where water flows fast over hard rocks.

River: A large stream.

Stream: Any body of running water that moves downslope under the influence of gravity in a defined channel on Earth's surface.

Suspended load: The fine-grained sediment that is suspended in the flow of water in a stream.

Waterfall: A steep drop in a stream bed causing the water in a stream channel to fall vertically or nearly vertically.

more rocks and sediment than one that flows gently. Turbulence is due to the friction caused by rocks and steps in the stream's channel.

Factors that influence the velocity of a stream include its gradient (slope of its channel), the amount of sediment it carries, the shape of its channel, and its discharge (volume of water flowing past a given point over a given period of time). A low gradient, a high amount of sediment, a rough channel (both bed and banks), and a low discharge will all slow the velocity of a stream.

A stream's load is the total amount of sediment it is carrying. The sediment load consists mainly of two parts. The first part is the coarse material such as sand and gravel that moves along the stream bed. This is known as the bed load. As it is carried along, this coarse sediment acts as an abrasive, scouring and wearing away the banks and bed of the stream. The stream then picks up any newly loosened and eroded material. The second part is the fine-grained material such as clay and silt that is suspended in the water as the stream flows along. This is the suspended load. Streams also carry a dissolved load. These dissolved substances are the result of the chemical weathering of rock, which alters the internal structure of minerals by removing or adding elements.

Stream channels

There are three types of stream channels: straight, meandering, and braided. Although there are no absolutely straight channels in nature, geologists refer to straight channels as those that are relatively straight with little lateral or side-to-side movement. They are typically found in the headlands, or area where the stream begins, usually a highland or mountainous region. They are also found following an underlying weak rock layer in an area, such as along a fault or a joint (a fault is a crack or fracture in Earth's crust along which rock on one side has moved relative to rock on the other; when no movement has occurred, the fracture is known as a joint). The velocity of the water in a straight channel is fast because the channel often has a steep gradient. Its discharge is also high. The channel is often deeper than it is wide, and most erosion occurs along the stream bed, although its sediment load is not yet large.

Meandering stream channels are quite common. In fact, virtually all flowing fluids meander. Jet streams, the fast upper-air winds that travel west-to-east around the planet, meander. So does the Gulf Stream, the warm surface ocean current that originates in the Gulf of Mexico and flows northeast across the Atlantic Ocean. In a meandering channel, the erosional energy of the water is directed side to side instead of downward, and so the channel moves across the landscape like a wiggling snake. (See the photo on page 269.) The series of S-shaped bends are called meanders (pronounced me-AN-ders; the term comes from the Menderes River in southwest Turkey, noted for its winding course). The velocity of the water is highest and the water level deepest on the outer parts of the meanders. High velocities and greater turbulence result in erosion as the stream eats into its bank, creating eroded areas called cut banks. Along the inner parts of the meanders, where the water level is shallow and velocity is slow, sediment is deposited to form crescent-shaped point bars. If erosion on the outside of a meander continues to take place, eventually the meander can become cut off from the rest of the stream. When this occurs, the separated

The meandering Tigre River, Argentina.
PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

meander forms a body of water called an oxbow lake. (For further information, see the **Floodplain** chapter.)

When a stream's discharge varies frequently and its sediment load is large, the sediment may be deposited to form bars and islands within the main channel. The water then flows around these deposits in small channels, which unite farther downstream. This type of channel is called a braided stream channel because the many crisscrossing smaller channels resemble hair braids. When discharge increases in the channel, the bars and islands may be covered or eroded and redeposited once the discharge decreases again. If vegetation takes hold on the bars or islands, these features may not be easily eroded.

Erosional features

The course of a stream's channel can be affected if the rock layer over which it passes changes from a hard, resistant layer to one that is weaker and more easily eroded. As the softer material is worn away, the resistant rock remains as a step or ledge over which the water in the channel flows. This drop in the stream bed that causes the water to fall vertically or nearly vertically is called a waterfall. Often the drop is steep. A waterfall may also develop where a stream flows over the edge of a plateau or in

Earth's Tallest Waterfalls

Waterfall	Height	Location
Angel Falls	3,212 feet (979 meters)	Venezuela
Tugela Falls	3,110 feet (948 meters)	South Africa
Tyssestrengene	2,795 feet (852 meters)	Norway
Browne Falls	2,744 feet (836 meters)	New Zealand
Utigardsfossen	2,625 feet (800 meters)	Norway
Colonial Creek Falls	2,584 feet (788 meters)	Washington, USA
Mtarazi Falls	2,499 feet (762 meters)	Zimbabwe
Yosemite Falls	2,425 feet (739 meters)	California, USA
Espelandsfossen	2,307 feet (703 meters)	Norway
Mongefossen	2,296 feet (700 meters)	Norway

areas where glaciers have eroded deep valleys in mountainous terrain and streams flowing from higher parts plunge to the valley floor. In a waterfall, as water continues to fall over the edge, it erodes the bed of the channel at the base of the waterfall. A basin or depression is created, and sediment carried by the stream is deposited here. Depending on their hardness, the rock layers behind the falling water may also be eroded over time by the action of the water. As these softer layers are cut into, the resistant layer under the bed of the stream ultimately loses support and falls into the water at the base of the waterfall. When this occurs, the waterfall retreats farther upstream.

Normally, over time, the stream will erode the resistant rock so the gradient of the channel is not as steep. The waterfall will be reduced to rapids, an area where water in the stream channel rushes downward over hard rocks. The reduction of a major waterfall to rapids may take tens of thousands of years. Eventually, the rapids, too, will be eroded away.

Other erosional features created by streams are canyons and V-shaped valleys. On plateaus and in mountains, a stream erodes a fairly narrow path through the landscape, often only as wide as its channel. It does so because most of its erosional force is directed along its bed. As the stream erodes downward, a process referred to as downcutting, steep slopes remain on either side of the stream's channel. If the stream is cutting through a region composed of rocks that are highly resistant to erosion, a narrow, steep-walled canyon is created. (For further information, see the **Canyon** chapter.) If the rocks in the region are more susceptible to erosion, rockslides and other types of landslides gradually modify the steep slopes to form a V-shaped valley. (For further information, see the **Valley** chapter.)

Depositional features

In addition to bars and islands in braided streams and point bars in meandering streams, streams create larger features by depositing sediment. Among these are floodplains, alluvial fans, and deltas.

When the flow of water in a stream becomes too high to be accommodated in the stream's channel, the water flows over the stream's banks and floods the surrounding land. As it does so, the water immediately slows down and drops its sediment load. Coarser sediment is deposited near the channel. Over time, as the process is repeated over and over, the sediment forms mounds called natural levees along the stream's banks. Finer sediment carried by the flood is spread farther away from the channel before it is finally deposited. The flat or gently sloping surface created by the repeated deposition of sediment along a stream is called the stream's floodplain. A floodplain is widened as a stream meanders across a landscape. (For further information, see the **Floodplain** chapter.)

When a stream whose channel has been confined in a narrow valley or canyon in a highland area flows out into a broader, flatter valley or plain, its velocity and gradient suddenly decrease. No longer confined to a narrow channel, the water spreads farther as it moves away from the base of the highlands. Large rocks and other heavy material are deposited first, followed by other material in decreasing size. As more water flows onto the valley and more sediment is deposited, a wide, fan-shaped pile known as an alluvial fan forms.

When a stream enters a body of standing water, such as an ocean or a lake, again there is a sudden decrease in velocity. The stream drops its sediment load in a deposit called a delta. Deltas build outward from a coastline, but will survive only if ocean currents are not strong enough to remove the sediment. As the velocity of a stream decreases on entering the delta, the stream becomes choked with sediment, similar to what occurs in a braided stream channel. Instead of braiding, however, the stream channel breaks into many smaller channels called distributaries that carry water and sediment to the delta's edges. (For further information, see the **Delta** chapter.)

Forces and changes: Construction and destruction

Water running down a slope becomes a stream when there is enough water to form a tiny rivulet with a channel to contain the water. In its early stage, a stream may carry water only after rain falls or snow melts. In this instance, it is said to be an intermittent stream. In contrast, a permanent stream is one that has cut its valley deeply enough so that groundwater seeps into it and keeps it flowing between rainfalls. Beneath Earth's surface, water fills the pore spaces and openings in rocks. This water,

The Literary Landscape

"The overall impression here, as one surveys the river spread out over the gravel bars, is of a suspension of light, as though light were reverberating on a membrane. And a loss of depth. The slope of the riverbed here is nearly level, so the movement of water slows; shallowness heightens the impression of transparency and a feeling for the texture of the highly polished stones just underwater. If you bring your eye to within a few inches of the surface, each stone appears to be submerged in glycerin yet still sharply etched, as if held closely under a strong magnifying glass in summer light."

—Barry Holstun Lopez, *River Notes: The Dance of Herons*, 1979.

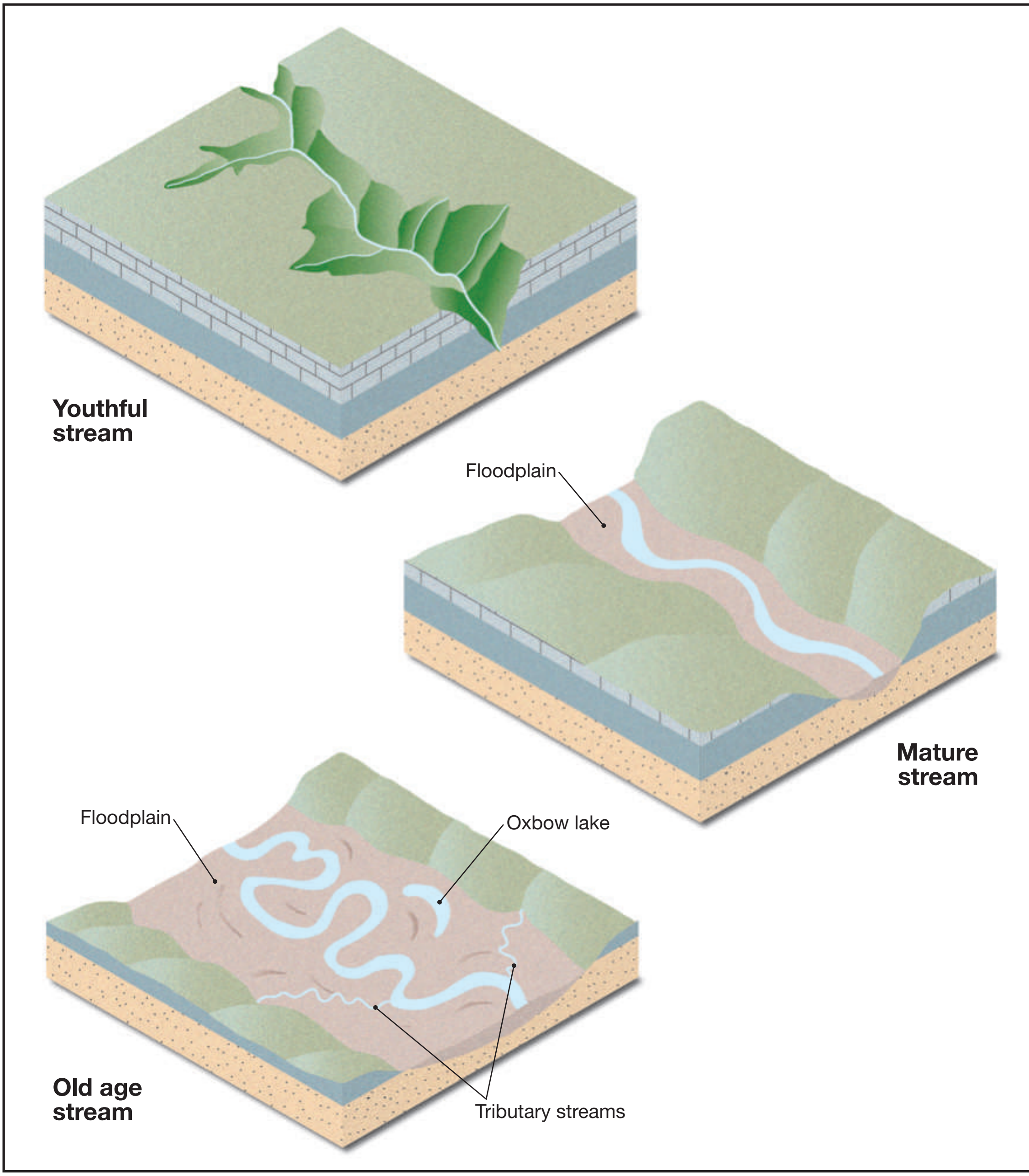
which comes from rain or melted snow that is drawn downward through the soil by gravity, is known as groundwater. At a certain level below ground, all the openings in the rocks are completely filled with groundwater. The upper surface of this saturated zone is known as the water table.

A stream has a natural tendency to reach a base level. This refers to the point at which the stream reaches the elevation of the large body of water, such a lake or ocean, into which it drains. Aided by gravity, a stream flows toward the level of its final destination as quickly as possible. The larger the difference in height between the stream and its destination, the greater the erosive or cutting force of the stream. For most larger streams, base level is sea level. For tributaries, smaller streams that flow into larger ones, base level is the entry point where they empty into the larger stream.

Streams erode because they have the ability to pick up sediment and transport it to a new location. That sediment may come from several sources: It may have been eroded from the bed and banks of the stream, or it may have fallen into the stream after moving (slowly or quickly) down a slope bordering the stream's channel.

A stream erodes through two actions: hydraulic action and abrasion. Hydraulic action is the force exerted by the water itself. It tends to work along the banks of streams, attacking and undermining layers of soil and rock. Abrasion is the grinding and scraping of the stream's banks and bed by the sediment carried in the stream as the suspended load and bed load.

The amount of sediment a stream moves depends on the velocity of the stream and the size of the sediment particles. Water moving at a low velocity can move only small, fine particles such as sand, silt, and clay. Sand is a mineral particle with a diameter between 0.002 and 0.08 inch (0.005 and 0.2 centimeter); silt is a mineral particle with a diameter between 0.00008 and 0.002 inch (0.0002 and 0.005 centimeter); clay is a mineral particle with a diameter less than 0.00008 inch (0.0002 centimeter). Water moving at a high velocity can move both small particles and large, coarse particles such as boulders.



Stages of stream development: a youthful stream, mature stream, and old age stream.

A stream will continue to carry its load as long as its velocity remains constant or increases (if it increases, it can carry an even larger load). Any change in the geography of the landscape that causes a stream channel to bend or rise (lessening its gradient) will slow the flow of water in the channel. As soon as a stream's velocity decreases, it loses the ability to carry all of its load and a portion will be deposited, depending on how much the stream slows down. Particles will be deposited by size with the largest settling out first.

Stream stages

Geologists characterize streams as youthful, mature, and old. Typically, streams have steep gradients near their sources, or beginnings, and gentle gradients as they approach their mouths, or ends. Discharge increases downstream as more tributaries connect with main streams as they flow toward their base levels. Because of this, stream channels also become deeper and wider downstream.

A youthful stream has a fairly straight channel and a steep gradient. It generally flows in a V-shaped valley in a highland or mountainous area with little shifting of its channel. Its velocity is high, and it is actively lowering its channel through downcutting in order to reach base level. In this stage, a stream has little, if any, floodplain. Rapids and waterfalls may mark its course.

A stream in its mature stage has a moderate gradient and velocity because it has eroded its bed downward and is closer to base level. Since it has slowed down, the stream begins to meander. While it is still eroding downward, the stream's main force of erosion is lateral (horizontal) as it begins winding back and forth, carving out a valley floor between valley walls or bluffs. Periodically, the stream will flood all or a part of its valley, depositing alluvium on its developing floodplain.

An old age stream has nearly reached its base level, and its gradient and velocity are very low. Because its velocity is low, it has lost its ability to erode downward. In fact, it deposits as much material as it erodes. The stream meanders greatly in its nearly flat valley. It has a wide, well-developed floodplain marked with oxbow lakes.

Graded stream

A stream with the correct gradient and channel characteristics to maintain the velocity required to transport its sediment load is known as a graded stream. It is a stream that is in equilibrium or balance. On average, it is neither eroding nor depositing sediment but simply transporting it. This involves a balance among base level, discharge, channel shape or size, and sediment load. Any changes to one or more of these by some event—lowering of sea level, the uplift of a land area containing a stream, the blocking of a stream channel by natural or artificial means—will result in erosion or deposition until a new balanced state is reached.

The world's second longest river, the Amazon, runs for about 3,900 miles through Peru and Brazil. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Spotlight on famous forms

Amazon River, Peru and Brazil

The Amazon River is the world's second longest river (the Nile River in Africa is the longest). It runs for about 3,900 miles (6,275 kilometers) from the Andes Mountains in northern Peru to the Atlantic Ocean near Belem, Brazil. When it enters the ocean, the Amazon discharges about 7,000,000 cubic feet (198,450 cubic meters) of water per second. The width of the Amazon ranges from about 1 to 8 miles (1.6 to 13 kilometers).

Although the Amazon is usually only about 20 to 40 feet (6 to 12 meters) deep, there are narrow channels where it can reach a depth of 300 feet (91 meters). Almost every year, the Amazon floods, filling a floodplain up to 30 miles (48 kilometers) wide. The fresh layer of sediment deposited by the flood makes the surrounding region extremely fertile.

The Amazon basin (the area drained by the Amazon River) is the largest river basin in the world. It covers an area of about 2,500,000 square miles (6,475,000 square kilometers), or almost 35 percent of the land area of South America. The volume of water that flows from the basin into the Atlantic is about 11 percent of all the water drained from all the continents of Earth.

The Iguazú Falls, located on the border between Argentina and Brazil, is composed of 275 waterfalls that are strung out along the rim of a crescent-shaped cliff about 2.5 miles long. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Iguazú Falls, Argentina and Brazil

From its source in the mountains not far from the Atlantic Ocean, the Iguazú (pronounced ee-gwah-ZOO) River flows westward across southern Brazil before entering Argentina and Paraguay. In the language of the native people of the region, Iguazú means "great waters." Along its 745-mile (1,200-kilometer) course, the river flows over 70 waterfalls as it seeks its base level.

The most famous of these waterfalls is located on the border between Argentina and Brazil. The Iguazú Falls is composed of 275 individual falls strung out along the rim of a crescent-shaped cliff about 2.5 miles (4 kilometers) long. The river drops 269 feet (82 meters) at the falls. The water in the river flows over the edge of the falls at an average rate of 553 cubic feet (17 cubic meters) per second.

The falls were created nearly 100,000 years ago when a volcanic eruption produced a lava flow that stopped abruptly, forming a huge, natural cliff.

Volga River, Russia

The Volga River in western Russia is the longest river in Europe. It begins in the Valdai Hills northwest of Moscow and flows for about 2,200 miles (3,530 kilometers) before forming a great delta where it enters the

The Volga River, in Russia, is the longest river in Europe, running for some 2,200 miles. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Caspian Sea. Its source is only 740 feet (226 meters) above sea level. Combined with its many tributaries, the Volga River drains an area of over 502,000 square miles (1,300,000 square kilometers).

Much of the water that flows in the Volga River comes from snowmelt. Many large dams have been built on the river to provide hydroelectricity and water for irrigation. Prior to the dams being built, the river carried an estimated 25.5 million tons (23 metric tons) of sediment to the Caspian Sea. The dams have also reduced the amount of natural floods along the river and the velocity of the river's flow.

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Valley

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

Valleys are one of the most common landforms on the surface of the planet. They are carved by flowing water or flowing ice through the process of erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. Valleys take on a wide variety of forms—from steep-sided canyons, such as the Grand Canyon on the Colorado River, to broad plains, such as the lower Mississippi River valley. The form of a valley depends on many factors, including what is eroding it, the slope of the land surface, the nature of the soil or rock where the valley is being created, and time.

The shape of the land

A valley is a relatively large hollow or depression bounded by hills or mountains on Earth's surface that is developed by stream erosion or glacial activity and that is drained externally. A basin is another hollow or depression on Earth's surface, but it has no outlet to drain the water. (For further information, see the **Basin** chapter.) Geologists refer to any body of running water moving downslope in a defined channel as a stream (a river is a large stream). A glacier is a large body of ice that formed on land by the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity. The three main types of valleys are the V-shaped valley, the flat-floored valley, and the U-shaped valley.

A V-shaped valley is a narrow valley that has a profile suggesting the form of the letter "V," characterized by steeply sloping sides. It results from a stream eroding downward, a process referred to as downcutting. V-shaped valleys form in mountains or other highland areas where streams are in their beginning or "youthful" stage and are flowing rapidly down steep slopes. The bottom of a valley is called its floor. In highland areas

Blue Ridge Mountain Valley, North Carolina. Valleys are carved by flowing water or flowing ice through the process of erosion, which is the gradual wearing away of Earth surfaces through the action of wind and water. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Words to Know

Alpine glacier: A relatively small glacier that forms in high elevations near the tops of mountains.

Base level: The level below which a stream cannot erode.

Erosion: The gradual wearing away of Earth surfaces through the action of wind and water.

Fjord: A deep glacial trough submerged with seawater.

Floodplain: An area of nearly flat land bordering a stream that is naturally subject to periodic flooding.

Glacial trough: A U-shaped valley carved out of a V-shaped stream valley by the movement of a valley glacier.

Glacier: A large body of ice that formed on land by the compaction and recrystallization of snow, survives year to year, and shows some sign of movement downhill due to gravity.

Hanging valley: A shallow glacial trough that leads into the side of a larger, main glacial trough.

Levee (natural): A low ridge or mound along a stream bank, formed by deposits left when floodwater slows down on leaving the channel.

Mass wasting: The spontaneous movement of material down a slope in response to gravity.

Meander: A bend or loop in a stream's course.

Rift valley: The deep central crevice in a mid-ocean ridge; also, a valley or trough formed between two normal faults.

Stream: Any body of running water that moves downslope under the influence of gravity in a defined channel on Earth's surface.

U-shaped valley: A valley created by glacial erosion that has a profile suggesting the form of the letter "U," characterized by steep sides that may curve inward at their base and a broad, nearly flat floor.

Valley glacier: An alpine glacier flowing downward through a preexisting stream valley.

V-shaped valley: A narrow valley created by the downcutting action of a stream that has a profile suggesting the form of the letter "V," characterized by steeply sloping sides.

near a stream's source, or beginning, the valley sides slope down almost directly to the stream's banks, or sides of its channel. The valley floor in this region is narrow or even nonexistent.

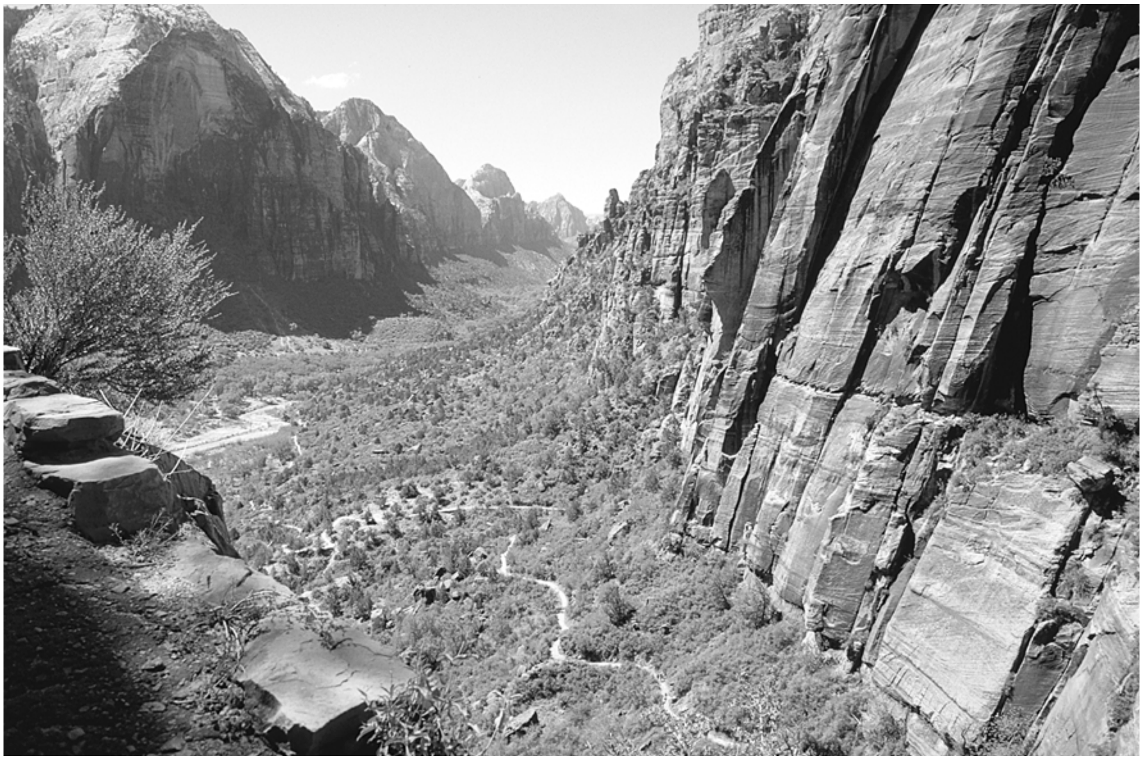
Downstream, as the gradient or slope of the stream's channel lessens and becomes more gentle, the floor of the valley widens. A stream in this stage is no longer considered youthful but "mature."A stream flowing at a moderate to low gradient tends to erode more along the banks of its channel than along its bed or bottom. Thus, the stream slowly sweeps across the valley floor in a series of S-shaped bends called meanders (pronounced me-AN-ders). Over time, as the stream continues to meander, it erodes away material on the valley floor, ever widening it. The shape of the valley changes progressively from a sharp V to a broader V to one that has a flat floor. This latter type of valley, with a floor that is horizontal and often wide, is known as a flat-floored valley. This type of valley is the most common.

Streams are systems for moving sediment—rock debris such as clay, silt, sand, gravel, or even larger material—across Earth's surface to the world's oceans and seas. Naturally and routinely, the flow of water in a stream may become too high to be accommodated in the stream's channel. The water then flows over the stream's banks and floods the surrounding land. As it does so, the water immediately slows down and drops any sediment it was carrying. Coarser sediment is deposited near the channel. Over time, as the process is repeated over and over, the sediment forms mounds called natural levees along the stream's banks. Finer sediment (sands, silt, and clay) carried by the water is spread farther away from the channel before it is finally deposited. The flat or gently sloping surface created by the repeated deposition of sediment along a stream is called the stream's floodplain. A floodplain may cover all or just a portion of the valley floor. (For further information, see the **Stream and river** and **Floodplain** chapters.)

A U-shaped valley is a valley that has a profile suggesting the form of the letter "U," characterized by steep sides that may curve inward at their bases and a broad, nearly flat floor. Specifically, a U-shaped valley is one carved by glacial erosion. Thick masses of ice that move slowly over Earth's surface, glaciers are found in regions close to the North and South Poles, the extreme northernmost and southernmost points on the globe, or in mountains at high elevations. Those that form over large areas of continents close to the poles are called continental glaciers or ice sheets. Two continental glaciers are found on Earth: one covers 85 percent of Greenland in the Northern Hemisphere and the other covers more than 95 percent of Antarctica in the Southern Hemisphere. Relatively small glaciers that form in high elevations near the tops of mountains are called alpine or mountain glaciers. (For further information, see the **Glacial landforms and features** chapter.)

Because of their size and weight, continental glaciers destroy topography, leveling the surface features of a landscape. The effect of alpine glaciers is not as extreme. They flow down pre-existing V-shaped valleys created by streams to form U-shaped valleys. Because of this, they are also known as valley glaciers. Whereas a stream only occupies the floor (or a main portion of it) in a V-shaped valley, a valley glacier occupies the entire valley, eroding both the sides and the floor as it moves, deepening and widening the valley. U-shaped valleys are also known as glacial troughs.

Draining an area, streams tend to flow across the landscape in a tree-like pattern: the smallest streams (the outer branches) flow into larger streams (the inner branches), which flow into the main stream (the trunk). Smaller streams that flow into larger ones are known as tributaries. When valley glaciers fill an area, they may occupy the valleys created



U-shaped valley in Zion National Park, Utah.
PHOTOGRAPH REPRODUCED BY PERMISSION OF FIELD MARK PUBLICATIONS.

by a main stream and its nearest tributaries. Tributary valleys almost always join the main stream valley at the same altitude or height, but glacial action deepens the main valley more than its side valleys. The shallower glacial troughs created by these smaller valley glaciers (known as tributary glaciers) are called hanging valleys. If temperatures in the area increase, causing the glaciers to melt and retreat, meltwater from the glaciers may form streams that run through these hanging valleys. In spectacular instances, streams in hanging valleys often fall to the floor of the main valley as a waterfall.

In certain instances, a valley glacier may flow all the way to a coastline, carving out a deep, narrow U-shaped valley. If the glacier melts, the valley may become flooded with seawater, forming an inlet known as a fjord (pronounced fee-ORD).

The term rift valley is used to describe an area where a section of Earth's crust (thin, solid outermost layer of the planet) has dropped down between two normal faults (cracks or fractures in Earth's crust along which rock on one side has moved relative to rock on the other). Essentially, whenever the planet's crust is subjected to compression or tension caused by heat forces beneath the crust, faults develop, and some blocks of rock

The Literary Landscape

"The famous Yosemite Valley lies at the heart of it, and it includes the head waters of the Tuolumne and Merced rivers, two of the most songful streams in the world; innumerable lakes and waterfalls and silky lawns; the noblest forests, the loftiest granite domes, the deepest ice-sculptured cañon, the brightest crystalline pavements, the snowy mountains soaring into the sky twelve and thirteen thousand feet, arrayed in open ranks and spiry pinnacled groups partially separated by tremendous cañons and amphitheatres; gardens on their sunny brows, avalanches thundering down their long, white slopes, cataracts roaring gray and foaming in the crooked rugged gorges, and glaciers in their shadowy recesses working in silence, slowly completing their sculpture; new-born lakes at their feet, blue and green, free or encumbered with drifting icebergs like miniature Arctic Oceans, shining, sparkling, calm as stars."

—John Muir, *Our National Parks*, 1901.

drop along these fractures relative to the ground on either side. A rift valley is not a true valley. The dropped-down block or crust that formed a depression on the surface of the ground is correctly called a graben (pronounced GRAH-bin). Rift valleys, which are found around the world on continents and the ocean floors, are commonly sites of volcanic and earthquake activity. (For further information, see the **Fault** chapter.)

Forces and changes: Construction and destruction

The dominant agent of erosion on the surface of the planet is flowing water. Although the ice in glaciers is solid, it also flows (though more slowly than water in a stream channel). Both streams and glaciers move downhill under the influence of gravity, the main driving force behind almost all agents of erosion. As they move downward, they transport sediment they have picked up or that has fallen into or onto them.

Stream erosion

The shaping of stream valleys is due to a combination of erosion by flowing water and mass wasting, the spontaneous movement of Earth material down a slope in response to gravity. This does not include material transported downward by streams, winds, or glaciers. Through mass wasting, material from higher elevations is moved to lower elevations where streams, glaciers, and wind pick it up and move it to even lower elevations. Mass wasting occurs continuously on all slopes. While some mass-wasting processes act very slowly, others occur very suddenly. The general term landslide is used to describe all relatively rapid forms of mass wasting. (For further information, see the **Landslide and other gravity movements** chapter.)

Once a stream forms, it seeks out its base level, which is the level below which the stream cannot erode. Base level is the elevation of the large body of water, such as a lake or ocean, into which a stream drains. The general or ultimate base level for most larger streams is sea level. For

The glacier-carved crescent-shaped Hunza Valley in Pakistan.
PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

a tributary, base level is the point where it empties into a larger stream. Aided by gravity, a stream tries to reach its base level as quickly as possible. The larger the difference in height between the stream and its base level, the greater the erosive or cutting force of the stream. Temporary base levels may form along a stream's course, such as those created by a lake or resistant rock.

The resistance of the rock over which a stream flows determines the shape of its initial stream valley. In a highland area, a stream's erosional force is directed along its bed, not its banks, as it seeks to lower its channel to base level. If the rock over which the stream flows in this area is hard and resistant to erosion, the stream will cut a narrow, steep-walled canyon. The valley created exists as a nearly vertical notch with no floor. If the rock is less resistant to erosion, the stream will still downcut, but the sides of the valley will take on the characteristic V shape as mass wasting—rockfalls and other types of landslides—widens the upper portion of the valley.

Rock hardness is an important factor in erosion, but a stream's ability to cut depends on how much sediment it carries and how fast it is flowing. The sediment carried by a stream may have been eroded from the bed and banks of the stream, or it may have fallen into the stream after a mass-wasting event moved it down a slope bordering the stream's channel. Water moving at a low velocity or speed can move only small, fine particles such as sand, silt, and clay. Water moving at a high velocity can move a larger amount of both small particles and large, coarse particles such as boulders. Water that flows erratically, giving rise to swirls and eddies, is said to be turbulent, and turbulent water can move the coarsest and greatest amount of particles.

A stream erodes through hydraulic action and abrasion. Hydraulic action is the force exerted by the water itself. This force works along the banks of streams, attacking and undermining layers of soil and rock. Abrasion is the grinding and scraping of the stream's banks and bed by the sediment carried by the stream.

When a stream flows out of a highland area, reaching an elevation that is closer to its base level, it begins to slow down. In this state, the stream is still eroding downward, but its main force of erosion is directly laterally or horizontally against its banks. It begins meandering, winding back and forth, carving out a valley floor between valley walls or bluffs. Periodically, the stream will flood all or a part of its valley, depositing sediment on its developing floodplain.

At the lower reaches of a stream, where it approaches base level, the valley it flows through will be open, wide, and flat-bottomed. Valley walls, if they even exist, will be far away from the stream channel.

Glacial erosion

Moving glaciers not only transport material as they move, they also sculpt and carve away the land beneath them. A glacier's weight, combined with its gradual movement, can drastically reshape the landscape.

A valley glacier moves to lower elevations under the force of gravity through a combination of internal flow and sliding at its base. The ice in a glacier is so dense and under such pressure that it begins to behave like a thick tar, flowing outward and downward. Glacial movement through this internal flow is very slow. On average, it measures only an inch or two (a few centimeters) a day. In a valley glacier, ice in the upper central part moves faster than ice at the sides, where it is in contact with the valley walls. The considerable weight of a valley glacier also creates enormous pressure at its base, and this pressure lowers the temperature at which ice melts. A layer of water develops between the glacial ice and the ground. The water reduces friction by lubricating the ground and allowing the glacier to slide on its bed.

A valley glacier is capable of eroding and transporting huge amounts of sediment. As the glacier moves, its ice flows into and refreezes in fractures in the rock walls and floor of the valley. The glacier then plucks that rocky material away with it, some of which may be boulders the size of houses. This

The 150-mile-long Shenandoah Valley in northern Virginia. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

material then becomes embedded in the ice at the base and along the sides of the glacier. As the glacier continues to move, the embedded material abrades or scrapes the rock surrounding the glacier like a giant file.

Following an existing V-shaped valley, a glacier erodes the valley, deepening and widening it. It may increase the width of the valley by as much as tens of miles (kilometers). The glacier also flattens the valley floor because ice tends to cut down over a wider area than flowing water. When the glacier finally retreats, a thick layer of glacial sediment called ground moraine remains, filling in any irregularities in the valley floor.

Spotlight on famous forms

Napa Valley, California

California's Napa Valley is world-renowned for having a wide variety of soils and climate conditions that help produce grapes that are made into quality wines. The narrow valley is 30 miles (48 kilometers) long and 1 to

6 miles (1.6 to 9.6 kilometers) wide. It occupies an area of about 300,000 acres (120,000 hectares).

At its northern end lies the region's largest mountain, Mount St. Helena. Its southern end opens to San Pablo Bay, an arm of the San Francisco Bay system. The valley is bordered by two mountain ranges, the Vaca Mountains on the east and the Macayamas Mountains on the west. Flowing through the middle of this valley is the 50-mile-long (80-kilometer-long) Napa River.

The valley began to form about four million years ago when heat forces beneath Earth's crust in this region forced land on either side of the present-day valley upward into mountains. Certain areas between the mountains were widened and lowered into troughs as a result. Napa Valley is such an area. After the valley's formation, eruptions from several volcanoes surrounding the valley blanketed the land in volcanic cinders and ash that accumulated to layers thousands of feet thick.

Shenandoah Valley, Virginia

The Shenandoah Valley in northern Virginia is part of the Great Valley of the Appalachians, which stretches from Pennsylvania to Alabama. The Shenandoah Valley, which is about 150 miles (241 kilometers) long, lies between the Blue Ridge Mountains on the east and the Allegheny Mountains on the west.

Both mountain ranges are part of the Appalachian Mountain system, which formed over 300 million years ago. The powerful erosive forces of water, wind, and frost have greatly eroded the Appalachians since then. Water runoff has carved the mountains' distinctive alternating pattern of ridges and valleys.

The Shenandoah River, which runs through the valley, is a tributary of the Potomac River. It was the first of the tributaries in the area to reach the soft limestone layer that is now the base of the Shenandoah Valley. Intercepting stream after stream west of the Blue Ridge Mountains, the Shenandoah River grew. As it did, it carved out the Shenandoah Valley, dissolving the limestone and carrying the sediments north to the Potomac.

Yosemite Valley, California

Lying in the Sierra Nevada Mountains in central California is a 0.5-mile (0.8-kilometer) deep depression. Measuring 7 miles (11 kilometers) long and 1 mile (1.6 kilometers) wide, Yosemite Valley lies at the heart of Yosemite National Park, which encompasses 761,170 acres (304,468 hectares).

The Merced River runs through the valley. Geologists estimate that a few million years ago, it began to carve a valley where the present-day

Yosemite Valley, seven miles long and one mile across, was formed during six key geologic stages that occurred over millions of years. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Yosemite Valley lies. The Sierra Nevada Mountains were uplifted and tilted westward, causing the river to gradually, then rapidly, erode a deep, steep-walled canyon. About 2 million years ago, North America's climate began to cool and glaciers began to form. During one of the major glacial periods, about 700,000 years ago, ice thickness in the area was up to 6,000 feet (1,829 meters). Massive, flowing glacial ice caused tremendous amounts of rock to be carved and transported to the area, creating massive rock formations that still exist.

The flow and retreat of glaciers through Yosemite Valley occurred many times until about 10,000 years ago, when the last major glacial period ended in North America. What remained was a U-shaped valley that was actually deeper than the present-day Yosemite Valley. Rock debris from the glacier had dammed the valley creating ancient Lake Yosemite, which covered the valley floor. Streams from hanging valleys above fell in towering waterfalls. The tallest of these is Yosemite Falls, which presently drops 2,425 feet (739 meters) to the valley floor. Ultimately, sediment filled in the lake until it formed the existing valley floor.

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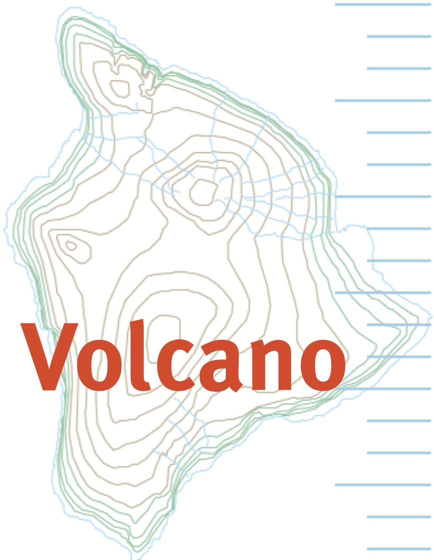


Volcano

Volcanoes are landforms whose shapes may remain unchanged for centuries or may change drastically in minutes. Some exist singly, looming over a flat landscape. Others exist in groups, forming mountain ranges. Scores of volcanoes remain unseen, hidden beneath the surface of the planet's oceans. These submarine volcanoes are known as seamounts. (For further information on oceanic landforms, see the **Ocean basin** chapter.)

The material and processes deep within Earth that form volcanoes have shaped the planet's surface since its beginning more than four billion years ago. Volcanologists, scientists who study volcanoes and volcanic phenomena, have identified the existence of more than forty thousand volcanoes on Earth. Currently, there are about six hundred active volcanoes scattered around the world. Volcanologists classify an active volcano as one that has erupted in the last few hundred years or shows signs of erupting in the near future. A dormant volcano is one that has not erupted for a few hundred years, but has erupted in the last few thousand years. An extinct volcano is one that has not erupted in the last few thousand years and will not, volcanologists believe, ever erupt again.

The word volcano comes from the name of the Roman god of fire and a small island that is part of a group of volcanic islands located just north of Sicily in the Tyrrhenian Sea. Ancient Romans believed that Vulcan, the mythological god who made tools and weapons for other Roman gods, operated his forge beneath the island of Vulcano. One of the present-day Aeolian (pronounced ee-OH-lee-an) Islands, Vulcano has been volcanically active for thousands of years. During the Middle Ages in Western Europe (roughly from 500 to 1500 C.E.), many people considered the smoking crater on Vulcano to be the entrance to hell. After this period, the word volcano was applied to all such eruptive landforms.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

The world's highest active volcano, Mount Cotopaxi, rises 19,388 feet above the surrounding highland plain in central Ecuador. Mount Cotopaxi is a stratovolcano with an almost perfectly symmetrical cone. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

The shape of the land

Technically, a volcano is a vent or hole in Earth's surface through which heated material escapes from underground. That material could be any combination of magma (called lava once it reaches Earth's surface), rock fragments, ash, and gas. Ejected through the vent, volcanic material accumulates to form a hill or, if over 1,000 feet (305 meters), a mountain around the opening. It is this accumulating landform that is more commonly referred to as a volcano.

Volcanologists recognize various volcanic landforms, such as shield volcanoes, stratovolcanoes, cinder cones, lava domes, calderas, and lava plateaus. The differing shapes of these landforms are determined by the composition of the magma flowing into the specific volcano from underground.

Magma is molten (melted) rock that contains particles of mineral grains and dissolved gas (primarily water vapor and carbon dioxide). The most abundant element found in magma is silicon, in the form of the oxide silica. (An oxide is a compound of an element and oxygen. As magma cools, the silica crystallizes to become the mineral quartz.) The

Words to Know

Asthenosphere: The section of the mantle immediately beneath the lithosphere that is composed of partially melted rock.

Basalt: A dark, dense volcanic rock, about 50 percent of which is silica.

Convection current: The circular movement of a gas or liquid between hot and cold areas.

Crust: The thin, solid outermost layer of Earth.

Hot spot: An area beneath Earth's crust where magma currents rise.

Lava: Magma that has reached Earth's surface.

Lithosphere: The rigid uppermost section of the mantle combined with the crust.

Magma: Molten rock containing particles of mineral grains and dissolved gas that forms deep within Earth.

Magma chamber: A reservoir or cavity beneath Earth's surface containing magma that feeds a volcano.

Mantle: The thick, dense layer of rock that lies beneath Earth's crust.

Mountain: A landmass that rises 1,000 feet (305 meters) or more above its surroundings and has steep sides meeting in a summit that is much narrower in width than the base of the landmass.

Plates: Large sections of Earth's lithosphere that are separated by deep fault zones.

Plate tectonics: The geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, shifting continents, forming mountains and new ocean crust, and stimulating volcanic eruptions.

Pyroclastic material: Rock fragments, crystals, ash, pumice, and glass shards formed by a volcanic explosion or ejection from a volcanic vent.

Ring of Fire: The name given to the geographically active belt around the Pacific Ocean that is home to more than 75 percent of the planet's volcanoes.

Silica: An oxide (a compound of an element and oxygen) found in magma that, when cooled, crystallizes to become the mineral quartz, which is one of the most common compounds found in Earth's crust.

Subduction zone: A region where two plates come together and the edge of one plate slides beneath the other.

Viscosity: The measure of a fluid's resistance to flow.

amount of silica in magma determines how easily the magma flows. When discussing the flow rate of magma, volcanologists refer to its viscosity (pronounced vis-KOS-eh-tee), which is the measure of a fluid's resistance to flow. If a fluid is thin and runny, like water, it has a low viscosity or is less viscous (pronounced VIS-kus). If a fluid is thick and slow-moving, like tar, then it has a high viscosity or is more viscous. Magma's viscosity is directly related to its silica content: The higher the silica content, the higher the viscosity and the slower it flows. Temperature and the amount of gas contained in magma also affect its viscosity, but opposite that of silica. When its temperature is high and it contains a vast amount of dissolved gas, magma has a low viscosity and flows quite readily.

Lava (magma that has erupted from a volcano) can create interesting rock formations once it has run down the side of a volcano and cooled. Two such formations generated by lava flows include aa (pronounced AH-ah) and pahoehoe (pronounced pa-HOY-hoy), which are quite common in the Hawaiian Islands. In fact, about 99 percent of the island of Hawaii is composed of aa and pahoehoe. The different textures of these volcanic rocks are caused by a difference in the viscosity of the lava flows that created them. Slow-moving, cooler, and more viscous lava hardens to form aa, rough blocks that have sharp, jagged edges. Lava flows that are hotter, have a high concentration of gas, and are less viscous harden to form pahoehoe, which has a smooth, coiled surface that resembles rope. While a hard skin develops on the surface of pahoehoe as it cools, hot lava continues to flow beneath the skin, causing the coiled-rope wrinkles that mark its surface. Lava may continue to flow inside hardened pahoehoe for miles.

Shield volcano

Shield volcanoes are broad landforms with gently sloping sides, resembling a warrior's shield lying on the ground with the curved face up. These types of volcanoes are typically created by successive nonexplosive eruptions of lava that have low silica content and, consequently, relatively low viscosity. The runny lava flows great distances over the wide surface of the volcano, forming thin sheets of nearly uniform thickness. The slope of a shield volcano is seldom more than 10 degrees at its summit and 2 degrees at its base. Hawaii, Tahiti, Samoa, the Galápagos, and many other oceanic islands are actually the upper portions of large shield volcanoes.

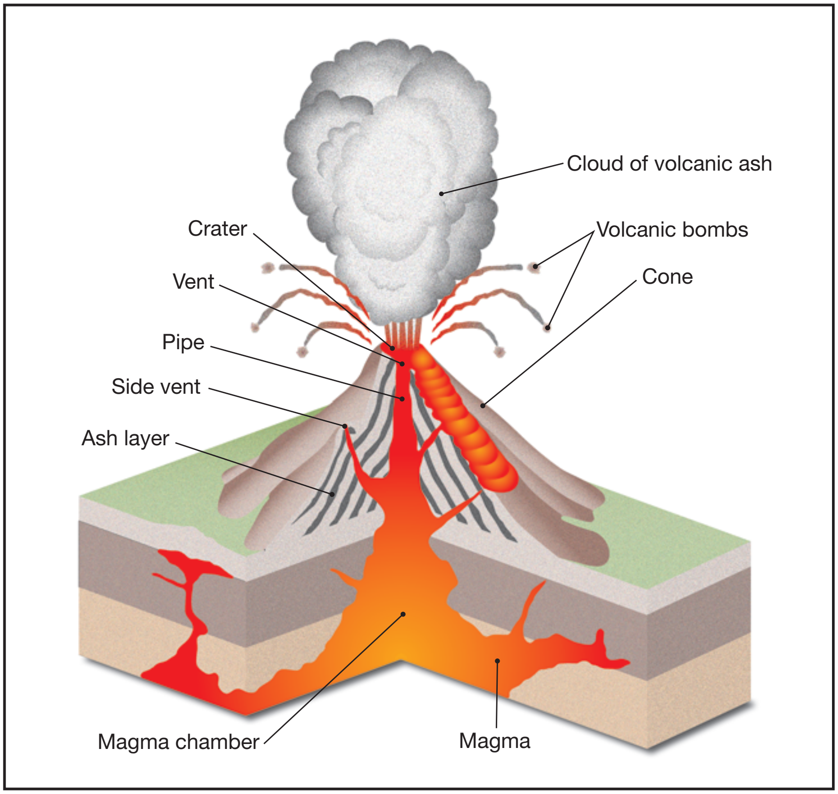
Stratovolcano

Stratovolcanoes, also called composite volcanoes, have the most symmetrical cone shape of any volcano types. They are among the most picturesque landforms on Earth. These steep mountains have slopes of up to 30 degrees at the summit, tapering off to 5 degrees at the base. They are built up of alternating layers of lava and layers of pyroclastic (pronounced pie-row-KLAS-tic; fragmented rock, crystals, ash, pumice, and glass shards) material, which have flowed down on different sides of the volcano at different times. The steep slope near the summit is due partly to thick, viscous lava flows that did not travel far downward from the vent. The gentler slope near the base is due to the accumulation of pyroclastic material that the volcano erupted violently and material eroded from the sides of the volcano. Examples of stratovolcanoes include Mount Fuji in Japan, Mount Mayon in the Philippines, and Mount Vesuvius in Italy. In the United States, Mount Rainier and Mount Baker in Washington and Mount Hood in Oregon are classic examples of stratovolcanoes.

The twisted, ropelike texture of pahoehoe. Pahoehoe is formed when a hard skin develops on the surface of lava, while hot lava continues to flow underneath. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Cinder cone

Cinder cones are the steepest of volcanoes, with slopes of 30 to 40 degrees. They are seldom taller than 1,640 feet (500 meters); many are not more than a few hundred feet high. Cinder cones are built entirely or almost entirely of blobs of lava that have broken up into small fragments



Cross-section of an active volcano.

or cinders after being ejected in mildly explosive eruptions. The cinders rain back down to form a cone around a bowl-shaped depression or crater at the summit. These volcanoes can grow very rapidly, but they are usually not active for long. Because the material that forms them is fragmented and easily eroded, cinder cones usually do not remain as landforms for an extended period of time. All cinder cones currently on Earth originated within the last 1 to 2 million years; most are less than 150,000 years old. Sunset Crater in Arizona, Stromboli in the Mediterranean Sea, Parícutin in Mexico, and Cerro Negro in Nicaragua are all examples of cinder cones.

Lava dome

Lava domes, also called volcanic domes, form in the craters of volcanoes (mostly stratovolcanoes) after a major eruption. Highly viscous lava with little gas content oozes out of the volcano's vent like toothpaste out of a tube. The pasty lava is too thick to flow, and it solidifies on top of the vent, forming a rounded, steep-sided mound. The building of lava domes can be a forceful process, with small but violent explosions blasting out pieces of the dome. Fresh viscous lava flows then replace and build on the old material, causing the dome to take on a variety of strange shapes. Examples of lava domes include Mono Dome in California and Santiaguito Dome in Guatemala. After Mount St. Helens in the state of Washington erupted in May 1980, a lava dome began to form in its crater. Currently, the dome rises more than 900 feet (275 meters) above the crater floor.

Caldera

Below the vent in a volcano is a passageway called a pipe. The pipe leads down to the magma chamber, a large area where magma collects below Earth's surface. In some highly explosive eruptions, a great percentage or all of a volcano's magma chamber may be emptied. When this occurs, the roof of the magma chamber may be left unsupported. It may then collapse under its own weight, forming a large, usually circular, steep-walled basin known as a caldera (Spanish for cauldron or kettle) across the top of the volcano. Calderas have a diameter ranging from 1 to 15 miles (1.6 to 25 kilometers). Over time, rain and snowmelt may collect in a caldera, forming a lake. Lake Toba, in Sumatra, Indonesia, fills the world's largest caldera. It measures 18.6 miles (30 kilometers) wide and 62 miles (100 kilometers) long. The central part of Yellowstone National Park in Wyoming is a caldera measuring 28 miles (45 kilometers) by 47 miles (75 kilometers). A huge eruption 600,000 years ago created the depression at the heart of the park.

Lava plateau

In some eruptions, lava pours forth through fissures or long, narrow cracks in the ground instead of through a central vent in a volcano. This thin lava tends to spread out rapidly and widely, flooding the surrounding landscape. Repeated outpourings of lava eventually build up to create flat lava plains called lava plateaus. Lava plateaus are also known as flood basalts, after the dark, dense volcanic rock called basalt that floods across the surface of the land. Although erupted in thin sheets, the lava flows accumulate to form deposits thousands of feet thick.

The most famous example of a lava plateau in the United States is the Columbia Plateau, covering most of southern Washington from its border with Idaho west to the Pacific Ocean and extending south into Oregon. In places, it measures 5,000 feet (1,524 meters) thick. The Deccan Plateau of west-central India is much larger, covering some 300,000 square miles (770,000 square kilometers) and accumulating in spots to a thickness of 6,000 feet (1,829 meters). Larger still is the Siberian Traps in central Russia, which formed about 250 million years ago. It covers about 750,000 square miles (1,942,500 square kilometers). If the lava that poured forth

A Venutian Volcano on Earth?

The only active volcano in the East African Rift Valley in northern Tanzania, Ol Doinyo Lengai (pronounced ol DOYN-yo LEN-guy) rises 9,479 feet (2,890 meters). Its name means "Mountain of God" in the language of the Masai people who inhabit this region. What makes the strato-volcano so strange and interesting to volcanologists and other scientists is the lava it erupts.

While most of the world's volcanoes erupt silicate lavas, which are made up primarily of silicon and oxygen, Ol Doinyo Lengai erupts a lava rich in calcium and sodium. Volcanologists call this type of lava natrocarbonatite, and it is erupted from no other active volcano on Earth. At about 950°F (510°C), natrocarbonatite lava is approximately one-half as hot as normal lava. It is also the most fluid lava in the world. With a very low gas content, it has a very low viscosity and flows like water.

Since it is not as hot as normal lava, natrocarbonatite lava does not glow as brightly. In sunlight, lava flows from Ol Doinyo Lengai may be mistaken for dark brown or black mudflows. The dark lava quickly solidifies, then changes color to gray. When it comes in contact with moisture, the lava undergoes a chemical reaction that turns it white. This change may occur immediately if it is raining or may take several months in dry conditions. The reaction to moisture also softens the lava, so a person walking on it may sink in slightly.

Ol Doinyo Lengai is unique on Earth, but not in the solar system. Scientists have discovered through satellite photos that similar volcanic structures and lava flows exist on the planet Venus.

to create the Siberian Traps were spread out evenly across the entire planet, it would create a layer 10 feet (3 meters) thick.

Forces and changes: Construction and destruction

A volcanic eruption is among the most powerful forces on Earth. When Mount St. Helens in the state of Washington erupted in May 1980, the energy it released was equivalent to the largest hydrogen bomb ever exploded (a hydrogen bomb equals the power of one thousand atomic bombs). The eruption of the ancient volcano that produced Crater Lake in Oregon, one of the best-known calderas in the world, was forty-two times as powerful as that of Mount St. Helens. One hundred times more powerful was the 1815 eruption of the stratovolcano Tambora on the Indonesian island of Sumbawa. The ash cloud released by the volcano lowered global temperatures by as much as 5°F (3°C) from late spring to early autumn the following year. Subsequent crop failures produced widespread famine.

Ol Doinyo Lengai volcano, Tanzania. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Earth's interior

The power to change the shape both of a volcano and the landscape around it comes from miles beneath Earth's surface. The interior of the planet is divided into different layers of varying composition. The rocky outer layer that forms Earth's surface is the crust, which varies in thickness from 3 to 31 miles (5 to 50 kilometers). The crust is thickest below land and thinnest below the oceans. Underlying the crust is a thick layer of rocks (different from those composing the crust) known as the mantle. The mantle extends down roughly 1,800 miles (2,900 kilometers) beneath the planet's surface.

The uppermost section of the mantle is a rigid or firm layer. Combined with the overlying solid crust, it makes up the lithosphere (pronounced LITH-uh-sfeer; from the Greek word *lithos*, meaning "stone"). On average, the lithosphere measures about 60 miles (100 kilometers) thick. The part of the mantle immediately beneath the rigid, cold lithosphere is composed of partially melted rock that is pliable, like putty. This

Cultural Landforms

According to Navajo legend, on a towering landform in what is now northwestern New Mexico, a battle took place between a warrior and monster birds that had been terrorizing the ancestors of the Navajo people. Because the warrior was victorious, the Navajo were able to settle in this area around the landform they came to call Tsé Bit'a'i (pronounced say bid-ah-ih; meaning "rock with wings"). When European settlers arrived centuries later, they thought the landform the Navajo held sacred looked like a giant sailing ship, and so they called it Shiprock.

Shiprock is located in the four corners area of America's Southwest, the only spot where four states (Utah, Colorado, Arizona, and New Mexico) meet. An area of sandstone cliffs and rugged mountains, it is the traditional homeland of several Native American tribes. Shiprock sits in the middle of what volcanologists call the Navajo volcanic field. It is littered with the remains of dozens of extinct volcanoes that last erupted twenty-five to thirty million years ago.

Shiprock stands 1,969 feet (600 meters) above the surrounding plain and measures 1,640 feet (500 meters) in diameter at its greatest width. It is a spectacular example of a volcanic neck or plug. When a volcano stops erupting and becomes extinct, remaining magma and other volcanic material may harden in the volcano's pipe, the passageway between the magma chamber and the vent. Typically, this material tends to be more resistant to erosion than the enclosing volcanic landform. Thus, long after the volcano has eroded away, the volcanic neck stands out against the landscape as the fossil remains of a once great volcano.

Volcanologists estimate that the summit of the original volcano stood almost 1,000 feet (305 meters) above Shiprock's current height. Radiating out from the volcanic neck into the flat, eroded plain are six long, thin, wall-like structures, the ancient volcano's only other visible remains. These vertical structures, called dikes, were created when magma pushed up through cracks that formed in the rock layers beneath the volcano. The rock layers have long since eroded away, leaving the dikes above the surface. The dikes range in length from 0.6 to 5.5 miles (1 to 9 kilometers).

section, called the asthenosphere (pronounced as-THEN-uh-sfeer; from the Greek word *asthenes*, meaning "weak"), extends to a depth of about 155 miles (250 kilometers).

Beneath the mantle is Earth's core, which is composed of a solid inner portion and a liquid outer portion. Both layers of the core are made of the metal elements iron and nickel. Scientists believe temperatures in the core exceed 9,900°F (5,482°C). If the heat energy created by such high

Shiprock is an eroded volcano plume, or volcanic neck, that stands more than 1,900 feet from the desert plain in New Mexico. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

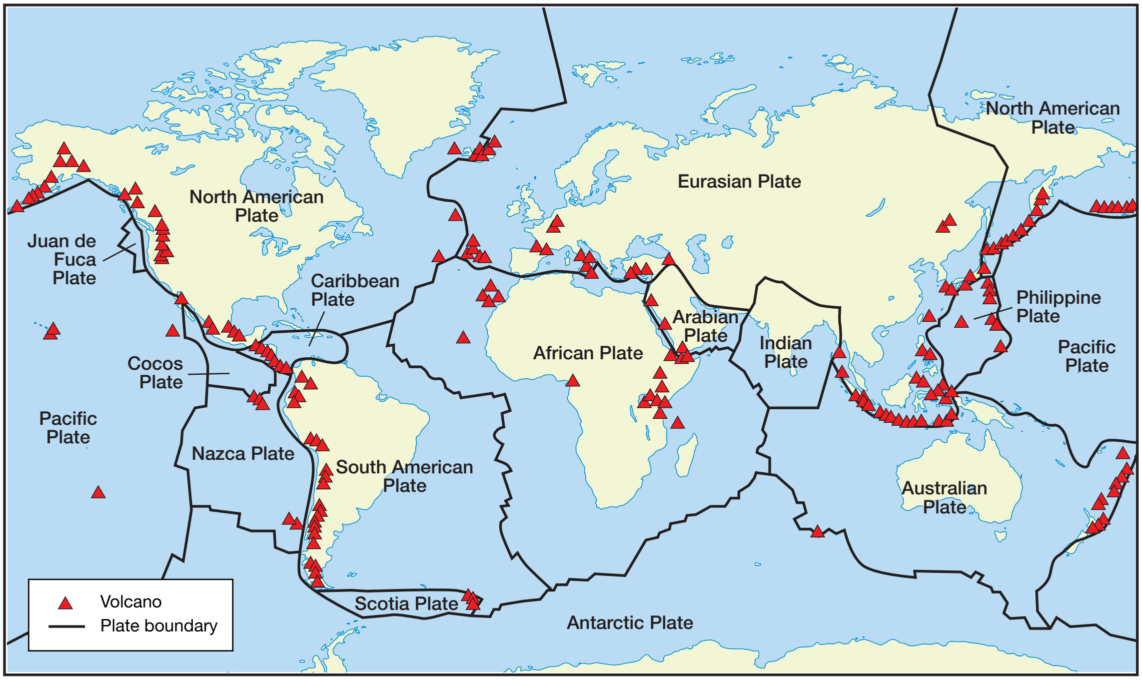
temperatures were not released, Earth would become so hot its entire interior would melt. This energy is carried to the surface of the planet by convection currents, the circular movement of molten material deep within Earth.

When a gas or liquid is heated, it expands and becomes less dense (or lighter). It then rises above cooler, denser gas or liquid that surrounds it. This action takes place in Earth's mantle. Under tremendous pressure and

Volcano Facts

- There are 224 volcanoes located in the continental United States and Alaska. About half of them are located in Alaska alone.
- The ash cloud from a volcanic eruption can produce lightning. Collisions between the rapidly moving ash particles produce electric charges, which build up until they discharge to form a lightning bolt.
- The most active volcano in the United States is Kilauea (pronounced kee-low-AY-ah) on the island of Hawaii. Kilauea has been erupting nearly continuously since 1983.
- Stromboli, one of the Aeolian Islands of Italy, has been erupting almost continuously with relatively small explosions and occasional bigger explosions and lava flows for the last 2,000 years.
- The first volcanic eruption ever to be described in detail was that of Mount Vesuvius, which erupted in 79 C.E. and buried the Roman cities of Pompeii and Herculaneum. Pliny the Younger, who witnessed the eruption from a distance of 18 miles (29 kilometers), wrote down his observations afterward.
- Volcanologists estimate that fifteen to twenty volcanoes are erupting around the world at any given moment.
- The 1883 eruption of Krakatau in Indonesia created a tsunami (pronounced tsoo-NAH-mee; a series of great ocean waves caused by a large displacement of water) greater than 115 feet (35 meters) in height that drowned an estimated 36,000 people. The volcanic explosion was heard almost 3,000 miles (4,827 kilometers) away.
- The most common elements in materials erupted by volcanoes are silicon, oxygen, magnesium, iron, aluminum, calcium, sodium, potassium, titanium, phosphorous, carbon, hydrogen, and sulfur.
- The fastest recorded speed of a lava flow was about 37 miles (60 kilometers) per hour at Nyiragongo volcano in Zaire.
- The temperature of basalt, the hottest type of lava, can reach almost 2,150°F (1,200°C).

high temperature, mantle rock near the core heats up and expands. This makes it less dense and more buoyant, and it slowly rises to the surface. Near the surface, the hot rock moves sideways along the underside of the lithosphere, losing its heat. As it cools, the rock becomes denser, or heavier, and sinks back toward the core, only to be heated once again. This continuous motion of heated material rising, cooling, and sinking within Earth's mantle forms circular currents: convection currents. The time involved for heated rocks to rise from the lower mantle to the surface, cool, and return to the interior is estimated to be around 200 million years.



Map of the active volcanoes around the world. Notice how the majority of volcanoes exist along the plate margins.

Plate tectonics

The slowly moving convection currents are able to release their heat energy near the surface of the planet because both Earth's interior and its surface are in motion. Earth's lithosphere is not solid, but is broken into many large slabs or plates that "float" on the hot, soft asthenosphere. There are seven large plates, eight medium-sized plates, and a number of smaller ones. These plates are in constant contact with each other, fitting together like a jigsaw puzzle. When one plate moves, it causes other plates to move. The movement of the plates toward or away from each other is in response to the pressure exerted by the convection currents. Scientists used the word tectonics (from the Greek word *tekton*, meaning "builder") to describe the movements. The scientific theory explaining the plates and their movements and interactions is known as plate tectonics.

The major geologic features of Earth, from volcanoes to mountains to basins to oceanic trenches, are all the result of plate movement. Plates move at rates from about 1 to 6 inches (2.5 to 15 centimeters) per year. The plates interact with each other in one of three ways: they move toward each other (converge), they move away from each other (diverge), or they slide past each other (transform). The boundaries where plates meet and interact are known as plate margins.

Walking in the Footsteps of Giants

It is called the Giant's Causeway: a mass of closely packed lava columns whose tops seem to form stepping stones that lead from a cliff along the coast of Northern Ireland and disappear under the North Channel. There are approximately forty thousand of these columns, most of which are roughly hexagonal (six-sided) in shape. The rest have between four and eight sides. The tallest columns stand 40 feet (12 meters) high, and the hardened lava in the cliff is 90 feet (27 meters) thick in places.

A causeway is a raised path or road over water or across land that is sometimes covered by water. The ancient Irish believed that a giant created this landform for such a purpose. According to legend, Finn MacCool (Fionn mac Cumhail is the Gaelic spelling of his name) was a warrior and commander of the armies of the kingdom of Ireland. One day, his fighting abilities were questioned by Benendoner, a Scottish giant. MacCool then challenged the giant, but Benendoner could not swim and so was not able to come to Ireland to answer the challenge. Enraged, MacCool used his sword to cut sections from the cliff, which he then threw into the channel between Ireland and Scotland to create the causeway so the two giants could meet to settle their dispute.

Scientists have known since the late eighteenth century that lava flows formed the strange columns, but the cause behind their regular geometric shape remained a mystery until the twentieth century. Scientists now know that the volcanic rock in the area is made of basalt, which flowed smoothly out of fissures or cracks in Earth's surface about sixty million years ago. As basalt cools, it shrinks. The basalt that formed the causeway, however, did not cool slowly and shrink evenly. Scientists believe water most likely may have washed over it, accelerating its cooling. As the basalt cooled rapidly, randomly scattered areas across its surface cooled before other areas. The stress of the rapid cooling and uneven shrinking would have caused cracks to form along the surface and continue downward, much in the same way that mud dries in a puddle of water that has evaporated.

There are three types of convergent plate margins or areas where two plates move toward each other: continental-continental, continental-oceanic, and oceanic-oceanic. When two continental (land) plates converge, they crumple up and compress, forming complex mountain ranges of great height. The rocks making up oceanic crust are denser (heavier) than those making up continental crust. So when an oceanic plate converges with another plate, either continental or oceanic, it slides beneath the other. The region where this occurs is

The basalt columns of Giant's Causeway on the coast of Northern Ireland. Scientists believe the strange formation was created when an ancient lava flow quickly cooled and solidified. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

known as the subduction zone, and this is where most of the world's explosive volcanoes form.

When an oceanic plate subducts, or sinks, beneath a continental plate, the leading edge of the oceanic plate is pushed farther and farther beneath the continent's surface. When it reaches about 70 miles (112 kilometers) into the mantle, high temperature and pressure melt the rock at the edge of the plate, forming thick, flowing magma. Since magma is less dense than the rock that typically surrounds it deep underground, the magma tends to rise toward Earth's surface. Driven by pressure created by gas bubbles within it, the magma forces its way through weakened layers of rock to collect in underground reservoirs called magma chambers.

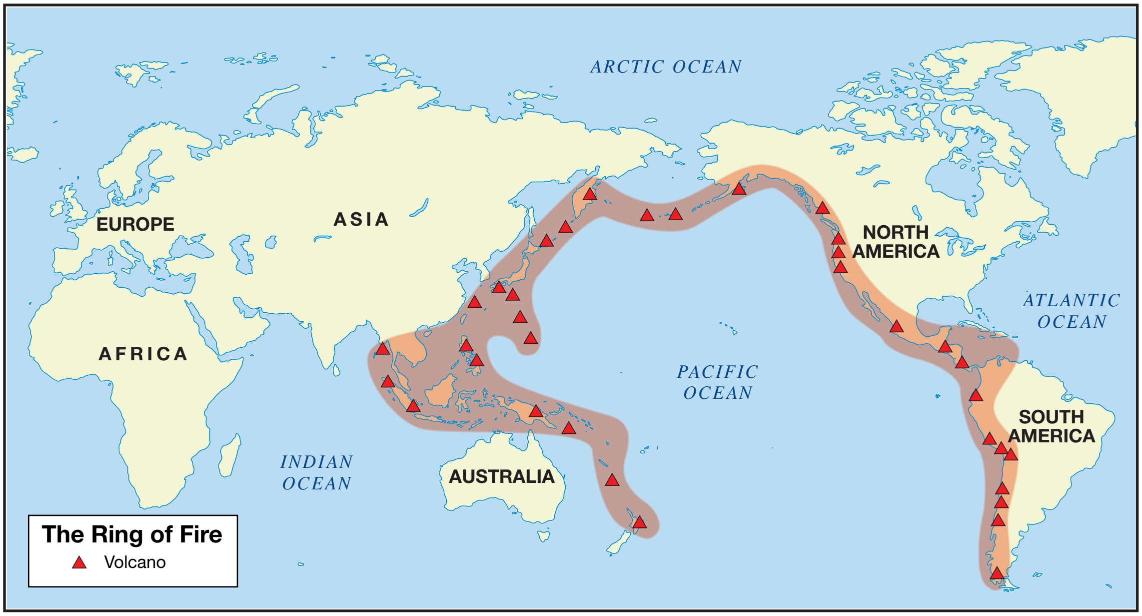
As magma rises through the mantle to Earth's surface, the surrounding pressure on it decreases, allowing the magma to expand. As more and more magma collects in a magma chamber, pressure from the expanding magma increases until it exceeds that of the overlying rock. An explosion then occurs, and the magma is forced out of the chamber upward through cracks or vents in the planet's surface. The severity of the explosion is dependent on the composition of the magma. If it has a low viscosity, its gases can escape rapidly, and it flows rather than exploding. If it has a high viscosity, its gases cannot escape as quickly. Pressure builds until the gases escape violently in an explosion.

Ring of Fire

Volcanoes are not scattered widely across the surface of Earth. Most are concentrated on the edges of continents, along island chains, or beneath the sea forming long mountain ranges. A majority of the world's active volcanoes above sea level are located in a geographic belt called the Ring of Fire. This belt encompasses the lands on the edges of the Pacific Ocean. It also marks the boundary where the Pacific Plate subducts beneath the plates surrounding it. The Ring of Fire follows the west coast of the Americas from Chile to Alaska. It runs through the Andes Mountains, Central America, Mexico, California, the Cascade Mountains, and the Aleutian Islands. It continues down the east coast of Asia from Siberia to New Zealand, through Kamchatka, the Kurile Islands, Japan, the Philippines, Celebes, New Guinea, the Solomon Islands, and New Caledonia.

Since a vast percentage of all magma reaching Earth's surface does so under the oceans, most of the planet's volcanoes are located there. Some protrude above the water as islands; others lie entirely beneath the surface. Most form along mid-ocean ridges, which are long, narrow structures where oceanic plates are diverging or moving apart and magma rises to fill the gap. The Mid-Atlantic Ridge, where the North and South American plates are diverging from the Eurasian and African plates, is a submerged mountain range with many volcanic features. The volcanic-rich island of Iceland lies directly over the Mid-Atlantic Ridge. (For further information on oceanic landforms, see the **Ocean basin** chapter.)

Hot spots are special areas where volcanoes form apart from plates converging or diverging, such as in the middle of the Pacific Ocean. At these places, magma rises from the mantle and erupts through Earth's crust



A majority of the world's active volcanoes above sea level are located in a geographic belt called the Ring of Fire.

to form a volcano. Volcanologists believe these plumes of magma can exist for millions of years. A famous example of hot spot volcanoes is the string of Hawaiian islands. These islands form a chain of volcanoes because the magma plume that created them has remained stationary while the Pacific plate has shifted. As the plate moved slowly over millions of years, each volcano was cut off from its magma source and a new one formed in its place over the hot spot. The northwesternmost island in the Hawaiian chain contains the oldest rocks and is volcanically extinct; the island of Hawaii, the southeasternmost in the chain, contains the youngest rocks and is the most volcanically active of all the islands. Volcanologists believe it sits directly over the hot spot. More than one hundred hot spots have been active around the planet during the last ten million years, creating some of the world's largest volcanoes, including the present-day Hawaiian volcanoes Mauna Loa and Kilauea.

Spotlight on famous forms

Mauna Loa, Hawaii

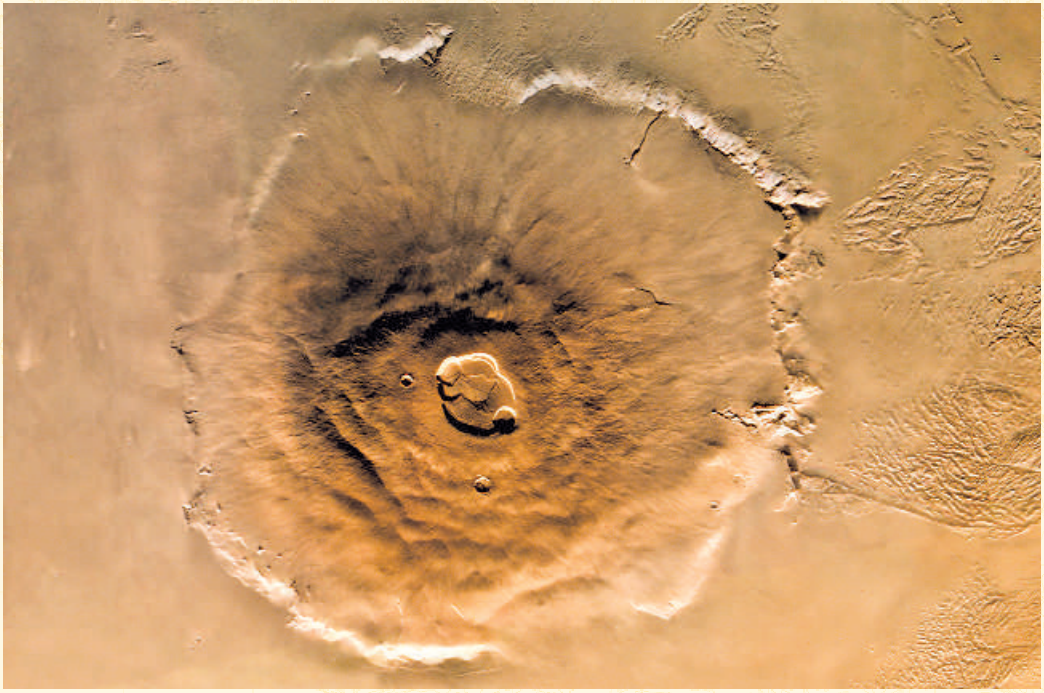
Mauna Loa, a very broad, flat shield volcano on the island of Hawaii, is the world's largest volcano and one of the most active. It rises 13,680 feet (4,170 meters) above sea level, and it extends more than 18,000 feet (5,544 meters) to the floor of the Pacific Ocean. From its base under the ocean to its summit, Mauna Loa measures about 32,000 feet (9,754 meters), which makes it taller than Mount Everest in the Himalayas, the

Largest Volcano in the Solar System

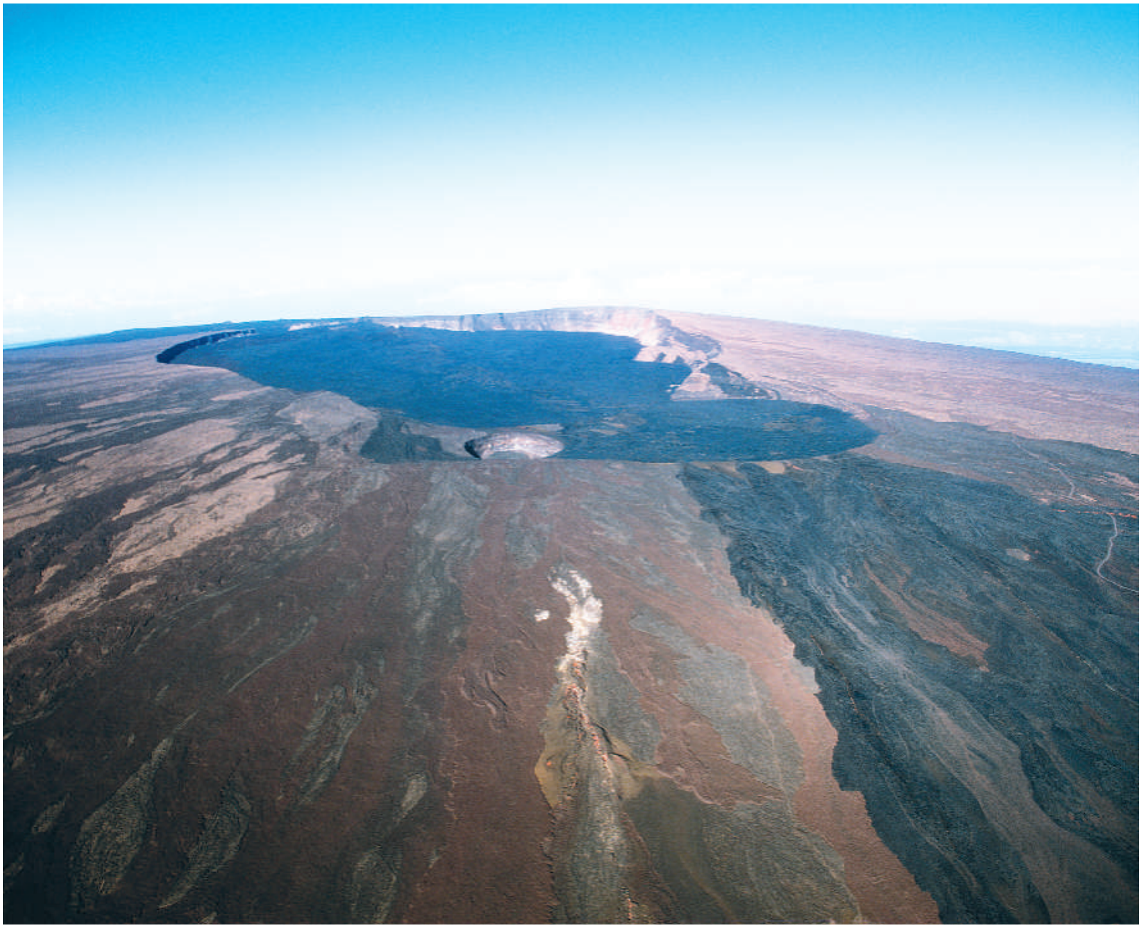
Olympus Mons on Mars is the largest of all known volcanoes in the solar system. It is a shield volcano that stands 16 miles (26 kilometers) high and measures 388 miles (624 kilometers) in diameter. A 4-mile-high (6-kilometer-high) scarp, or steep cliff, rims its outer edge. A caldera 50 miles (80 kilometers) wide is located at its summit. If Olympus Mons were placed on the face of Earth, it would cover an area the size of the state of Arizona.

Scientists believe Olympus Mons and other volcanoes on Mars were able to become extremely large because of two main reasons: First, there is less gravity on Mars, which allowed the volcanoes to grow without collapsing under their own weight. Second, the crust on Mars does not move as it does on Earth. This allowed lava to pile up in one large volcano instead of being distributed in an arc of volcanoes, such as the Hawaiian Islands on Earth.

Olympus Mons and all other volcanoes on Mars are extinct. Scientists estimate the youngest lava flows on the gigantic volcano are 20 to 200 million years old.



Olympus Mons, a volcano on the planet Mars. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.



world's tallest mountain on land. The volcano, whose name means "Long Mountain" in Hawaiian, makes up just more than 50 percent of the island of Hawaii. Mauna Loa encompasses an area of about 2,035 square miles (5,271 square kilometers).

Mauna Loa, located on the island of Hawaii, is the world's largest and most active volcano. Rising 13,680 feet above sea level, the flat shield volcano encompasses an area of about 2,035 square miles, or nearly 50 percent of the entire island. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

Thousands of thin flows of lava have built the volcano over hundreds of thousands of years. It currently has a volume of approximately 9,600 cubic miles (40,000 cubic kilometers). Since its first documented historical eruption in 1834, Mauna Loa has erupted thirty-three times. Its most recent eruption occurred in the spring of 1984. The lava flows it has produced in the past two centuries have covered 310 square miles (803 square kilometer).

At Mauna Loa's summit is a caldera named Mokuaweoweo (pronounced MO-koo-AH-WAI-o-WAI-o; translated literally as "fish section"). It measures 3 miles (5 kilometers) long, 1.5 miles (2.4 kilometers) wide, and 600 feet (183 meters) deep. Volcanologists believe the caldera formed 600 to 700 years ago when the volcano's magma chamber collapsed after an eruption.

Mount Cotopaxi, Ecuador

The world's highest active volcano, Mount Cotopaxi, rises 19,388 feet (5,909 meters) above the surrounding highland plain in central Ecuador. A stratovolcano with an almost perfectly symmetrical cone, Mount Cotopaxi is covered in glaciers above 14,930 feet (4,550 meters). Deep valleys are cut into its steep sides, radiating downward from its summit. The crater at its summit measures 2,625 feet (800 meters) by 2,133 feet (650 meters).

Cotopaxi, which in the local Quechua (pronounced KECH-wa) language means "neck of the Moon," has a well-recorded history of explosive eruptions. In 1534, when an invading Spanish army began an attack against the native Incas, the battle was cut short by a massive eruption. Since then, Mount Cotopaxi has erupted more than fifty times, most recently in 1904. An eruption in 1877 melted snow and ice from the summit, producing mudflows (thick mixtures of mud, water, and other surface fragments) that traveled more than 60 miles (100 kilometers) from the volcano.

Mount St. Helens, Washington

Located in southwestern Washington, Mount St. Helens is a relatively young stratovolcano, approximately forty thousand years old. Before its spectacular eruption in May of 1980, it had lain dormant since 1857. Native Americans in the area surrounding the volcano called it Louwala-Clough, meaning "smoking mountain." In the past five centuries, the volcano has produced four major eruptions and dozens of lesser ones. It is the most active volcano in the Cascade Range, a mountain chain that extends about 700 miles (1,125 kilometers) from British Columbia, Canada, to northern California.

Prior to May 18, 1980, Mount St. Helens rose to a height of 9,677 feet (2,950 meters). The fifth-tallest mountain in Washington, it had a nearly perfect cone shape, and its summit glistened in a perpetual cap of snow and ice. When the volcano exploded on that May morning in a continuous nine-hour eruption, it lost its uppermost 1,300 feet (396 meters). A massive earthquake under Mount St. Helens caused its north flank to slide away in the largest landslide in recorded history. This landslide triggered a destructive, lethal sideways blast of hot gas, steam, and rock debris that swept across the landscape as fast as 680 miles (1,095 kilometers) per hour. Within minutes of the blast, an ash plume from the destroyed crater rose 15 miles (24 kilometers) into the sky.

Eruption of Mount St. Helens volcano, 1980. The volcano, located in the state of Washington, rose to a height of 9,677 feet and was a perfect cone shape before the eruption. The explosion caused the breaking away of the uppermost 1,300 feet, and resulted in the largest landslide in recorded history. **PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.**

After the eruption, Mount St. Helens's summit stood only 8,364 feet (2,549 meters) above the destroyed landscape surrounding it—about 0.67 cubic miles (2.75 cubic kilometers) of material had been removed from the volcano. Its new horseshoe-shaped crater measured 1.2 miles (1.9 kilometers) by 1.8 miles (2.9 kilometers), and the crater floor was 2,084 feet (635 meters) deep. Within months after the main eruption, small eruptions produced thick lava that formed a lava dome in the crater. Over the next six years, subsequent eruptions generated viscous lava that added layer upon layer to the dome. At the beginning of the twenty-first century, the lava dome towered more than 900 feet (275 meters) above the crater floor.

Crater Lake, Oregon

Measuring 5 miles (8 kilometers) in diameter, Crater Lake has a surface area of 20.6 square miles (53.4 square kilometers). It is enclosed by steep rock walls that rise up almost 2,000 feet (610 meters) above its surface. With a depth of 1,943 feet (592 meters), Crater Lake is the deepest lake in the United States and the seventh-deepest in the world. No springs or other inlets feed the lake. The water that evaporates or seeps out of the lake is replaced mostly by winter snows, which average 44 feet (13.5 meters) a year.

Crater Lake in southern Oregon is the best-known caldera in the United States. The lake measures 5 miles in diameter and has a surface area of 20.6 square miles. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

Crater Lake occupies the remains of Mount Mazama, the name given by volcanologists to this ancient cluster of overlapping stratovolcanoes that originally stood at about 12,000 feet (3,658 meters). The caldera formed when Mazama exploded violently 7,700 years ago. The eruption spewed about 18 cubic miles (75 cubic kilometers) of pyroclastic material onto thousands of square miles of surrounding landscape and caused the volcano's magma chamber to collapse. Minor eruptions afterward built a cinder cone on the floor of the caldera. Now known as Wizard Island, the cone rises 764 feet (233 meters) above the surface of the lake on its west side.

After forming, the caldera gradually filled with more than 5 trillion gallons (19 trillion liters) of water from rainfall and melting snow. The deep blue color of the lake is due to its great depth, the clarity of its water, and the way light interacts with water. Sunlight (white light) is made up of all the colors in the spectrum: red, orange, yellow, green, blue, indigo, and violet. Red light has the longest wavelength, violet the shortest. Just as a prism splits sunlight into different bands of color, so does water. As sunlight enters water, the water molecules easily absorb the longer wavelengths of light (reds, oranges, and yellows). The shorter wavelengths are more easily scattered than absorbed. Because of the depth of Crater Lake, all of the longer wavelengths of light are absorbed. Since the lake's water is so clear, the shorter wavelengths of blue and violet are able to penetrate much farther down before being scattered and redirected toward the surface. This creates what the human eye sees as an intense blue color.

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