U·X·L

ENCYCLOPEDIA OF LANDFORMS AND OTHER GEOLOGIC FEATURES

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1

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

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
		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.

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 exrraterrestrial 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, conrinuous 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.

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 exisring 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 theit 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 vettical 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.

Basin

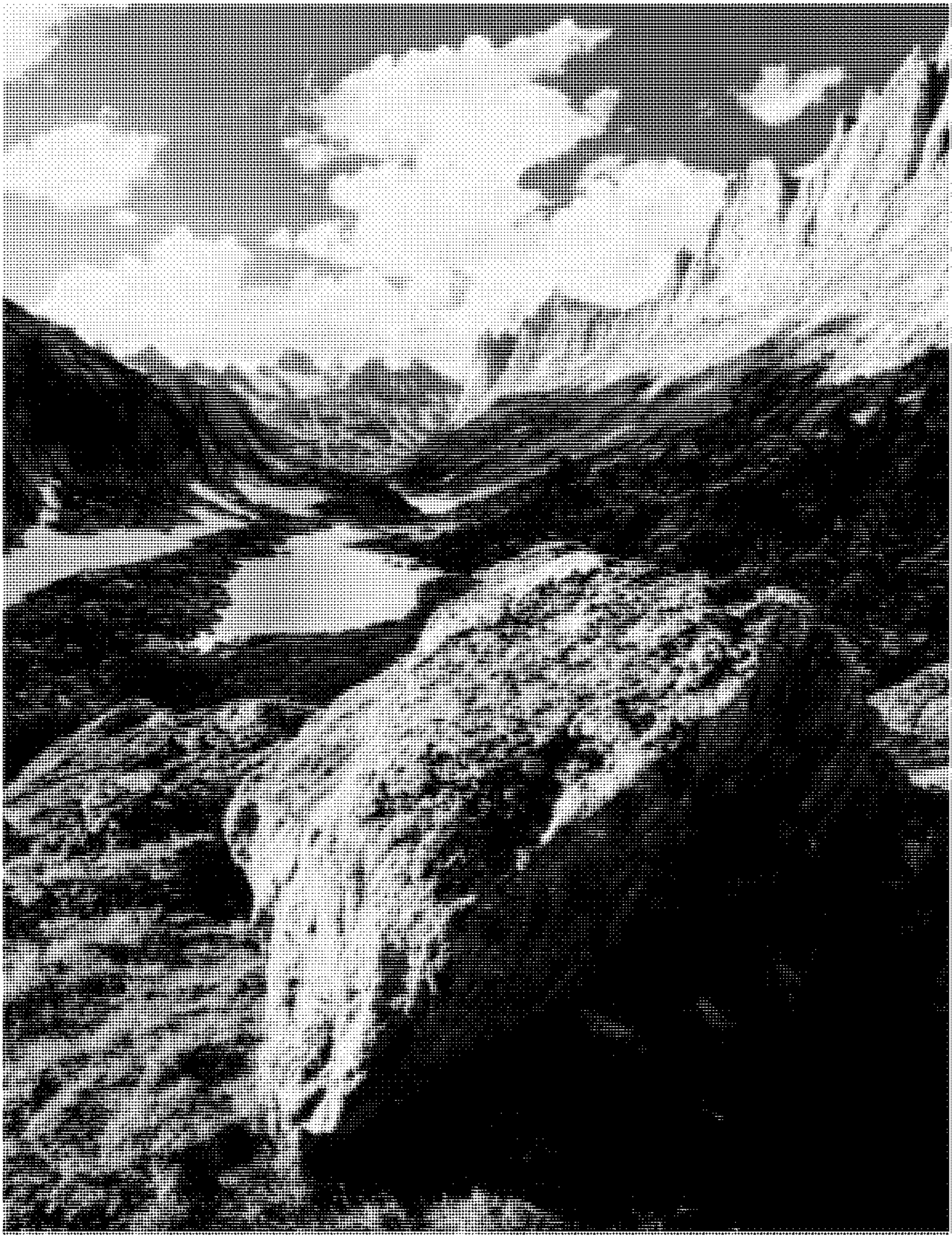
Throughout Earth's 4.5-billion-year history, the heat at its core has rearranged the surface over and over. The crust, the surface layer of the planet, has been compressed, pulled apart, raised, and lowered. The force of these various movements has fractured the crust, breaking it into sections. The 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.

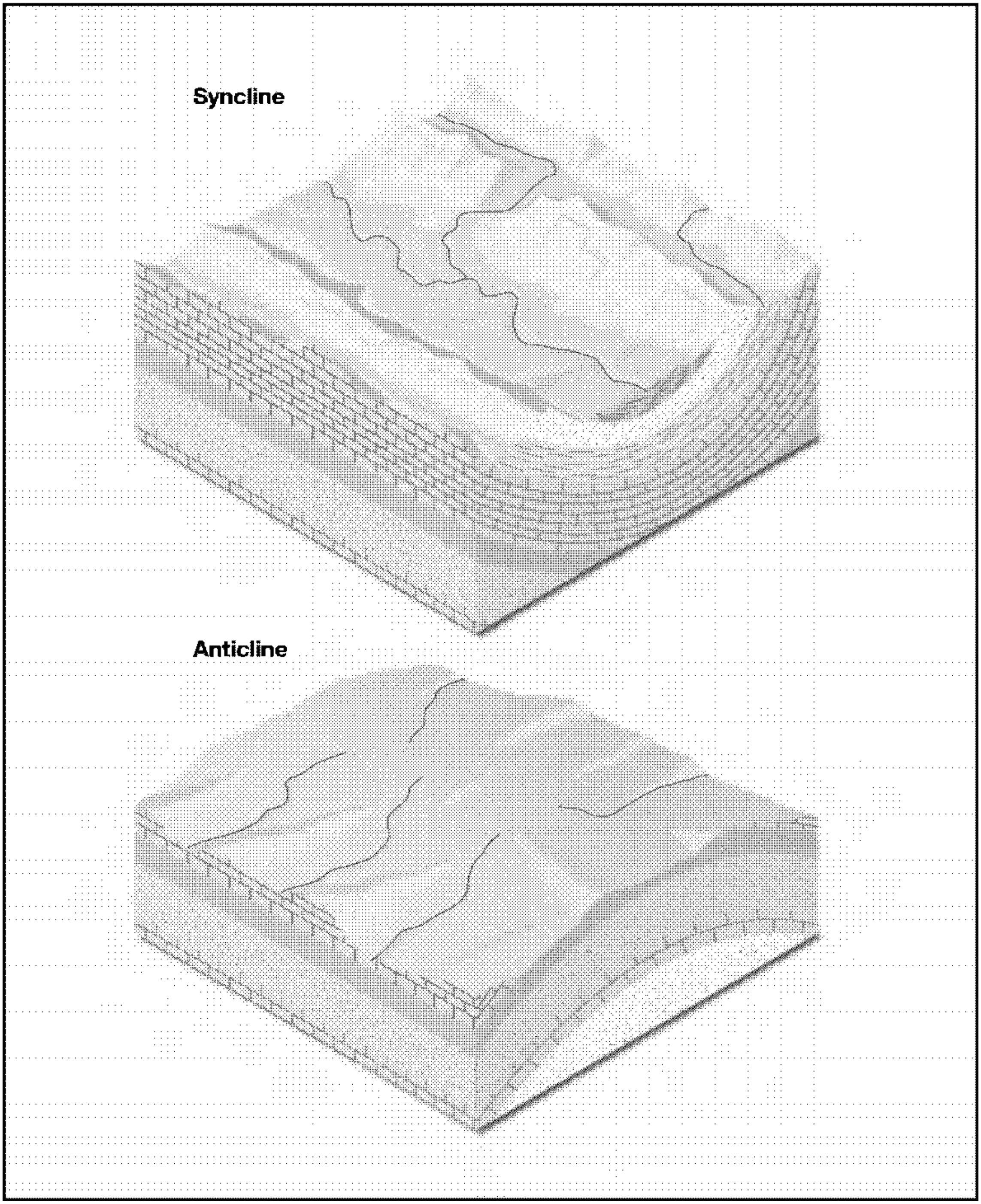
Stress: The force acting on an object (per unit of area).

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.

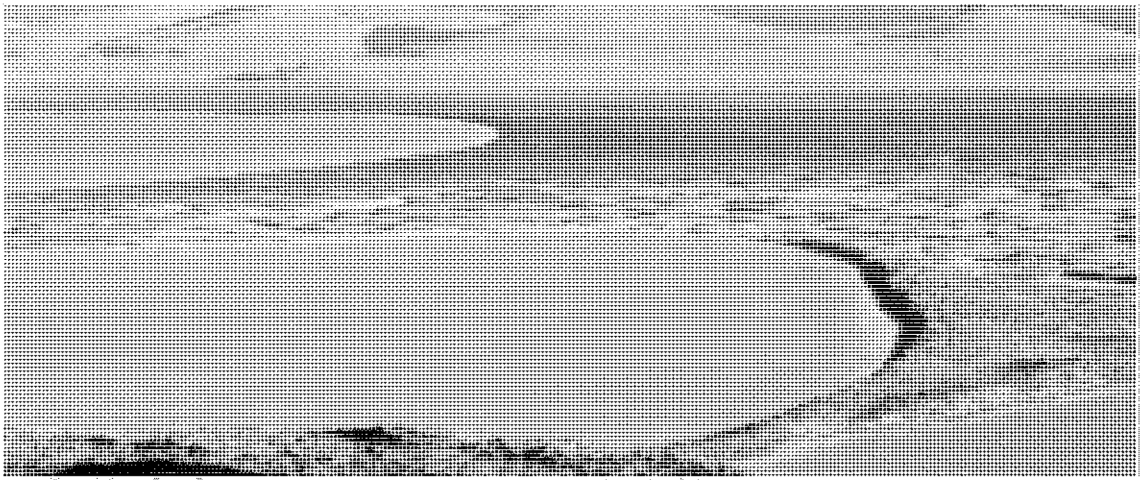
A basin created by folding is a large, synclinelike fold in which all sides dip toward the center. Basins formed in this manner are subject to the dueling forces of plate tectonics and erosion. Once formed, the basin will fill with sediment carried down into it by water that washes over its sides.

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.

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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. Insread, 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 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.

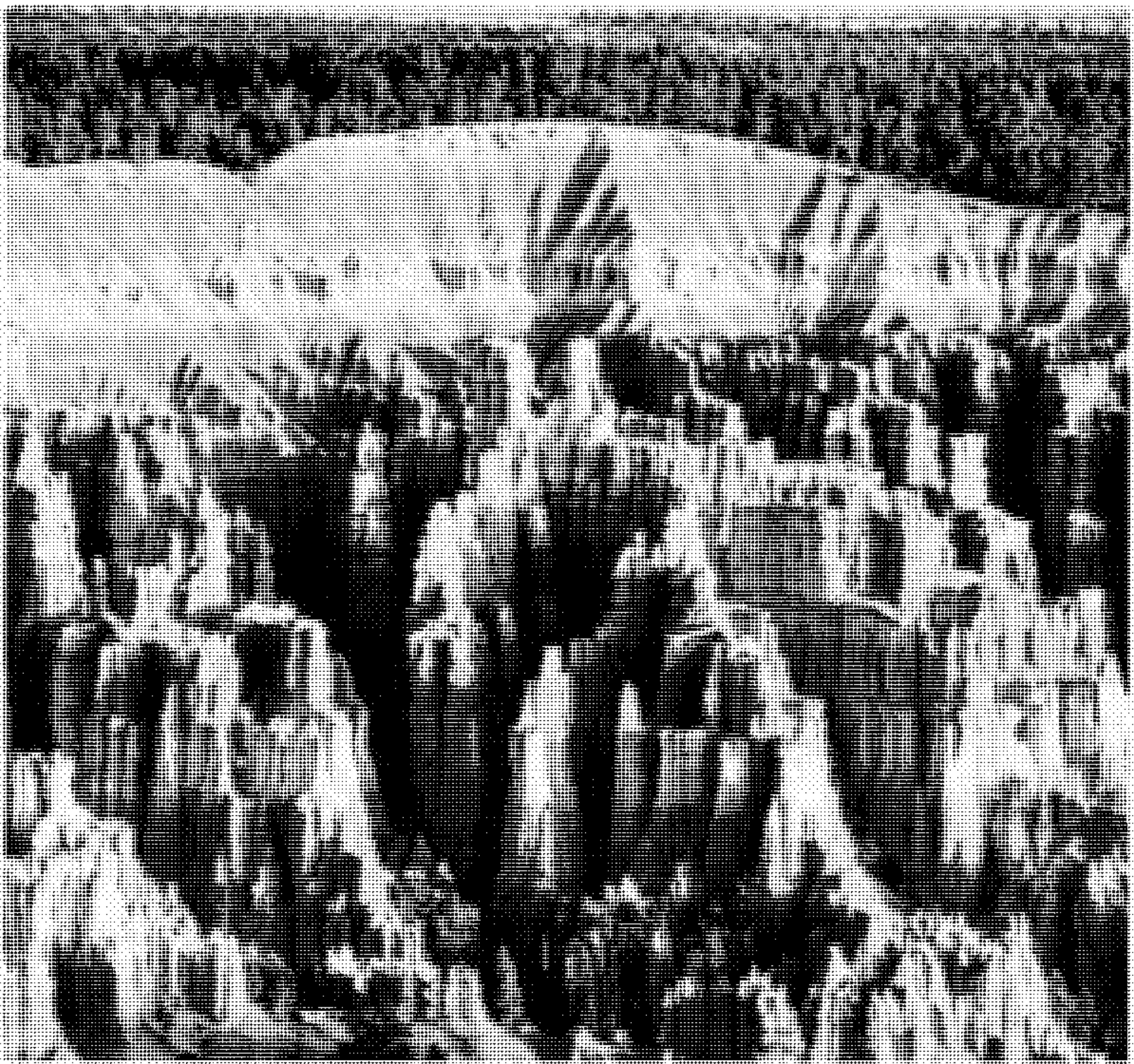
The walls of V-shaped canyons, especially those located in arid environments, are further eroded by rain and ice. In areas where there is little plant cover, dry soil and rock fragments are carried away easily as rain washes over the canyon walls into the river below. When water seeps into cracks between 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

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 Solitoire*, 1968.**



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.

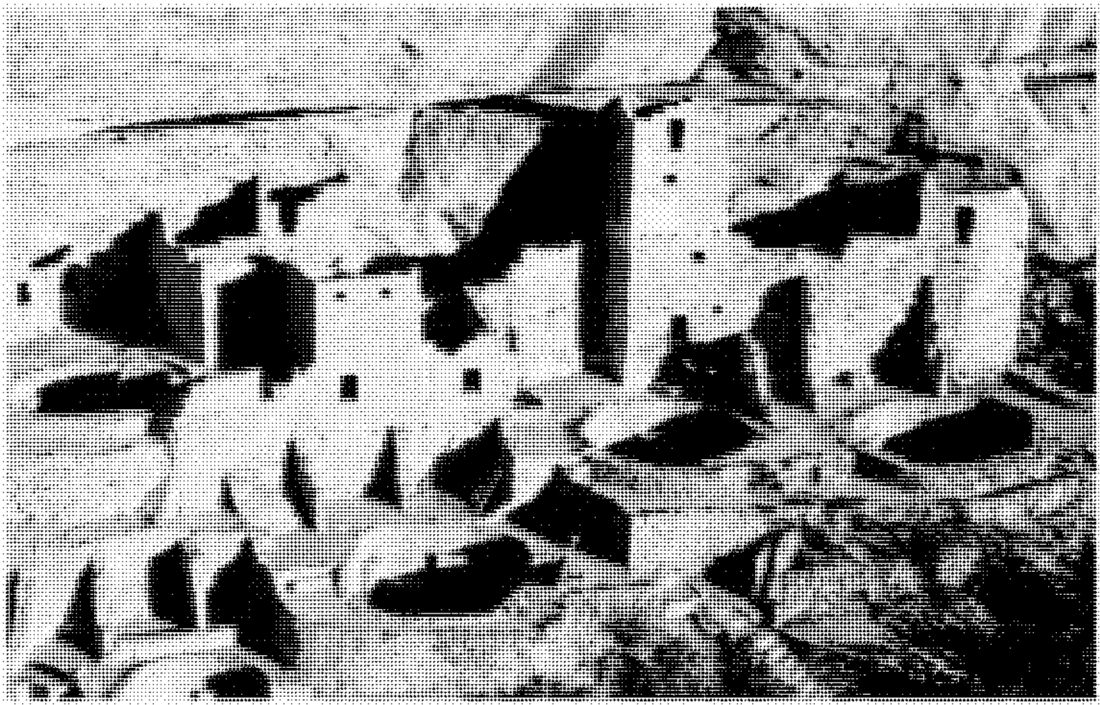
From about 350 to 1300, the canyon served as a home for the Anasazi. These people, thought to be the ancestors of the modern Pueblo, constructed spectacular dwellings both on the canyon floor and high up the walls on ledges between the sandstone layers. Several hundred different ruins are located in 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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3

Cave

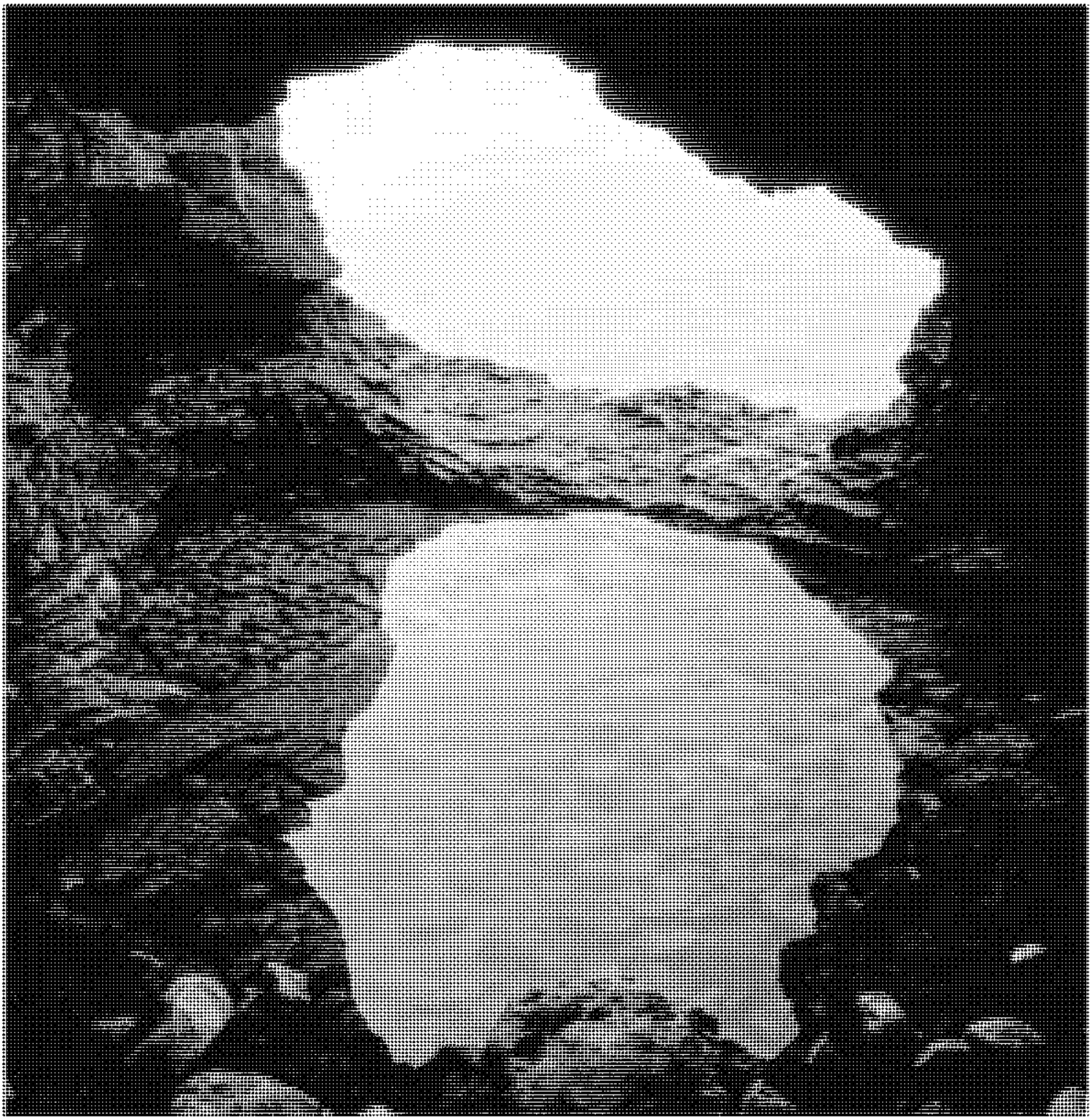
They are beautiful and sometimes otherworldly. Existing beneath the surface of the planet, caves have attracted humans for hundreds of thousands of years. Considered by some cultures as sacred, caves have been used in rituals and ceremonies. They have served both as shelter and burial tombs. The human 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.

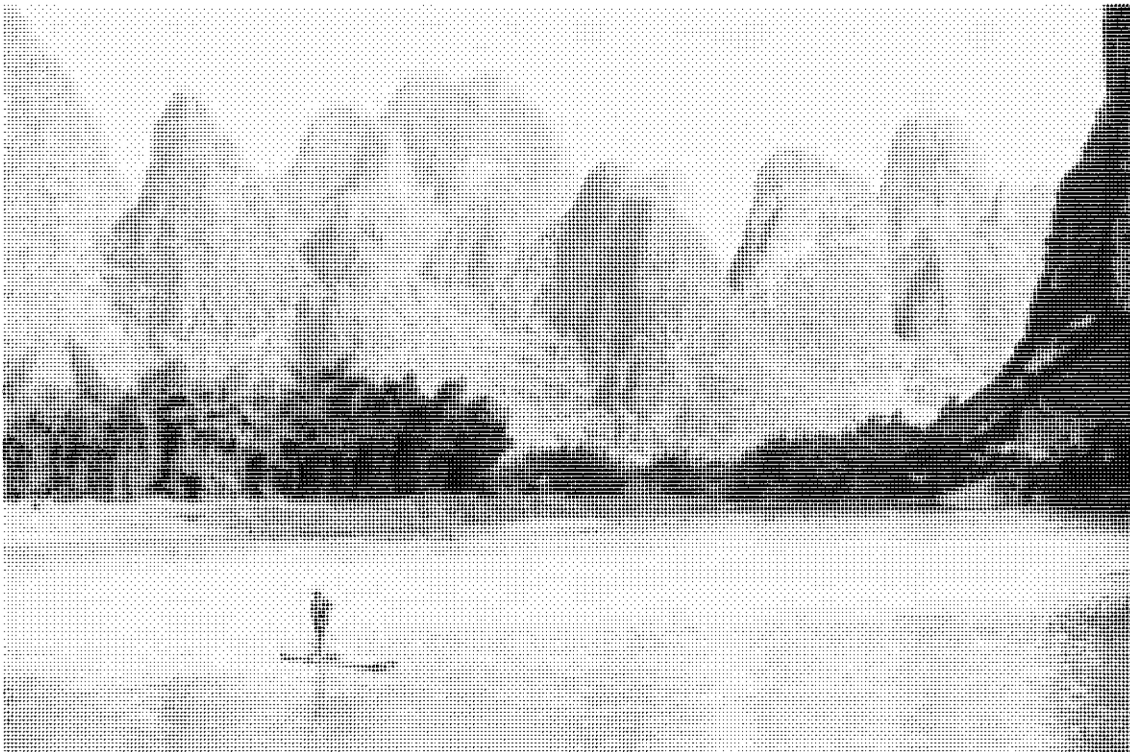
lava tube caves, glacier caves, sea caves, and other caves are obvious, those that form solution caves—the most common caves of all—are not. Solution caves are not formed by volcanic activity or by the abrasive forces of water or wind. The primary force behind their formation is chemical weathering,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

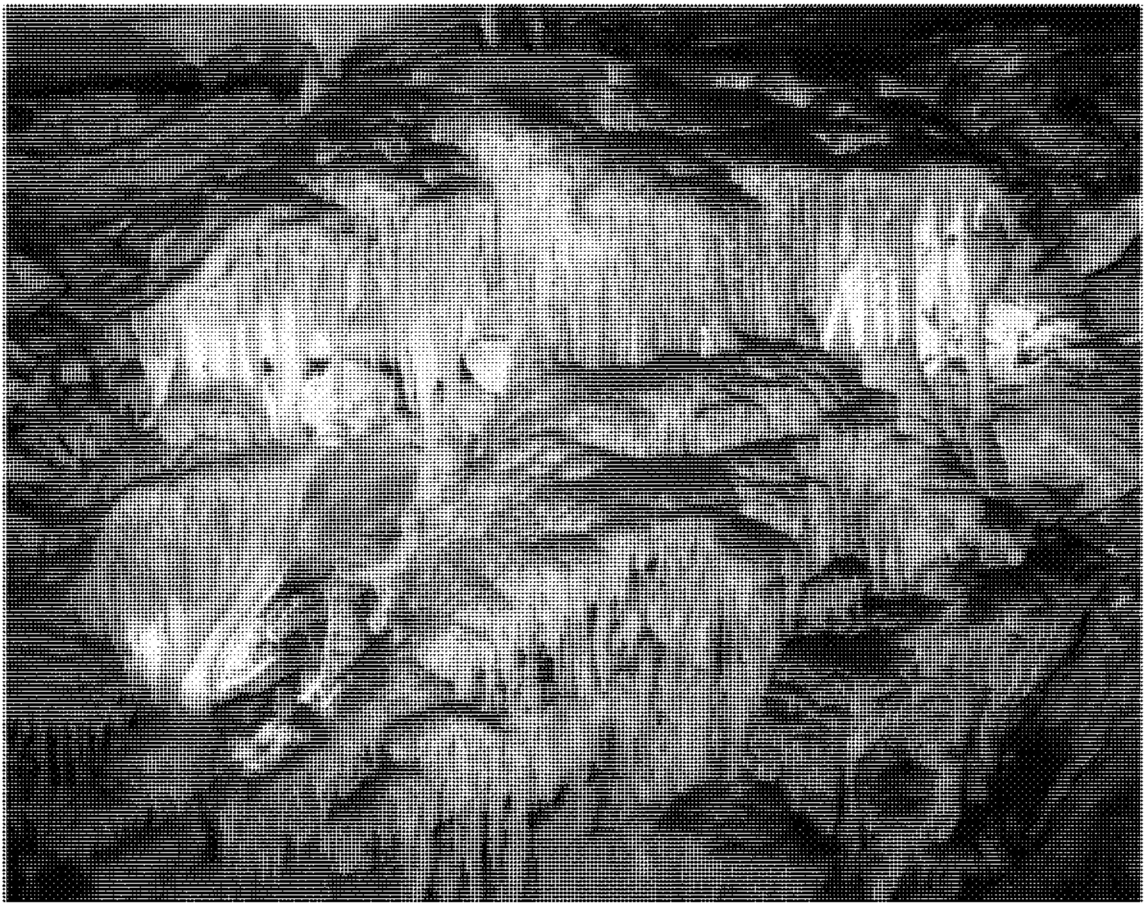
In addition to unusual speleothems, Lechuguilla contains rare bacteria that feed on the sulfur, iron, and manganese minerals present in the cave. Scientists believe these bacteria may have played a part in the formation of the cave and its speleothems. They also believe the sulfur-laden environment of 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 exttaordinary 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

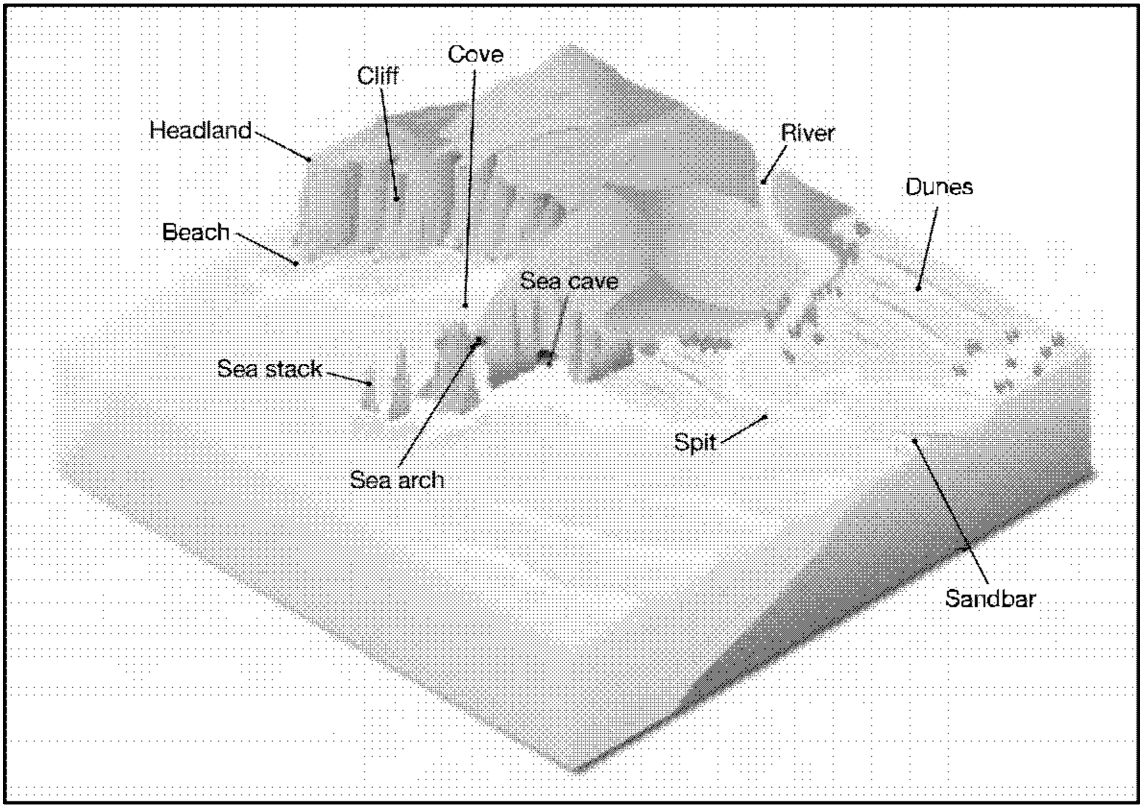
"At the foot of this cliff a great ocean beach runs north and south unbroken, mile lengthening into mile. Solitary and elemental, unsullied and remote, visited and possessed by the outer sea, these sands might be the end or the beginning of a world. Age by age, the sea here gives battle to the land; 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

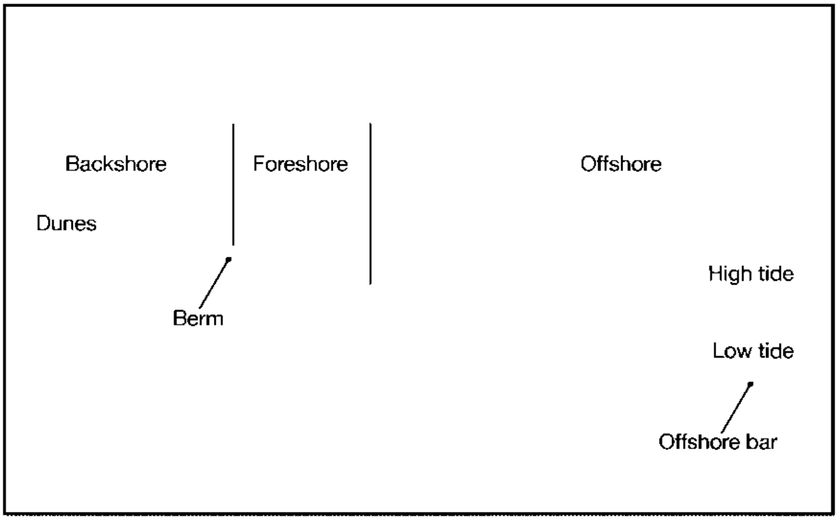


Coastal features and landforms of both emergent and submergent coasts.

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 supporr 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.

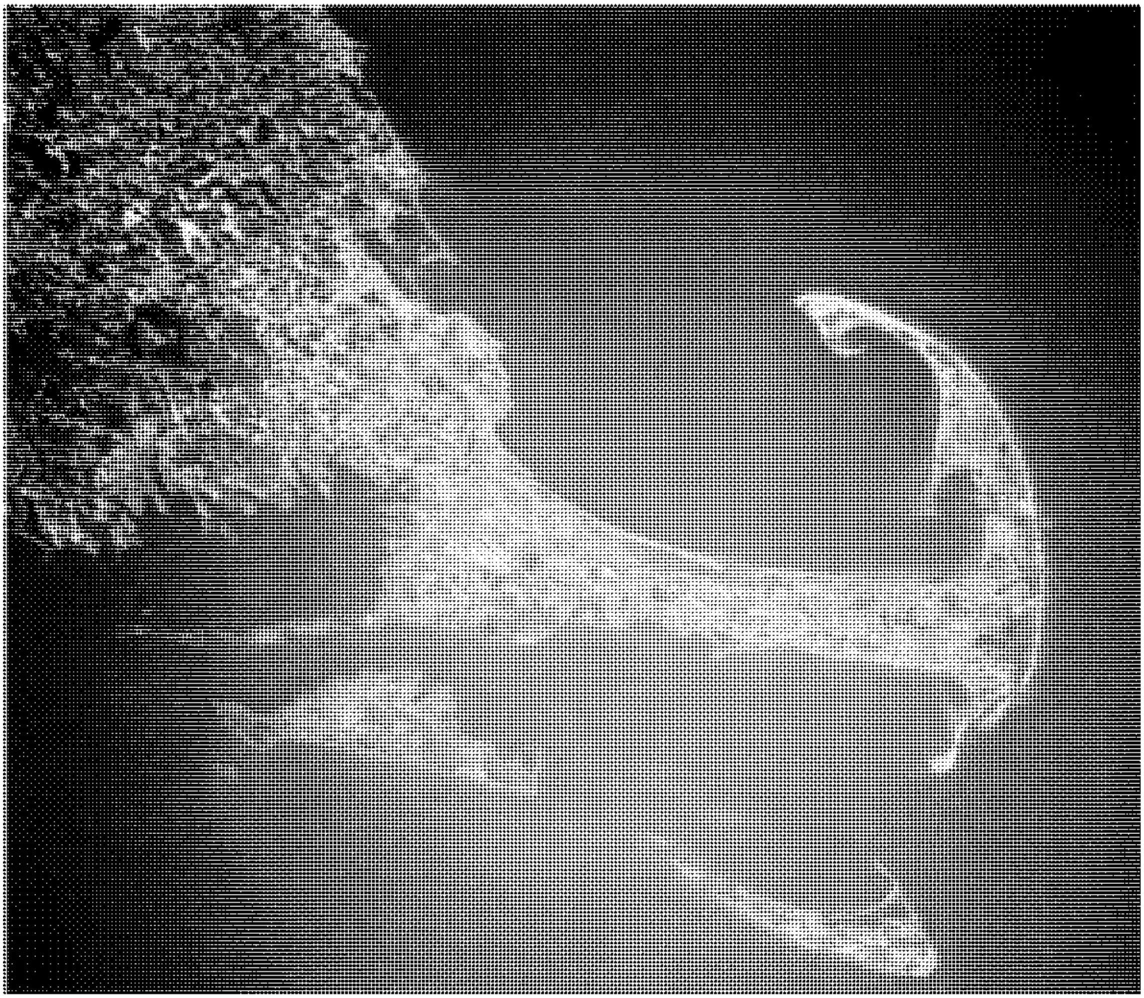
Although they do not change as quickly, rocky coasts will eventually change. An irregular coastline of headlands and bays will be straightened by erosion. Wave action will cut away at headlands, quickly break up rock debris and other material, then deposit it along the shoreline of the bay.

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.

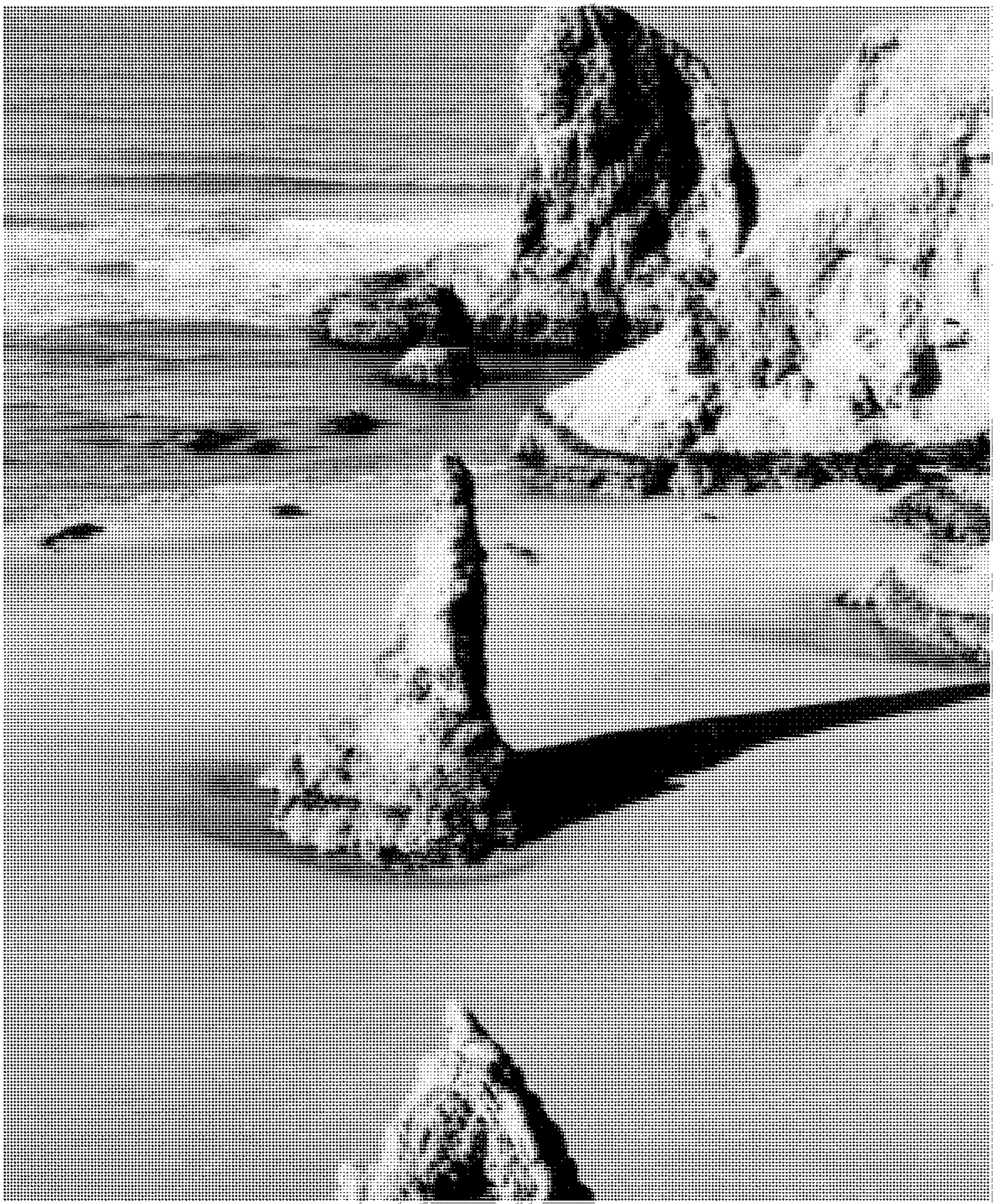
This emergent coast has been sculpted by pounding waves that create some of the most violent surf anywhere. The erosive process of the surf takes many years to produce noticeable results, but its force is relentless. Due to erosion, the rocky coast has retreated inland. Evidence of this are the numerous 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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5

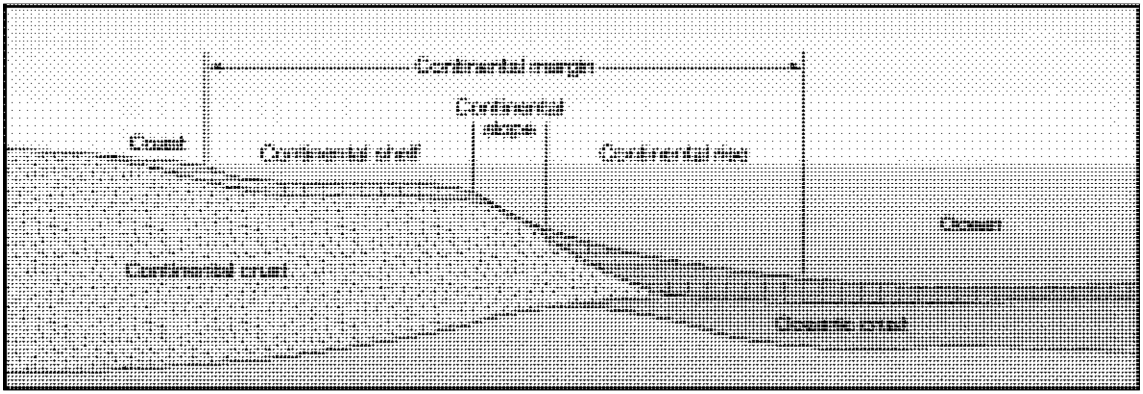
Continental margin

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.

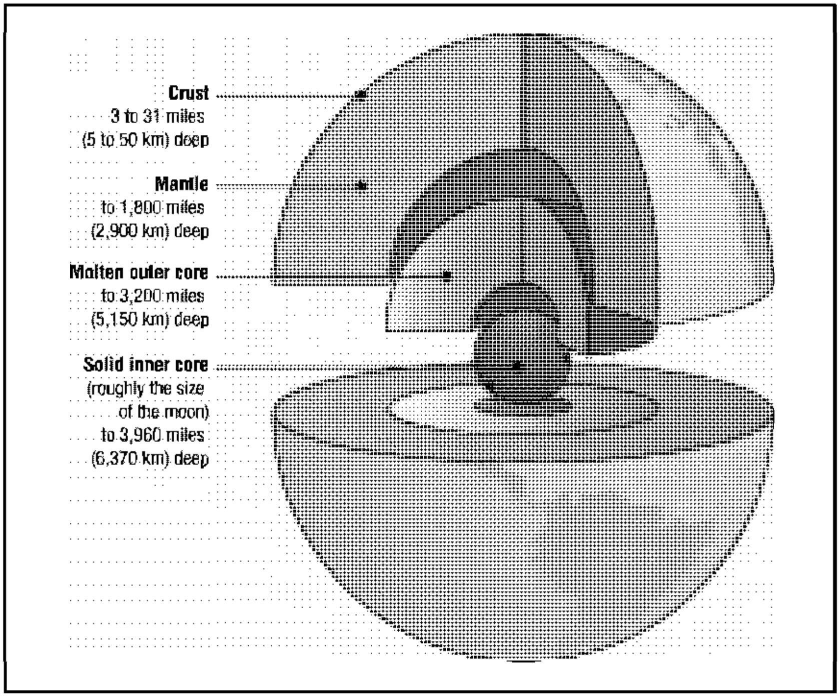
The theory of plate tectonics

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. Whar 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.

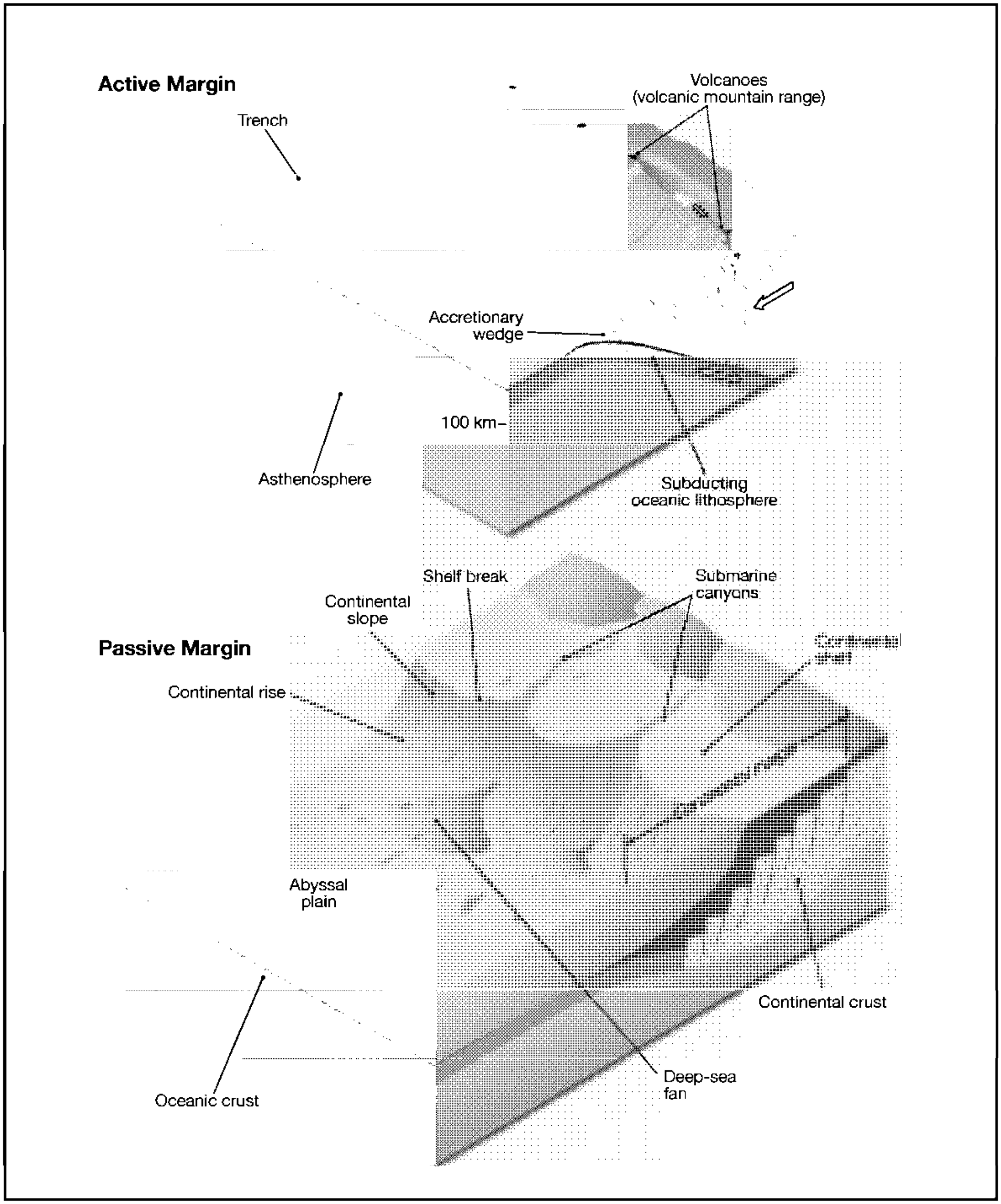
As the plates move, they interact in several different ways. Where they diverge, or move away from each other, new lithospheric rock is created as magma rises up through the crust at the plate boundary and gradually begins to cool. Many boundaries of diverging plates are on the floors of the oceans.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

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6

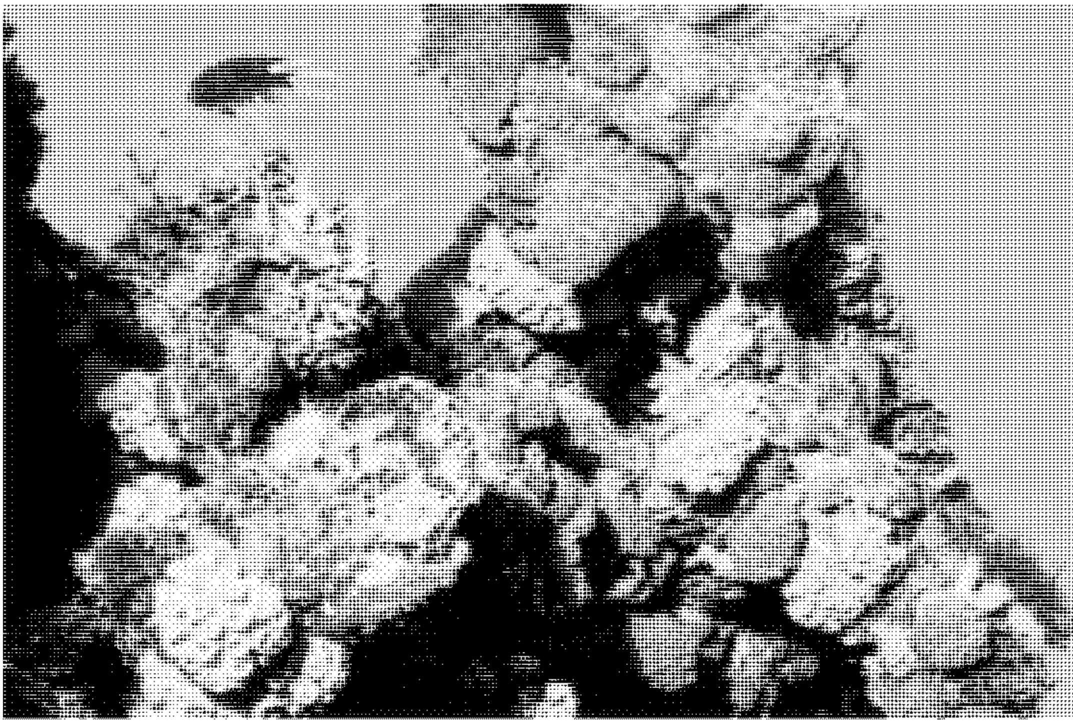
Coral reef

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.

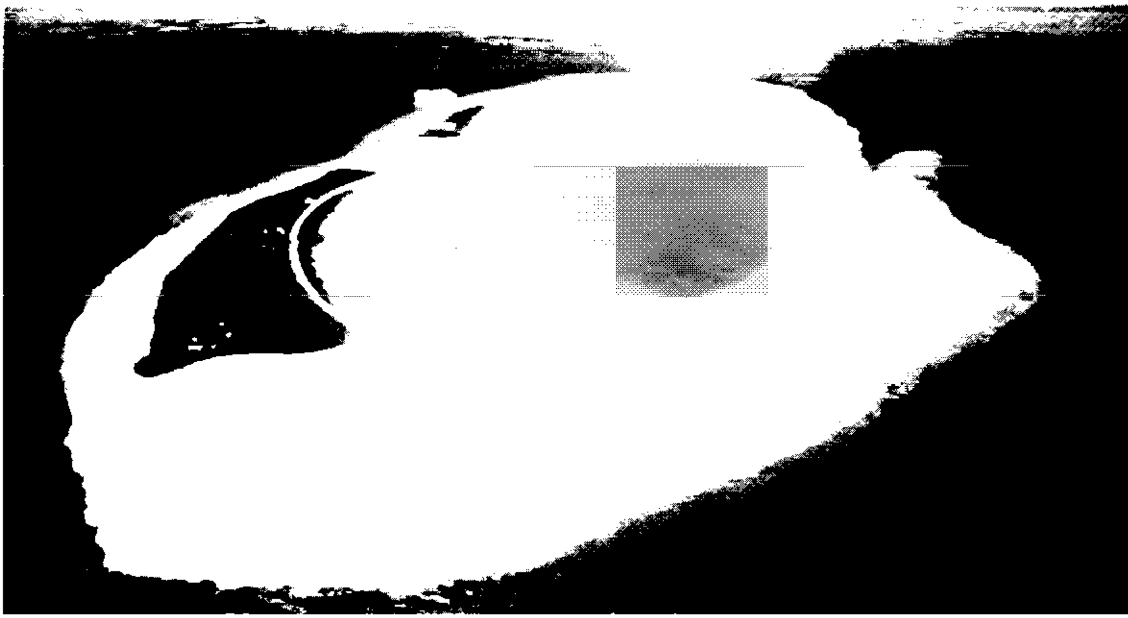
Coral reefs are generally divided into three classes: fringing reefs, barrier reefs, and atolls (pronounced A-toles). The simplest and most common type of coral reef, fringing reefs, form close to the shoreline of islands and continents. A shallow lagoon, a quiet stretch of water separated from the open 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 rhe 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 strucrures 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.

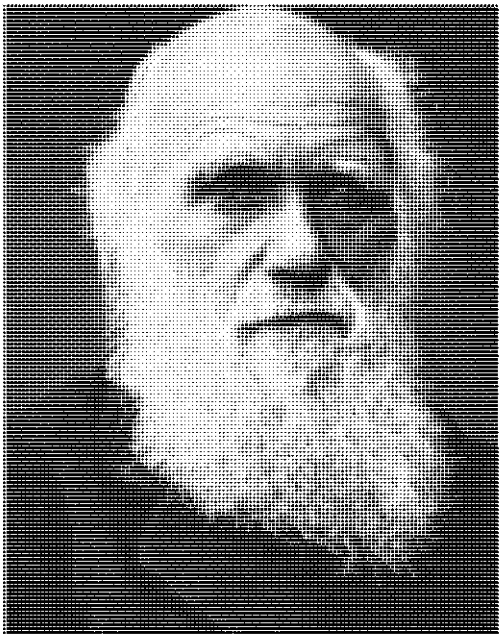
While a coral polyp is alive, it periodically rises up in its cuplike skeleton and secretes more calcium carbonate to form a new base or floor. In this way, the polyp enlarges its skeleton, creating chambers underneath its base. When a polyp dies, its skeleton remains, becoming the foundation on which 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.

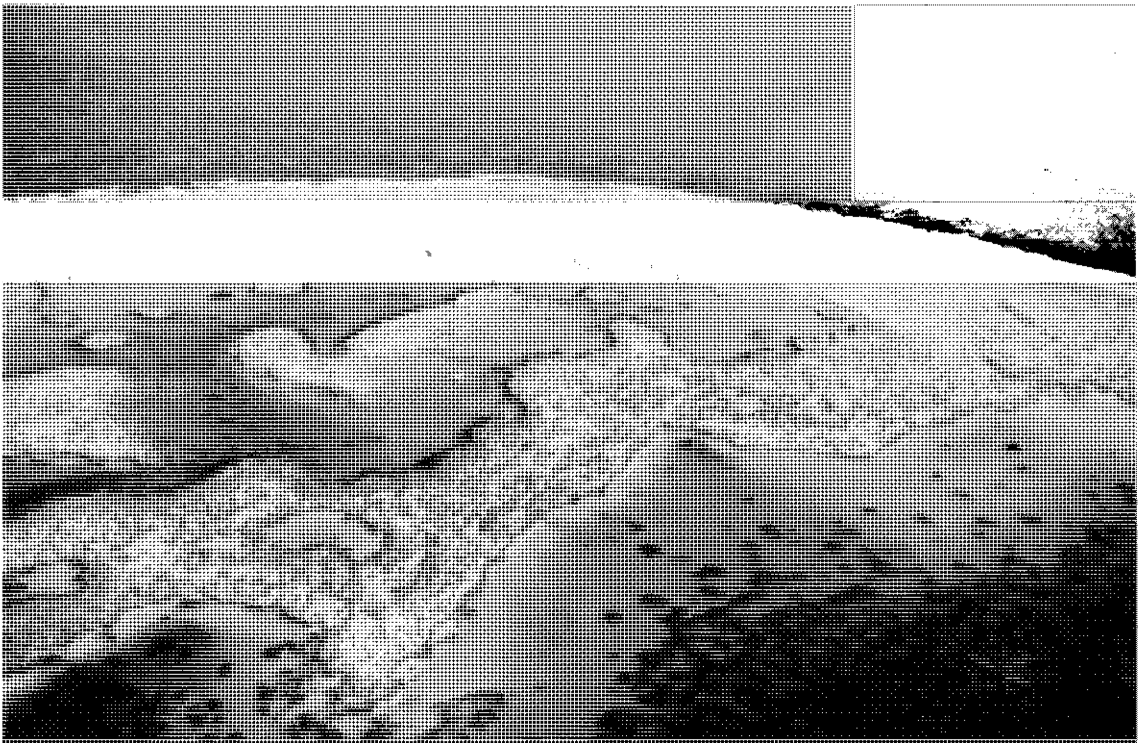
Global warming, an increase in the world's temperatures, is the biggest threat facing coral reefs. It is thought to be caused, in part, by the burning of fossil fuels and the depletion of the ozone layer, both brought about through human activities. Scientists believe a warming of water temperature, 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 rhe 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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7

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).

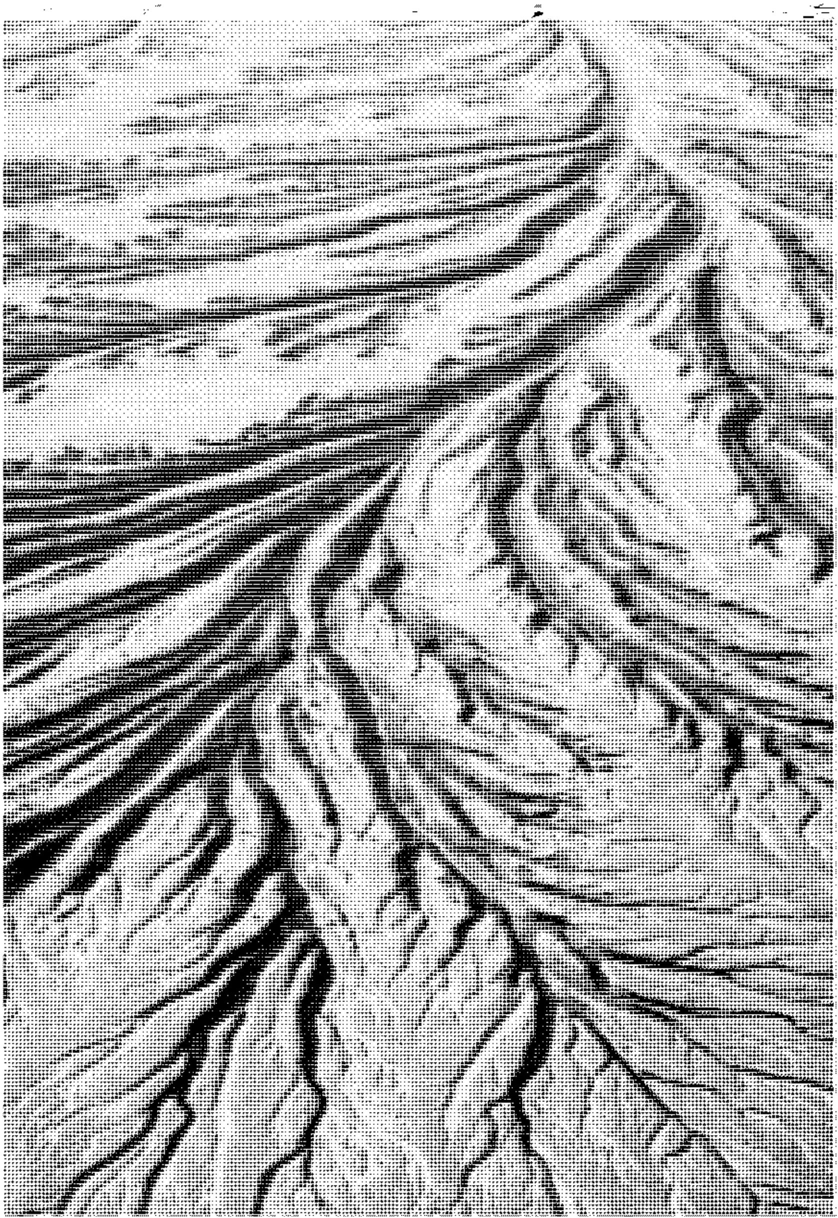
The shape of the land

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 norrhern slope of the Himalayan Mounrains. From rhere, ir flows across rhe Assam Valley of India inro Bangladesh. The rising Himalayan Mountains provide much of the sediment load of these two rivers.

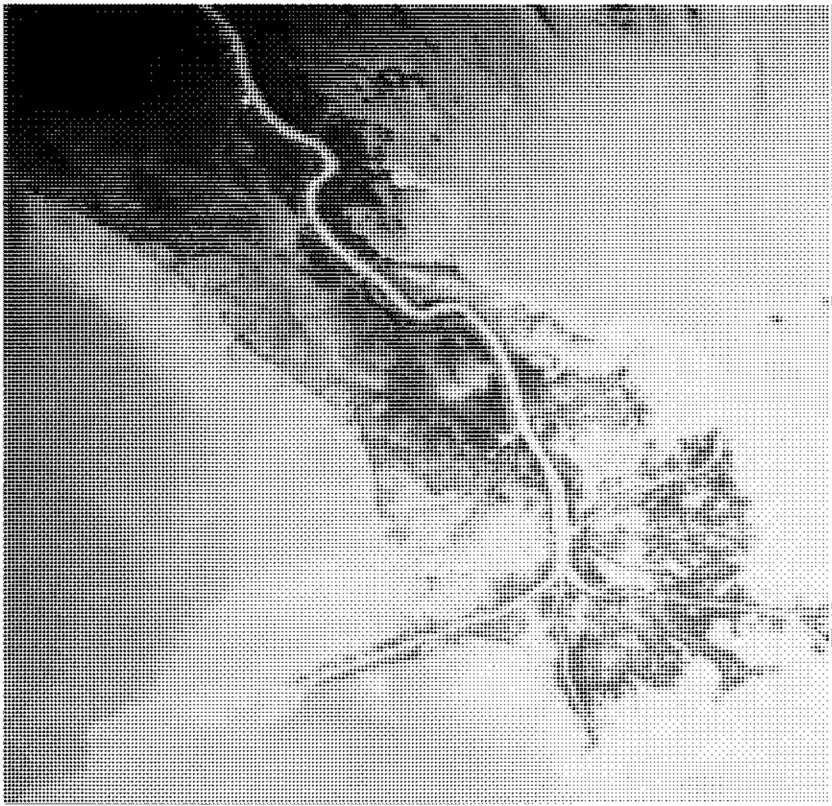
In Bangladesh, the rivers join to form the Padma, the main channel to the sea. The united rivers branch into many distributaries, forming the vast and fertile Ganges River Delta. The delta region covers roughly 25 percent of India's total territory. The delta's sourhern portion is covered largely with 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.

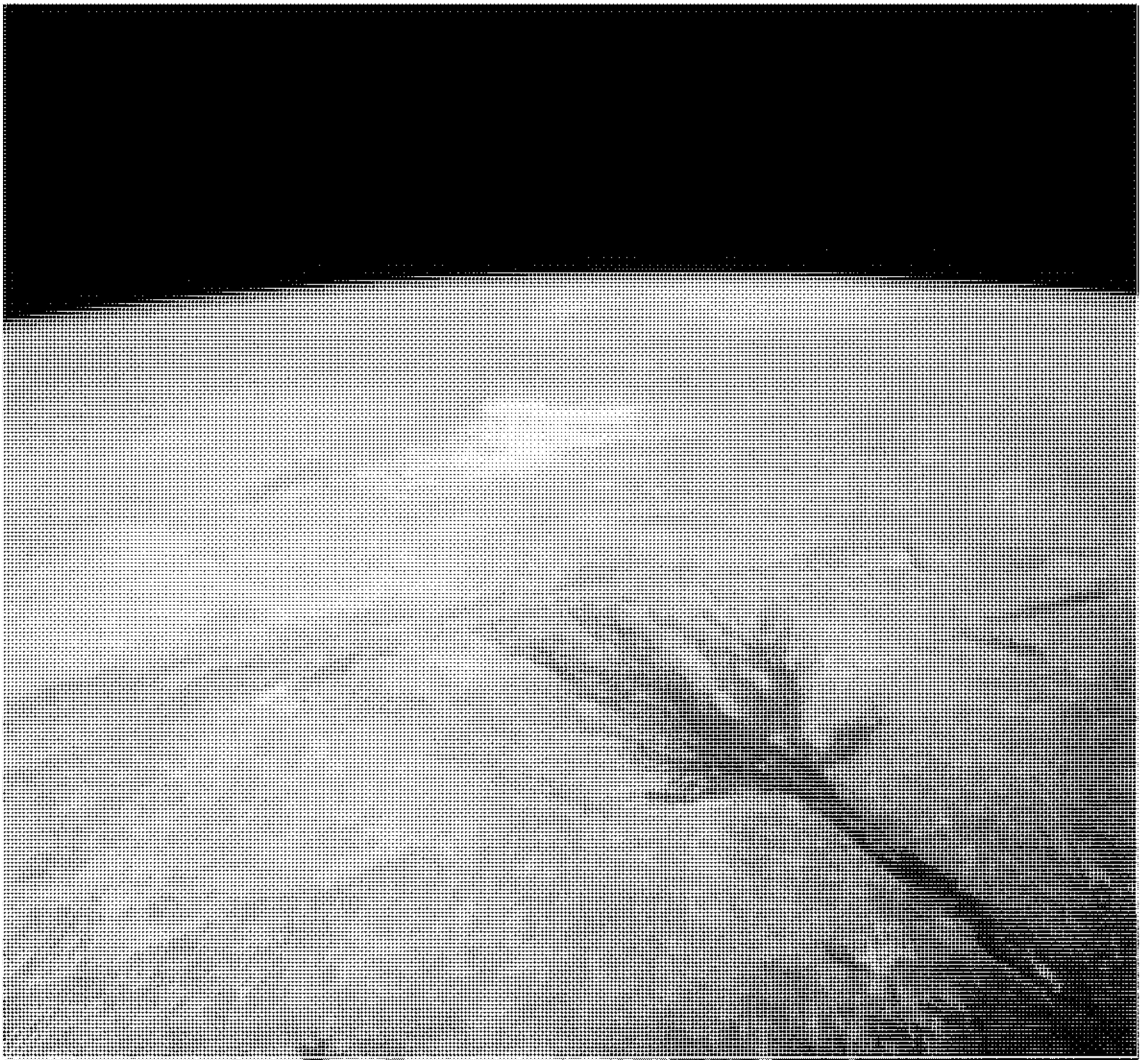
sea, taking a shorter and more energy-efficient route. The Mississippi River has done this at least five times in the last 5,000 years.

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 rhe 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.

For More Information

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Dune and other desert features

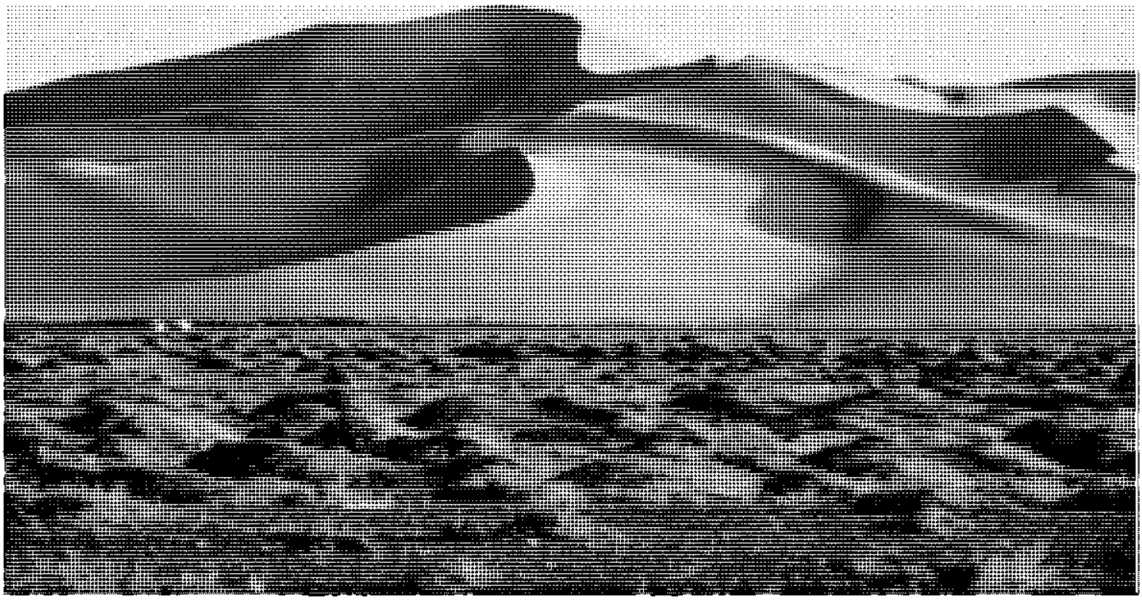
8

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.

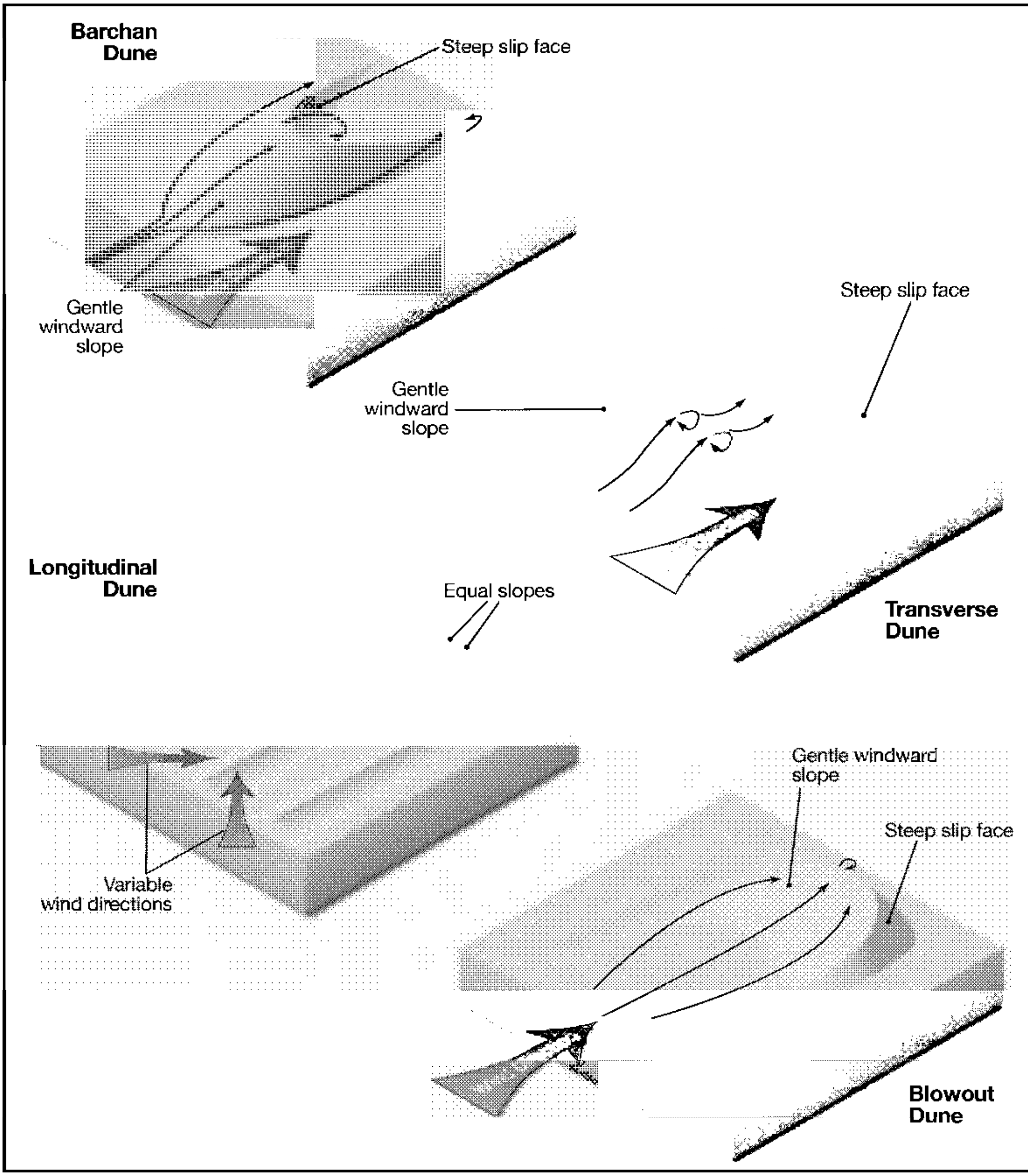
Ventifact: A stone or bedrock surface that has been shaped or eroded by the wind.

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.

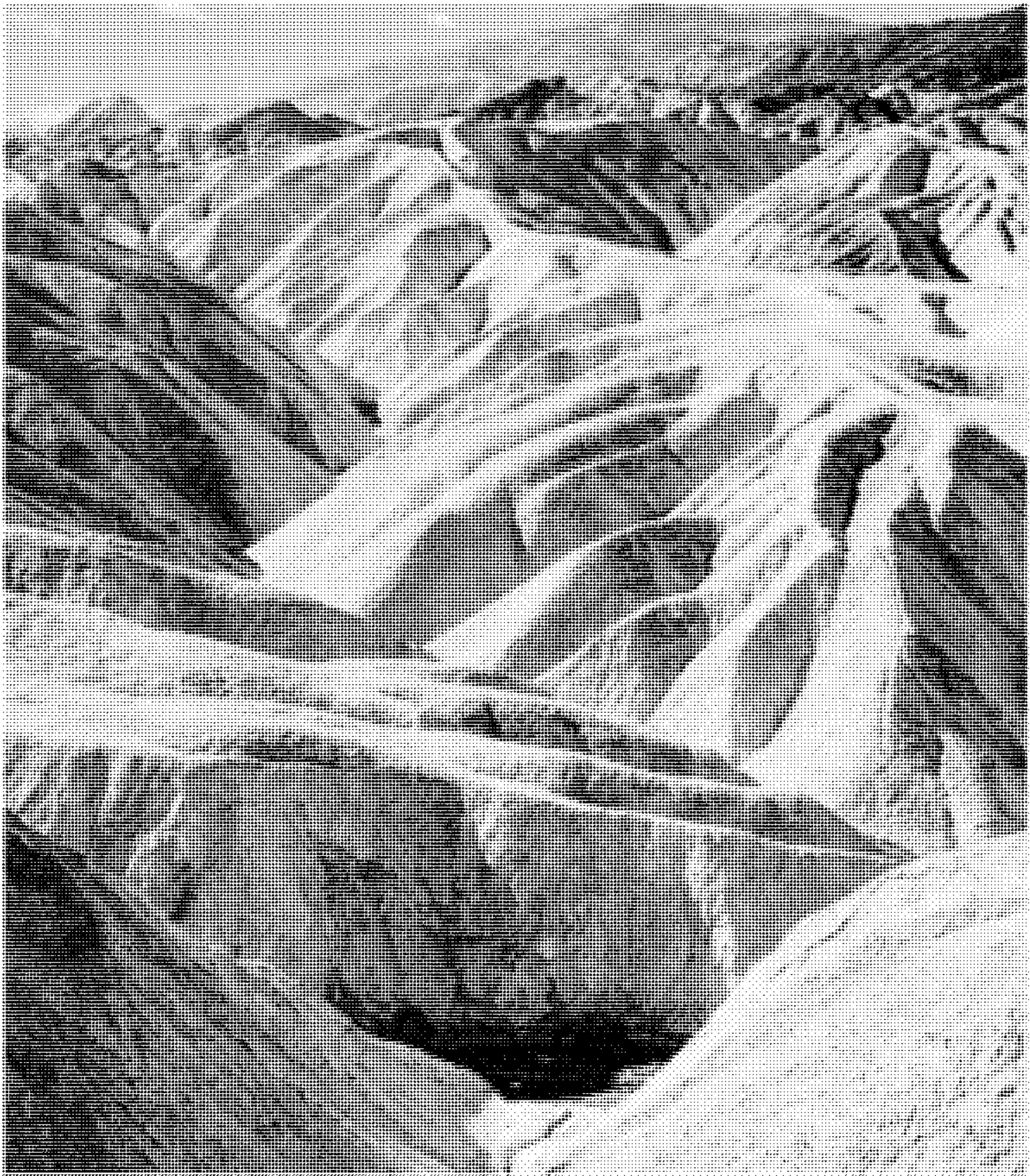
When the rushing water finally reaches a plain or flat area, it loses power since gravity is no longer helping it flow down a steep slope. As it slows, the water is unable to carry the sediment—gravel, clay, sand, and silt—it picked up on its way downhill. Large rocks and other heavy material are deposited 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 primarly 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.

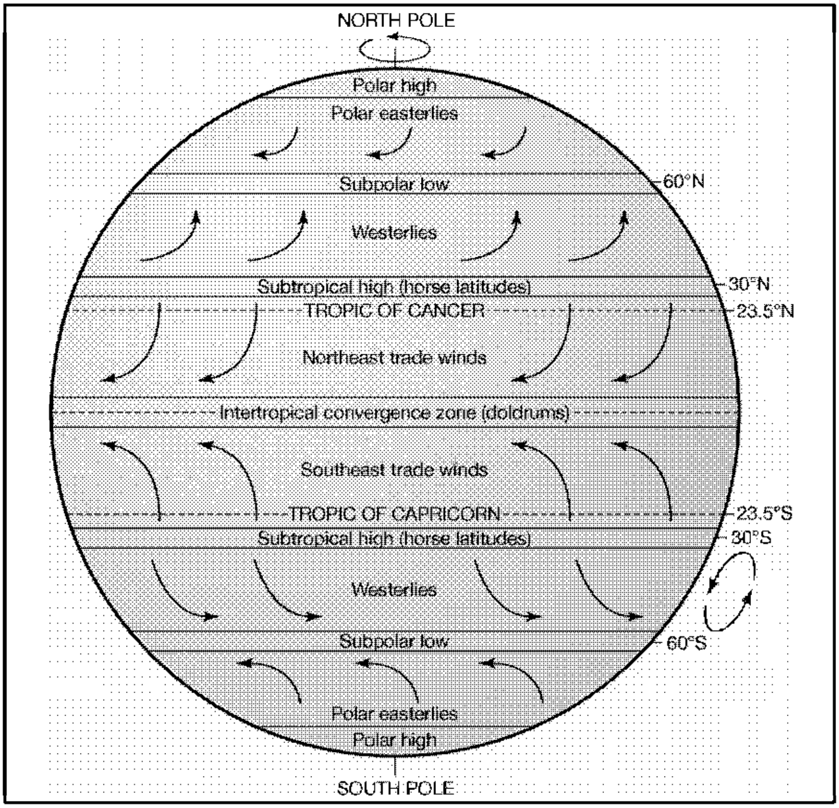
due to compression caused by atmospheric pressure (atmospheric pressure increases closer to the planet's surface). During its descent, the warming air pushes the air below it back toward the equator, since air flows always move toward areas of low pressure. Passing over land on its way back to the equator, 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.

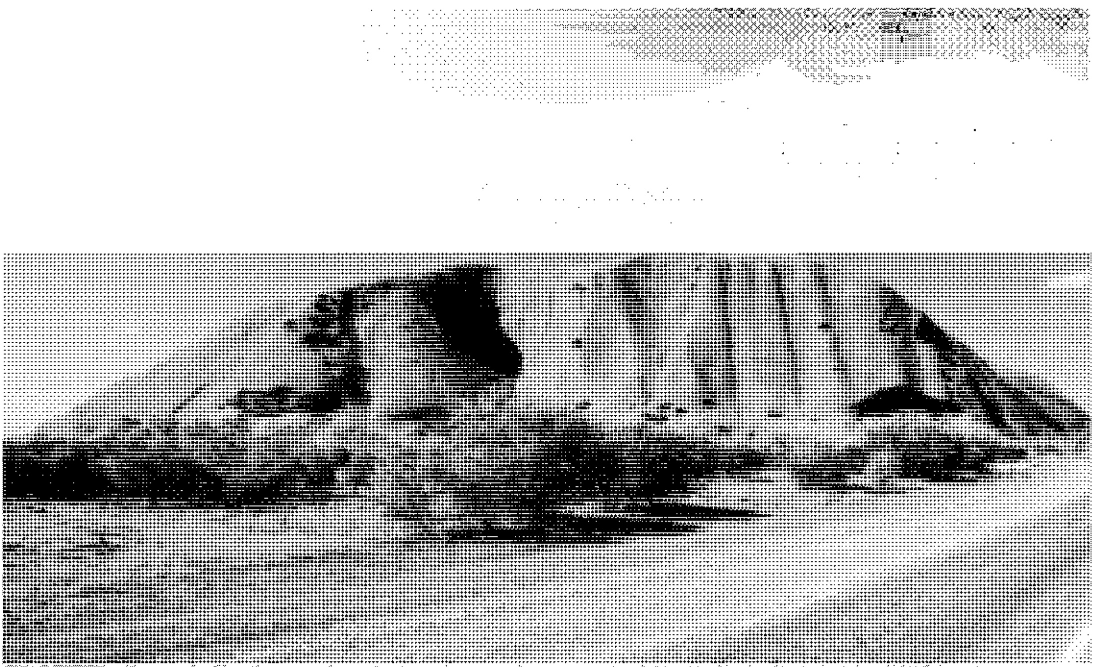
Estimated to be between 400 and 600 million years old, the monolith measures about 1.5 miles (2.4 kilometers) wide and 2.2 miles (3.5 kilometers) in length. Geologists believe that two-thirds of the rock, measuring some 3.7 miles (6 kilometers), lies beneath the desert floor. The rock mound's changing 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.

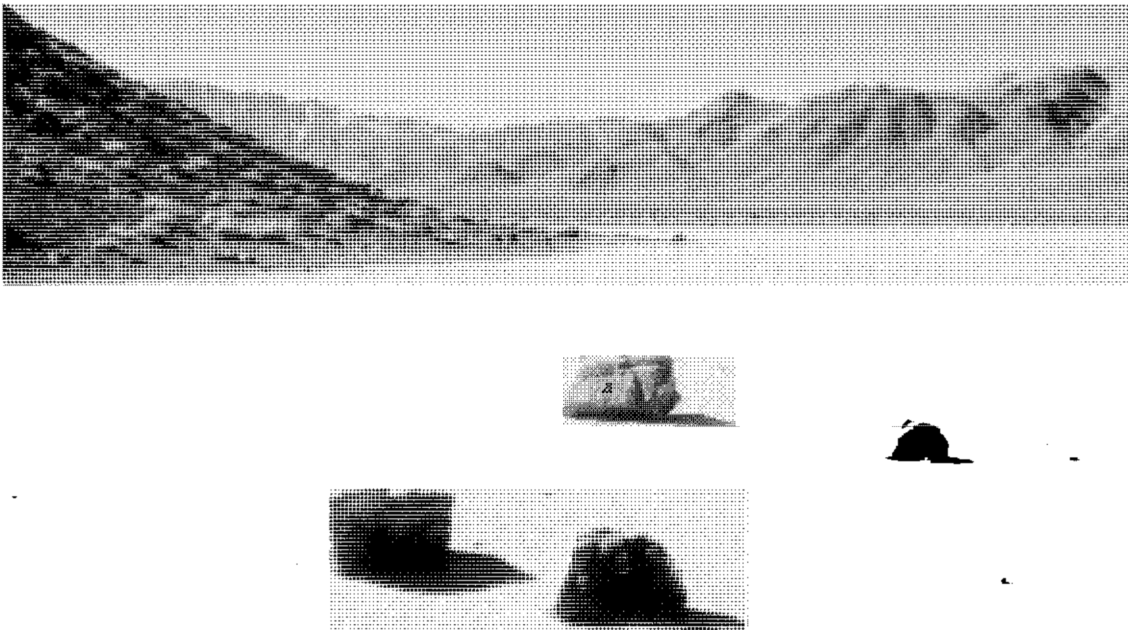
In the western part of this desolate environment lie some of the world's most prominent yardangs. Rising up to 282 feet (80 meters), these streamlined ridges have been carved by the wind out of the silty clay and sand lining the desert floor. Lying parallel to the prevailing north-northwest winds, the 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



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.

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.

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

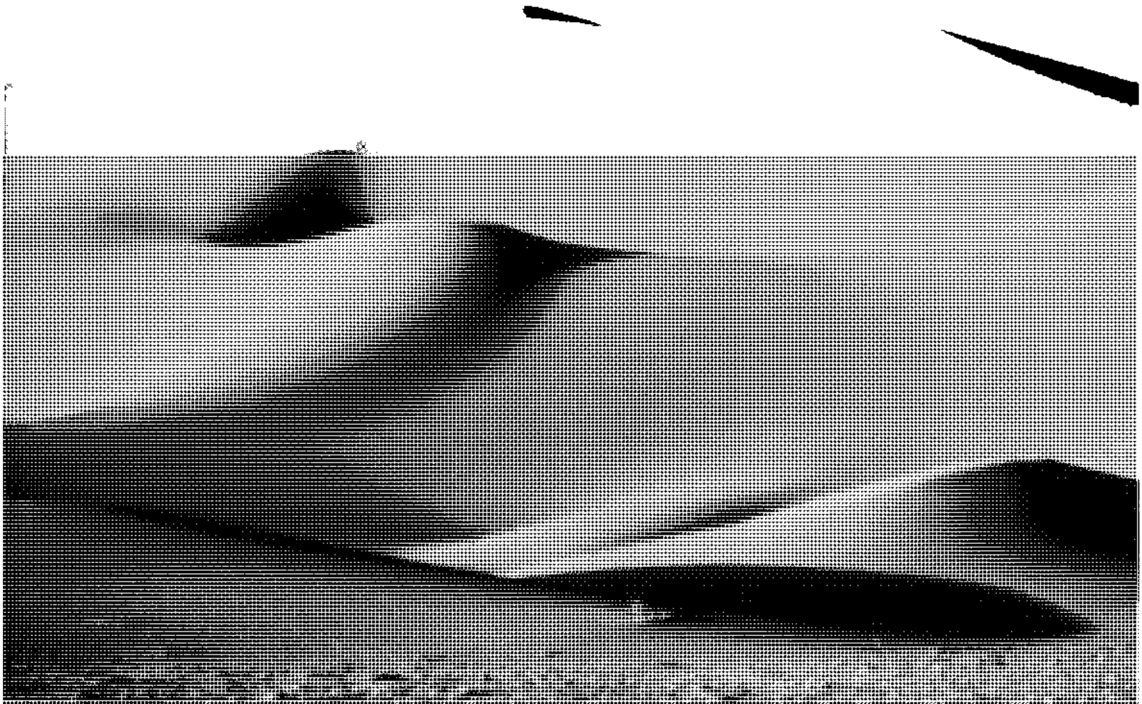
Space shuttle on the back of a 747 at Rogers Dry Lake, California. PHOTOGRAPH REPRODUCED BY PERMISSION OF THE CORBIS CORPORATION.

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

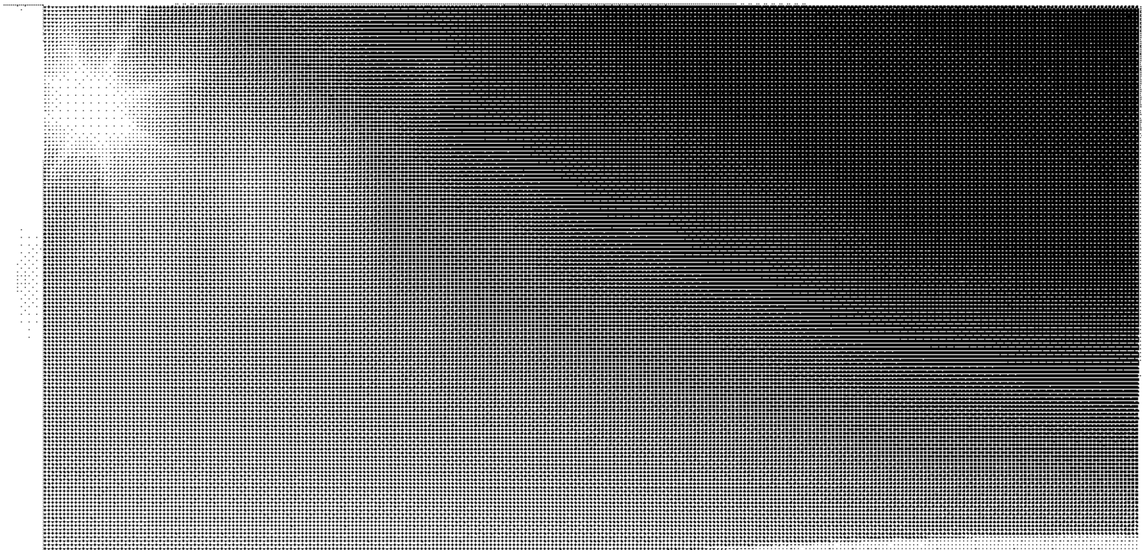


Beni Abbes Dunes in the Sahara Desert, Africa. The Sahara Desert is the world's largest desert, covering about 3.5 million square miles—an area almost as large as the United States. PHOTOGRAPH REPRODUCED BY PERMISSION OF PHOTO RESEARCHERS, INC.

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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