NASA/NOAA GSFC

Geomorphology and Its Tools

(Chapters 1 and 2)

Geomorphology is the study of Earth's dynamic surface, its history, and its active processes. Geomorphology is a synthetic science drawing from many disciplines, including geology, physics, chemistry, and biology. Integral to Earth surface processes are the balances between forces, the transport of mass, and the distribution and redistribution of energy on our planet. Part I contains two chapters. Chapter 1 broadly introduces the field of geomorphology, laying out the interactions among the geosphere, hydrosphere, and biosphere that define Earth as a system and geomorphology as a discipline. It is followed by a short history of geomorphic thought. Chapter 2 introduces techniques that geomorphologists use to understand the form, changes, and history of Earth's surface. These techniques range from direct field observations to indirect chemical, mathematical, physical, and isotopic approaches. Once you have finished reading this part of the book, you should understand what geomorphology is and know the tools geomorphologists use to study Earth's surface.

Earth is a planet of water and land. Blue oceans dominate the planet. The continents range from brown in arid regions to green where vegetation thrives in areas that receive more precipitation. White clouds–some swirled in storms, others stretched out in linear weather fronts–hide some of Earth from view. Perspective is of a viewer looking down from almost 13,000 kilometers. NASA Portraits of Earth made from composite natural color images taken by the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard a polar orbiting satellite.

Earth's Dynamic Surface

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Introduction

Geomorphology is the study of the processes shaping Earth's surface and the landforms and deposits that they produce. The word itself was introduced into the English language in the late nineteenth century, through the combination of the Greek word *geo* (earth) and the suffixes *-morphos* (form) and *-ology* (study of). Geomorphologists learn to observe and interpret landscapes systematically in order to understand how processes shape Earth's surface, decipher the history of a place, and recognize (and potentially mitigate or manage) the impacts of environmental hazards on societies. Whether one is on the way to work or exploring remote regions of the globe, geomorphology offers insights into how water and sediment move, how rocks break down to create soil, how tectonic forces raise mountains, and how uplift is locked in a geologic duel with erosion. Geomorphology provides a new way to see the world because landscapes tell stories that can be read if one has the proper knowledge and tools.

Until recently, geomorphology was a qualitative, interpretive science. Classification of landforms and topographic features informed speculation about the history of landscapes and provided information useful for the development of human settlements and the infrastructure they require. In the latter half of the twentieth century, geomorphology underwent a dramatic transformation with the advent of quantitative characterization and analysis of both landforms and the processes driving the development and evolution of topography. As the plate tectonics revolution illuminated the mystery of mountain

M. Miller

A braided, high-gradient stream roars down a canyon in the Tien Shan mountains, Kyrgyzstan. The large levees along the channel are studded with meter-size boulders, indicating that the channel was impacted by debris flows that most likely originated from landslides off the steep basin slopes.

IN THIS CHAPTER

building and solved the problem of continental drift, radiometric dating techniques provided accurate landscape chronologies, and developments in electronics, sensors, and computational techniques allowed quantitative characterization of geomorphological processes. These developments allowed scientists to reliably connect process with the evolution of landforms. Today, geomorphology is an integrative science that brings a wide range of methods and techniques to bear on understanding the processes that shape Earth's dynamic surface.

Geomorphology is an inherently synthetic discipline that draws on geology, physics, chemistry, and biology to understand landscape-forming processes and to decipher how weathering, erosion, and deposition sculpt the land. It is a science with innate intellectual and aesthetic appeal. Geomorphology also has fundamental societal relevance because we live on Earth's surface, and the dynamic processes that shape topography influence human societies by controlling the spatial distribution of arable land, where and when floods and landslides occur, the geography of erosional uplands, the locus of coastal erosion, the retreat of glaciers, and the offset of land surfaces by earthquake-generating faults in different parts of the world **[Photograph 1.1]**. The study of geomorphology intersects with a variety of geologic and geographic disciplines because topography reflects the interaction of driving forces that elevate rocks above sea level, the erosional forces that wear rocks down, and the factors that determine resistance of the land surface to erosion—including how weathering progressively weakens slope-forming materials and how vegetation reinforces and stabilizes them.

Most people think of the land surface as stable and unchanging because we do not usually notice subtle, ongoing changes in our daily experience. Geomorphologists see landscapes as constantly changing and evolving, usually slowly but sometimes catastrophically shaping and remodeling our world. Knowing what to look for and knowing how to see is key to understanding landscapes. Recognizing landscapes as dynamic systems is central to understanding how natural forces shape Earth's surface, influence land use, and respond to human actions.

Tectonics (the movement of Earth's lithosphere) and **volcanism** (the eruption of molten rock) drive the **endogenic** (internal, or generated from within) processes that raise mountains and elevate topography above sea level. Tectonics determines the first-order topography, or megageomorphology, of Earth. In these ways, Earth's internal dynamics provide the raw material for erosional processes to shape landscapes and landforms. Endogenic processes are the result of Earth's internal heat, which drives plate tectonics through deep convection of the planet's mantle. The vast array of erosional processes that influence Earth's surface arise from **exogenic** (external, or generated from outside) processes imposed on landscapes through the action of wind, water, and ice. Exogenic processes are driven by the Sun's energy and the temperature gradient between the poles and the equator.

In framing how to study geomorphology, we consider three systems that intersect at and near Earth's surface. Specifically, we focus on the **geosphere**, which includes the rocks comprising Earth's **crust** and the global tectonic system that elevates the rocks that get sculpted into topography; the **hydrosphere**, which encompasses the oceans, atmosphere, and the surface and subsurface waters that erode, transport, and deposit sediment; and the **biosphere**, living things that are part of ecosystems that help shape and are in turn shaped by landscape dynamics. Global patterns within and among these three basic systems set the broad regional templates within which geomorphological processes shape landforms and landscapes evolve.

Geosphere

Planetary-scale processes drive the motion of Earth's **tectonic plates** and control the locations of mountains, plains, plateaus, and ocean basins. Earth's rigid lithosphere is broken into seven major and a number of minor plates that move independently from one another, creating **mountain belts** and **volcanic arcs** where plates converge and great **rift valleys** where the plates spread apart **[Figure 1.1]**. Many major surface features of the planet, including mountain ranges, earthquake-prone fault zones, and volcanoes, occur along tectonic boundaries, but plate boundaries do not necessarily coincide with the edges of the continents. Tectonic setting generally determines the distribution of different rock types with different degrees of resistance to erosion. Weakly cemented sedimentary rocks typically are found in depositional basins. Hard, erosion-resistant metamorphic and igneous rocks are exposed in the cores of most mountain ranges. The global distribution of rock types and rates and styles of crustal uplift, deformation, and extension reflect the history and patterns of tectonic motion that set the stage for topographic evolution and landscape development.

Isostasy

The most obvious feature of global topography is the difference between the most common land surface elevation of the **continents** (~1 km) and the ~4 km depth of the seafloor in **ocean basins [Figure 1.2]**. These two dominant elevations reflect the contrast in density between **continental crust** and **oceanic crust**, the result of recycling of Earth's crust over geologic time to produce continents rich in elements lighter than those that compose oceanic crust.

Earth's crust rides on the denser material of the planet's upper mantle, in much the same way that less dense ice floats in water **[Figure 1.3** on page 10**]**. This phenomenon, called **isostasy**, leads to a balance in regard to the total mass of rock above the depth of isostatic compensation, a reference level within the **asthenosphere** (a ductile or slowly deforming layer in the upper mantle) at which the pressure exerted by the overlying columns of rock is equal.

PHOTOGRAPH 1.1 Why Geomorphology Matters. (a) Flooded home and sandbags in southwestern Montana. (b) Looking upstream at a landslide that blocked a stream channel in the Alaska Range, creating a temporary lake. (c) Heavy rains triggered many debris flows in Brazil during January 2011. This flow filled a streamside swimming pool with mud and undercut the streambank, destroying homes built along the stream. (d) A building in northern Alaska tumbled into the sea as the frozen ground (permafrost) below melted and the coast became more susceptible to erosion. (e) Rocks from a 100,000 m^3 rockfall in Yosemite Valley in 1982. The slide closed the highway for several months. The rockfall originated in jointed granite about 200 m above the highway. (f) Bouldery fault scarp at the site of an 1872 rupture on the Owens Valley Fault Zone, southern California. The land on the left moved up several meters, exposing the once-buried boulders.

Continents stand higher than ocean basins because continental crust is composed of less dense, silica-rich granitic rocks, whereas oceanic crust is made of denser rocks with a more iron-rich basaltic composition. Similar to icebergs, which lie mostly below the water surface, a deep root of low-density continental crust extends down to displace denser mantle material and support high-standing mountains. Some such roots, like those under the

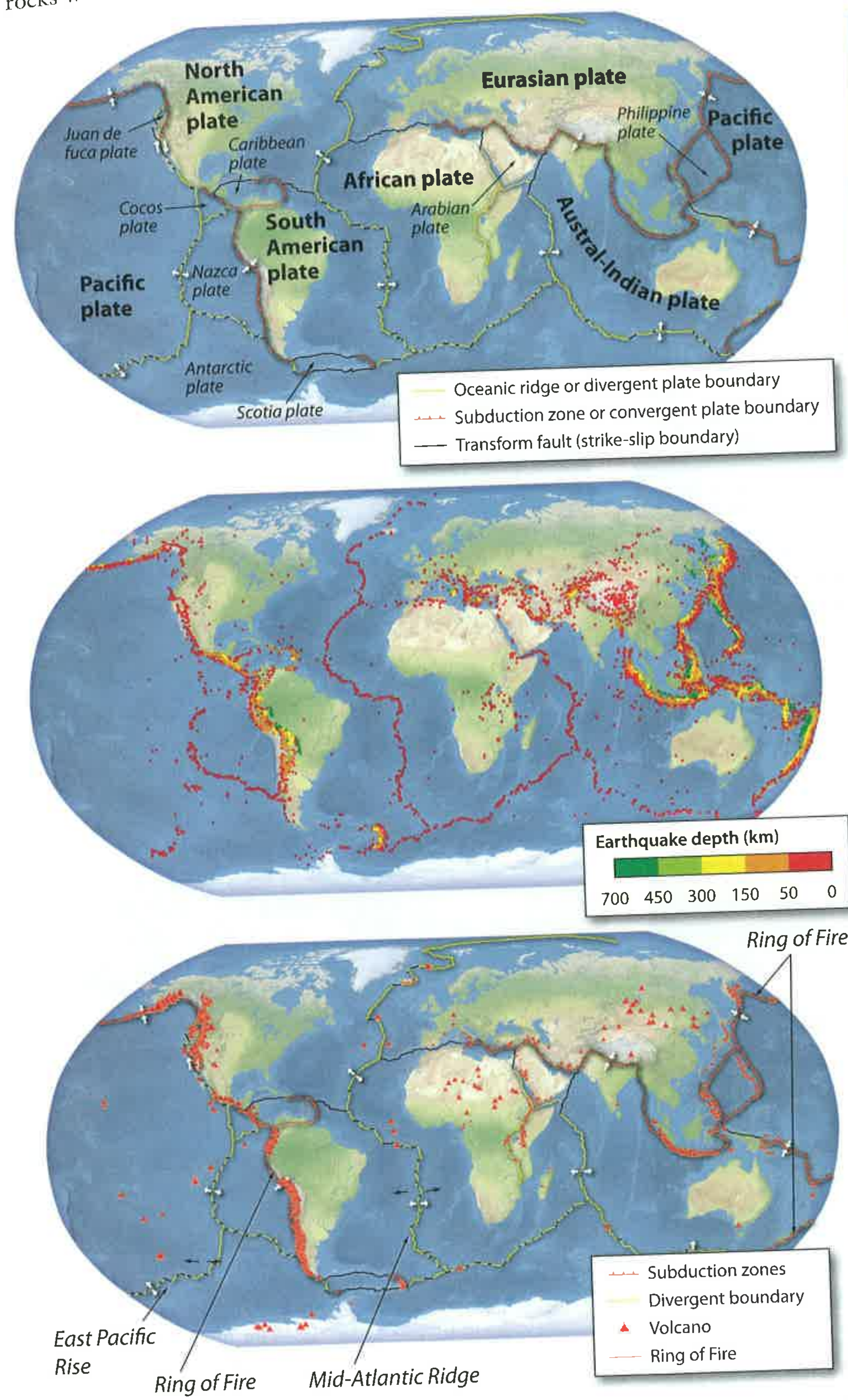
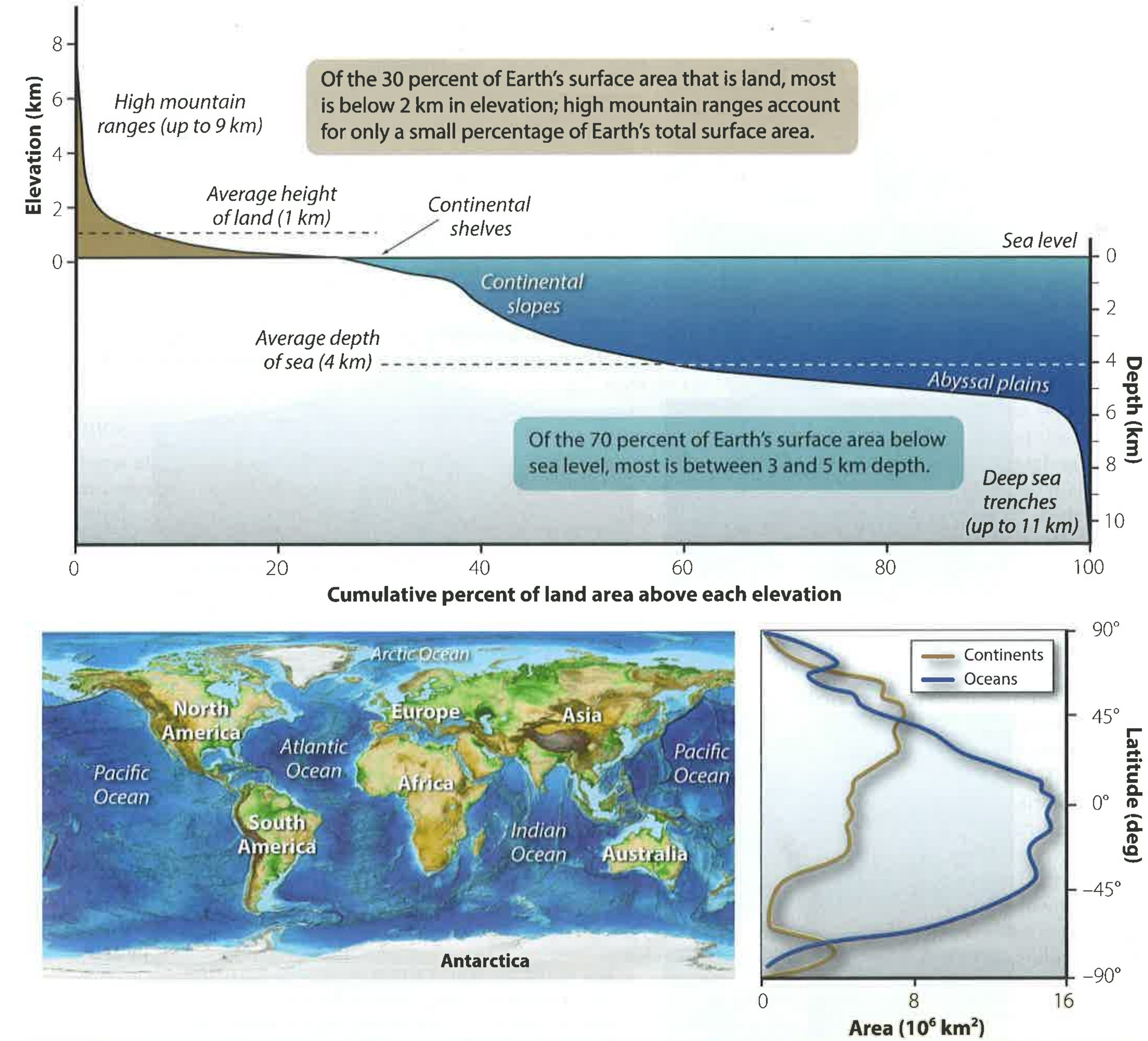


Plate boundaries govern the distribution of many distinctive geomorphic features, including mountain ranges and volcanoes. **Convergent boundaries** are associated with high mountain ranges and explosive volcanism. **Divergent boundaries** also generate high-standing topography, but volcanism there is less explosive and more effusive. **Strike-slip boundaries** (transform faults) offset landforms laterally and create local relief where faults bend.

The global distribution of earthquakes follows closely the boundaries of tectonic plates. The largest and deepest earthquakes occur at and near convergent boundaries, especially **subduction zones.** Likewise, earthquakes are concentrated along mid-ocean spreading centers. Shallow earthquakes also occur in plate interiors.

Many of the world's volcanoes are found on and near plate boundaries. The Pacific Ocean Basin is encircled by subduction zones and their associated volcanoes that together form the "Ring of Fire." The Mid-Atlantic Ridge and the East Pacific Rise are divergent plate boundaries where new oceanic crust is created by volcanism. Volcanoes are also common in terrestrial rift zones, such as East Africa.

FIGURE 1.1 Volcanoes, Earthquakes, and Plate Boundaries. The character of Earth's dynamic surface reflects the forces acting upon it. The movement of tectonic plates, shaking during earthquakes, and volcanic eruptions influence the development of regional topography.



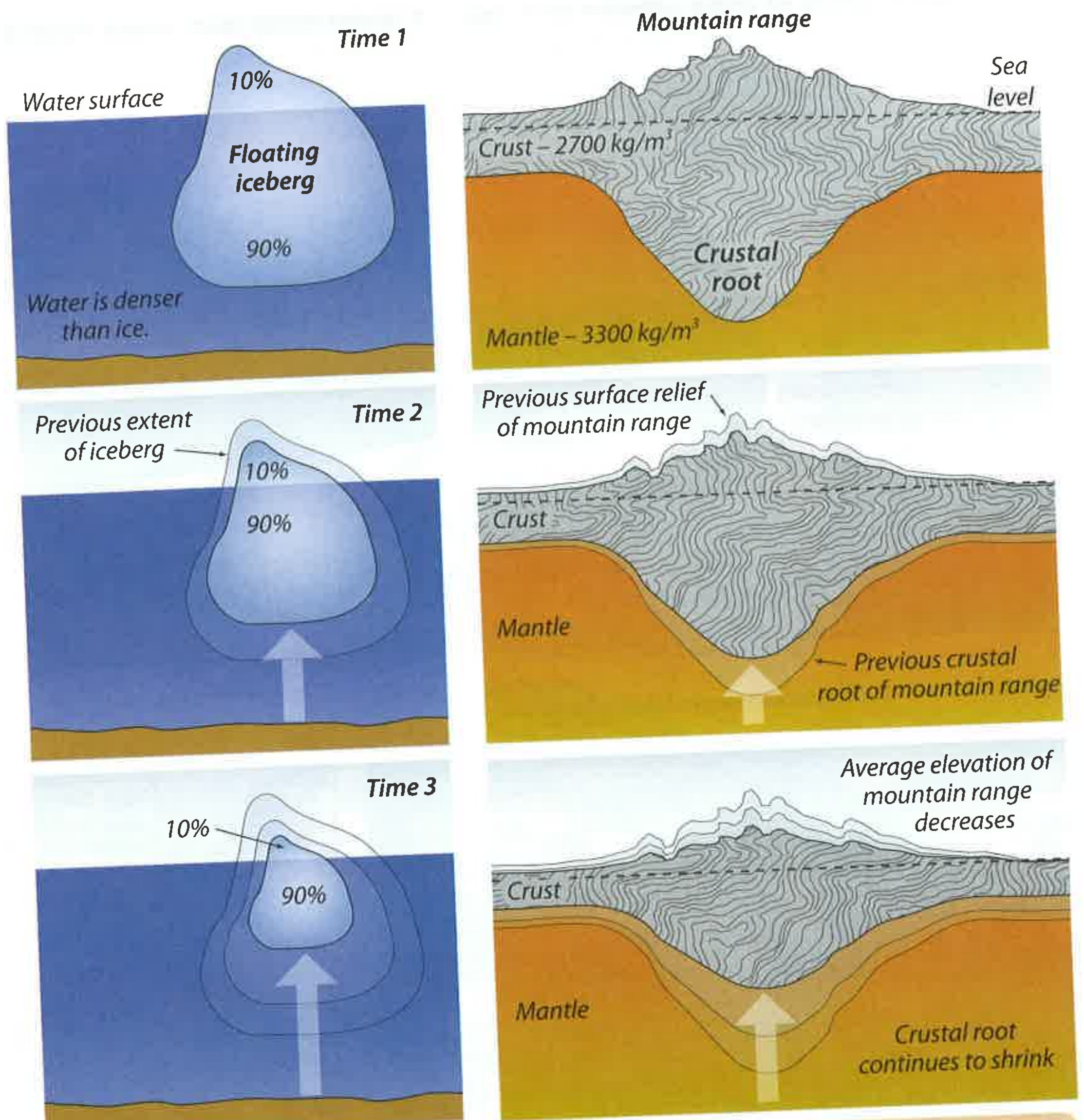
Both the **continents** and the **ocean basins** include large, relatively flat areas. On continents, these flat areas are the **cratons.** Under the oceans, these flat areas are the **abyssal plains.** Areas of higher elevation and **relief** include continental mountain ranges and **mid-ocean ridges.**

The area of ocean and continents are not equally distributed with latitude. There is more exposed land in the Northern Hemisphere and more ocean in equatorial regions.

FIGURE 1.2 Global Topography. The surface of the Earth has two dominant elevations—the deep ocean basins at an average depth of about 4 km below sea level and the continental cratons, where the average elevation is about 1 km above sea level.

Himalaya, can be greater than 50 km thick—more than 6 times the height Mount Everest rises above sea level. Even the ancient, worn down Appalachian Mountains are supported by a crustal root tens of kilometers thick.

Due to isostasy, erosion that removes rock and soil from Earth's surface results in **isostatic compensation** or **uplift** of the remaining rock as denser material moves in at depth to compensate for eroded material. Consider how an iceberg continues to float even as it melts; the remaining ice rises to replace that lost off the top. With typical continental crust having a density of about 2700 kg/m^3, while typical mantle rocks have a density of more than 3300 kg/m^3, isostatic uplift can offset almost 82 percent of erosion (i.e., 2700/3300 = 0.82). Hence, for every meter



The familiar saying, "just the tip of the iceberg" reflects the difference in density between ice and liquid water. Ice is 10 percent less dense than water, causing icebergs to float and expose only their tips. Ninety percent of the mass of an iceberg is below the surface. As the iceberg melts and loses mass, it responds by floating a bit higher in the water, keeping the ratio constant between exposed and submerged mass.

Just as the tip of an iceberg protrudes above the ocean surface leaving most of the iceberg submerged, mountain ranges **are buoyed up by** large, thick **crustal roots.** This **buoyancy reflects** the contrast in density between less dense, silica-rich, felsic **continental crust** (~2700 kg/m^3) and the underlying, more dense iron- and magnesium-rich mafic **mantle** rocks (~3300 kg/m^3). As surface processes erode the mountain range, this buoyancy drives **rock uplift.** The result is for every meter of erosion, there is about 80 cm of rock uplift. Active mountain ranges, such as the Himalaya, have deep crustal roots, whereas ancient inactive ranges, such as the Appalachians, have shallower roots.

FIGURE 1.3 Introduction to Isostasy. Just as an iceberg of low density floats on water of higher density, mountains with thick crustal roots float on the denser mantle rocks. As ice above the water surface melts or mountains erode (Time 1, Time 2, Time 3 = time steps), the underlying material rises to take its place.

of rock stripped off by erosion, isostatic compensation triggers more than 80 cm of rock uplift, resulting in net surface lowering of a little less than 20 cm. Isostasy means that subduing or erasing a mountain range requires eroding through its root because it takes erosion of more than 5 times the thickness of rock to reduce average elevation by a comparable amount. Consequently, today's landscape can reflect tectonic events that occurred in the distant past, as it can take an extremely long time to erode mountains away because their roots rise almost as fast as the surface erodes. For example, peaks in the Appalachian Mountains stand more than 2000 m tall in a region where the last tectonic activity capable of producing large mountains (continental collision) occurred several hundred million years ago.

Tectonics

As tectonic plates move, the lithosphere is rafted along by thermal convection of Earth's deep mantle. Plate margins are classified as convergent, transform, and divergent boundaries [**Figure 1.4**]. **Convergent boundaries** are those where two plates move toward and collide with one another. **Transform boundaries** are those where two plates slide laterally past one another—for example, along California's earthquake-prone San Andreas Fault Zone. **Divergent boundaries** are those where two plates spread apart.

Mid-ocean ridges are divergent plate boundaries where mantle upwelling at **seafloor spreading centers** creates new oceanic crust. The older crust is pushed aside and moves away from the ridge as new material is extruded; this basaltic crust forms the floors of Earth's oceans. The new oceanic crust cools, grows more dense, and thus sinks. This thermal subsidence explains why the ocean floors in general get deeper the farther they are from mid-ocean ridges. Continental divergent boundaries are found where spreading centers extend onto land, resulting in extensional rift valleys that parallel the plate boundary. Such valleys typically host lakes, large alluvial fans, and volcanoes.

Subduction zones are convergent plate boundaries where old, denser oceanic crust sinks beneath less dense continental crust or younger, more buoyant oceanic crust. The plate boundary on the Pacific side of the Andean Mountains in South America and the trench seaward of the Japanese islands are examples of subduction zones. Less dense continents and islands do not subduct.

Continental margins are called **active margins** where they coincide with plate boundaries and **passive margins** where there is no relative motion between the continent and the seafloor, as for example along the east coasts of North America, South America, Africa, and Australia. Great mountain belts, like the Himalaya, form in **continental collision zones** where two continents made of low-density crustal rocks are squeezed between converging plates, shoving one beneath the other. In the case of the Himalaya, the Indian subcontinent has been ramming into Asia for the past 50 million years. The collision has piled up crust to form the Tibetan Plateau, much like how sand piles up in front of an advancing bulldozer blade. Continental collision zones build high mountains because crustal thickening gradually elevates the surface while building a deep crustal root.

Tectonically active mountain belts, like the Himalaya, the Andes, and the Cascades in the Pacific Northwest, are found along convergent margins (continental collision zones and subduction zones). Mountain belts also form above subduction zones where material scraped off the downgoing slab piles up (like the Olympic Mountains in Washington). Farther inland, linear chains of volcanoes are parallel to the subduction zone. The volcanoes result from partial melting at depth of the slab, overlying mantle, and moist, subducted oceanic sediments. Other ranges, such as the Appalachian and the Ural mountain chains, record ancient continental collisions at plate boundaries that are no longer tectonically active. Crustal thickening, when convergence is sustained for long enough and at a rate greater than the rate of erosion, can cause the height of mountain ranges and the stress they exert at depth to exceed the mechanical strength of the lithosphere. Where this happens, it leads to development of high plateaus, like Tibet and the Altiplano. Lithospheric strength limits plateau elevation and further convergence results in lateral extrusion of material that expands the area of high terrain without further surface uplift.

Continents are composed of mountain belts called **orogens** (sometimes referred to as orogenic belts), extensional rift zones, and ancient, tectonically stable and generally low-relief **cratons** [**Photograph 1.2**]. Active mountain belts typically consist of sedimentary and crystalline rocks that are highly deformed and erode rapidly, at rates up to several millimeters per year. Inactive mountain belts erode much more slowly, just a fraction of a millimeter per year. Tectonically stable continental landscapes, like the interior of Australia, erode even more slowly, at rates on the order of 1 meter per million years. Rift zones, like the East African Rift, are places where active divergent plate boundaries extend into continents, tearing landmasses apart, raising steep rift flanks, and emplacing relatively young volcanic rocks.

Continental shelves (see Figure 1.2) are submerged plains at the edges of the continents. During the last several million years, these areas were repeatedly exposed to subaerial erosion as cycles of glaciation periodically locked up sufficient ice on the continents to lower sea level by more than 100 m. Continental shelves extend beyond present-day shorelines, and they range from narrow features a few kilometers wide on tectonically active margins to broad areas of relatively shallow marine inundation that extend hundreds of kilometers offshore on passive margins.

Within tectonic plates, upwelling plumes of hot rock from deep in the mantle, called **hot spots**, dramatically influence topography because they produce prodigious and intense volcanism and can drive uplift thermally by heating rock and thus making it less dense. In oceanic settings, hot spots build chains of islands and seamounts like

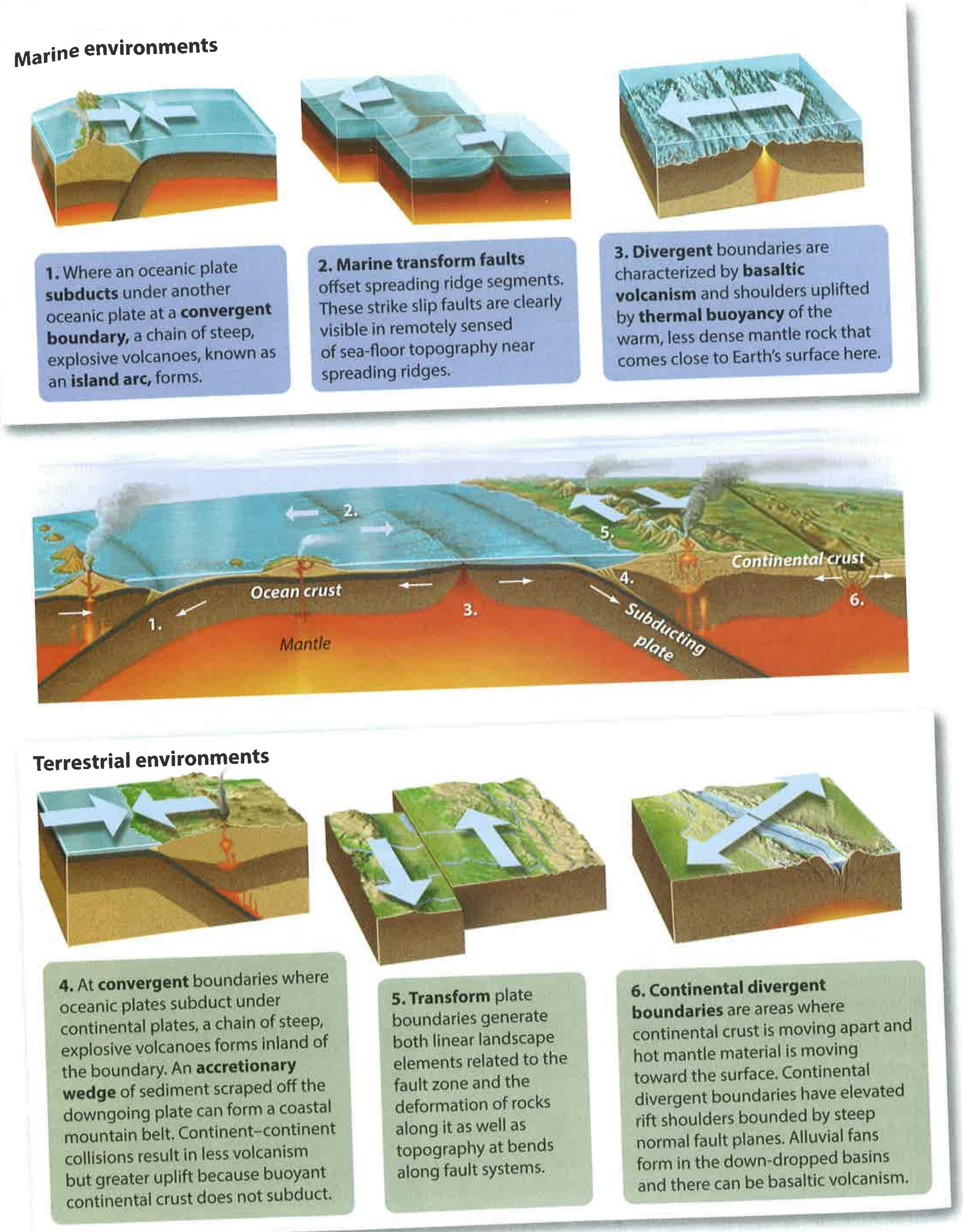


FIGURE 1.4 Plate Margin Types. Each type of plate tectonic boundary (convergent, divergent, and transform) is associated with a particular suite of landforms that enables geomorphologists to predict landscapes and active surface processes in different parts of the world.

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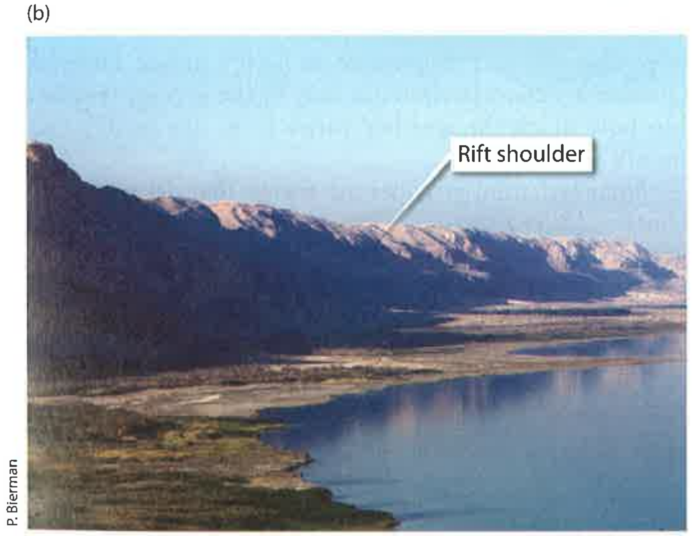
M. Gellhausen

(b)



P. Bierman

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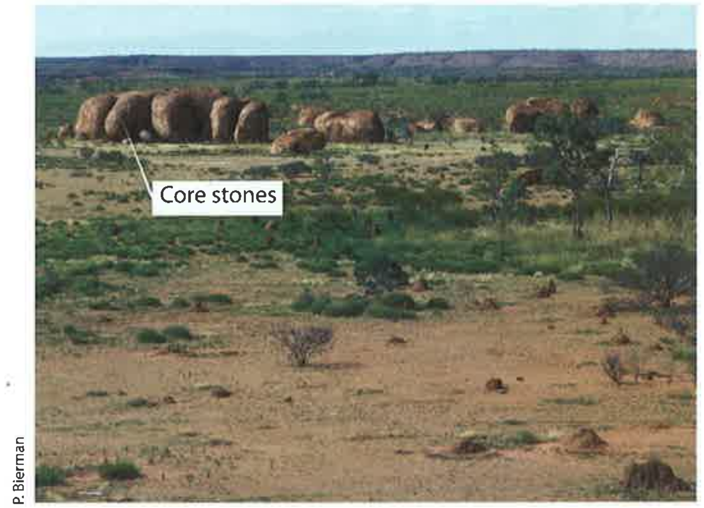


P. Bierman

PHOTOGRAPH 1.2 Continental Landscapes. (a) The mountains of the Dolomite Range of Italy are steep and shed large cones of talus (broken rock). (b) The Dead Sea rift shoulder in Israel is steep, its topography controlled by a rift-bounding normal fault at its base. (c) The Australian craton is in large part flat-lying with little relief. The most weathering-resistant crystalline rocks are exposed as rounded core stones.

the Hawaiian Islands and the Emperor seamounts. In continental settings, hot spots produce areas of high elevation and volcanic activity, like the Yellowstone plateau and caldera in Wyoming. Because hot spots are rooted in the mantle below the crust, they remain stationary as plates move over them, and they result in topographic features that track the direction and rate of plate movement. For example, in the linear volcanic chain of the Hawaiian Islands, the younger islands lie progressively southeastward of older islands, a trend that translates into systematic differences in soil properties (e.g., soil fertility) and degree of topographic dissection (increased valley incision) with increasing island age.

Lithology and Structure

Lithology (rock type) and geologic structures like sedimentary layering, faults, and folds greatly influence erosional resistance. Lithology affects the style of weathering and the soil it produces, the durability of weathered material, and the strength of materials from which hillslopes form. Different rock types vary greatly in their chemical composition, texture, and material strength. For example, the stair-stepped walls of the Grand Canyon, in which hard units hold up steep cliffs and weak units form topographic ledges, provide a well-known example of how lithology affects topography [Photograph 1.3].

Rock structure also plays a key role in determining erosion resistance, because the degree to which rocks have been tectonically fractured, sheared, or deformed

L. Galuzzi

PHOTOGRAPH 1.3 The Grand Canyon of the Colorado River in Arizona. Here, rock type controls topography with strong rocks, such as sandstones and well-cemented limestones, forming steep cliffs, and weak rocks, such as shale, holding gentler slopes and being buried beneath debris.

M. Miller

PHOTOGRAPH 1.4 Folded Manhattan Schist, Central Park, New York City. Weathering has etched out the foliation showing the folds.

influences their material strength. Sedimentary rocks are generally stratified and have bedding planes that create material discontinuities and zones of weakness. The degree of consolidation and the amount and type of interstitial cement also affect the strength and geomorphic expression of sedimentary rocks. Crystalline rocks, like granite, are typically more massive and stronger than many sedimentary rocks. Preferentially oriented cleavage planes and fabrics in metamorphic rocks often dominate their geomorphic expression. Geologic structures that expose rocks with different resistance to erosion can generate distinctive topographic signatures that allow geologists to recognize features like folds, faults, and fracture patterns solely from their geomorphic expression [Photograph 1.4].

Different rock types weather at different rates and produce weathering products with various material strengths and other properties that influence landform development. For example, weathering and erosion often lead to hill and valley terrain with high-standing topography capped by hard, erosion-resistant rock (like quartz-rich sandstone or quartzite) and areas of subdued topography that are underlain by relatively weak rock that is more susceptible to weathering and erosion (such as siltstone and shale). Rocks of a particular lithology may, however, behave differently in different climates. For example, limestone commonly holds vertical cliffs where it is exposed in the arid landscape of Arizona's Grand Canyon but supports only gentle slopes in the humid Appalachian Mountains. The patterns of rock types resulting from the geologic history of a region provide the raw material from which regional topography develops.

Hydrosphere

The distribution and movement of water over Earth's surface, as well as its form (rain, snow, or ice), greatly influence weathering, erosion, and landscape evolution. **Overland flow**, in which rainfall or snowmelt runs off across the land surface, is rare in well-vegetated, humid and temperate landscapes except near seasonally wet river courses. This rarity is the result of plants. Their roots and the organic-rich material that makes up the surface soil horizon (duff) lead to high **infiltration rates**. Depressions, such as the pits left when trees fall over, slow overland flow, allowing it to **infiltrate** (soak into the ground). Shallow subsurface flow is common as water moves through soils and shallow permeable rock on its way to rivers and streams. Subsurface flow also influences rock weathering and soil development. Overland flow is an important runoff mechanism in many arid regions with little vegetation and in disturbed areas where the soil has been burned, compacted, degraded, or paved over. The dynamics of glaciers and seasonally frozen ground dominate hydrologic processes in alpine and high-latitude regions.

Climate and Climate Zones

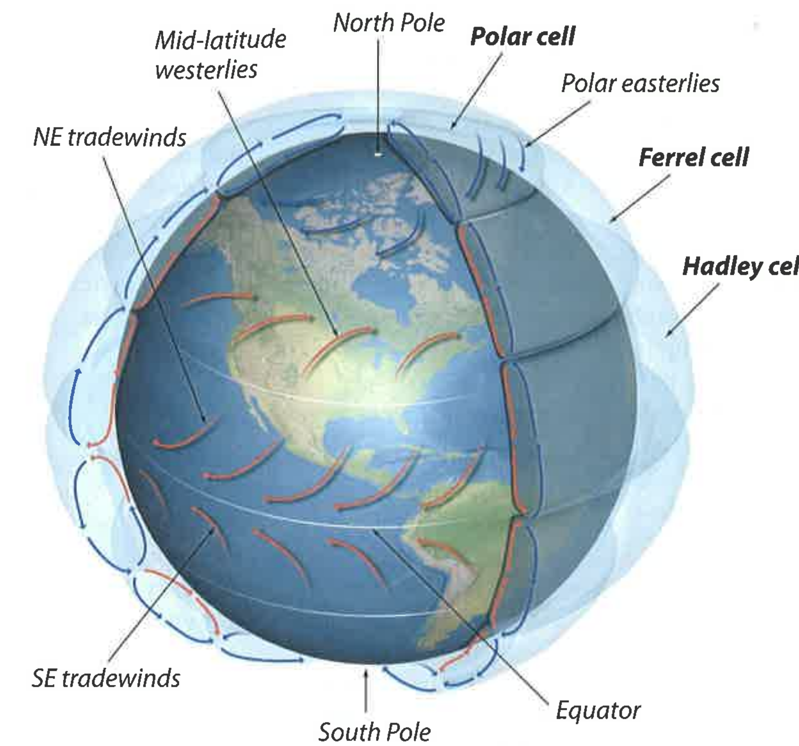
Climate describes long-term spatial and temporal patterns of precipitation and temperature on Earth's surface. Different climates are characterized not only by the average weather but how much the weather varies from day to day and month to month.

Solar radiation provides the energy that drives Earth's climates; it evaporates water from the oceans into the atmosphere, drives atmospheric circulation, and thereby produces wind and storms. The amount of incoming solar energy (**insolation**) varies with latitude, producing an air-temperature gradient between the poles (low insolation and therefore low temperatures) and the equator (high insolation and higher temperatures). The different **albedo** (reflectivity) of the ocean and the land surface also results in temperature gradients. About 30 percent of the energy our planet receives from the Sun is reflected back into space by clouds, particulate matter, and aerosols in the atmosphere and the ground surface.

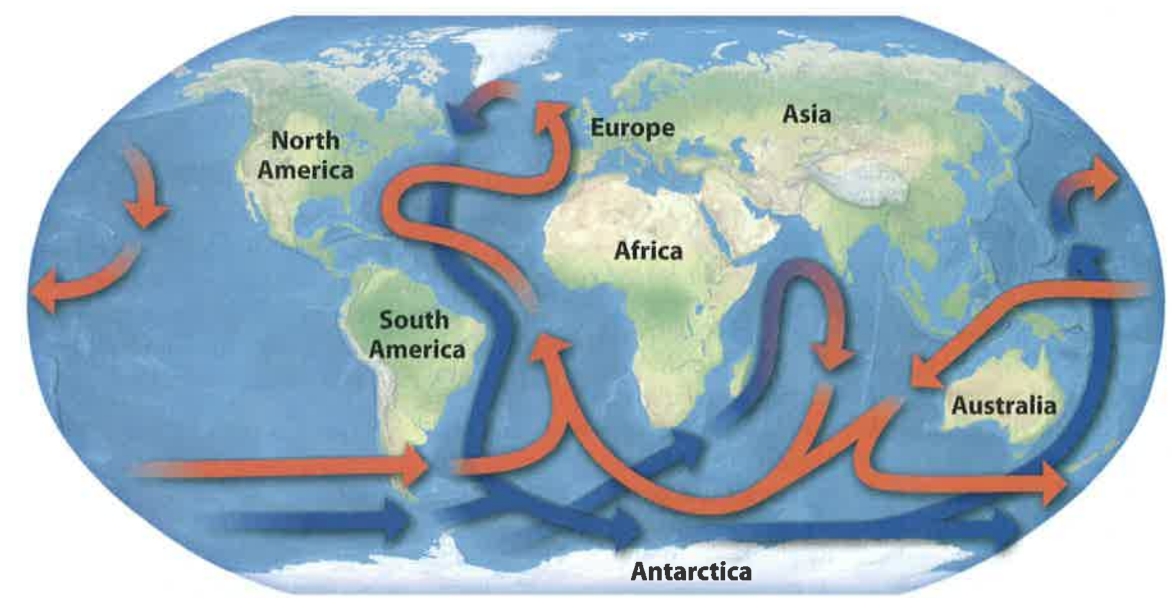
Energy gradients drive atmospheric and oceanic circulation, which result in substantial poleward transfer of heat that delivers warm air and water to higher latitudes. Because Earth's total heat budget is relatively constant, well-defined temperature and precipitation patterns impart different, predictable climates to different regions. Over time, global and regional climates shift in response to changes in solar insolation, including those that arise from changes in Earth's orbit and from fluctuations in the concentrations of heat-trapping greenhouse gases (see Chapter 13).

Atmospheric circulation on our rotating planet gives rise to orderly circulation of rising and falling air masses as well as easterly and westerly zonal winds [Figure 1.5]. These systematic latitudinal variations in temperature, precipitation, and wind create a pole-to-equator sequence of climate zones that have distinctive ecological and geomorphological characteristics. Climate patterns in the Northern Hemisphere are generally mirrored in the Southern Hemisphere. Patterns of atmospheric circulation greatly influence the distribution of precipitation (and thus surface processes) by controlling the moisture content and trajectory of moving air masses.

Latitudinal temperature differences give rise to three great convective cells of atmospheric circulation. In the equatorial **Hadley cell**, moisture-laden air rises in the zone of high surface temperature at the equator. As the air ascends, it cools and loses its capacity to hold moisture, creating a zone of high precipitation in the tropical equatorial zone. Atmospheric circulation in this zone is dominated by the equatorial easterlies (trade winds) that



Large-scale **atmospheric circulation** is dominated by latitudinal circulation cells, defined by bands of rising warm, moist air along the equator (**Hadley cell**) with descending dry air in the mid-latitudes that defines the global belt of deserts. Similar temperate (**Ferrel**) and **Polar** circulation cells characterize atmospheric circulation at higher latitudes.



Ocean thermohaline circulation involves sinking of cold, salty water at the poles (shown in blue). This sinking water produces deep cold currents and shallow warm surface currents (shown in red).

FIGURE 1.5 Global Oceanic and Atmospheric Circulation. Air and water circulate through Earth's atmosphere and oceans, moving heat around Earth in response to unequal input of energy from the Sun over time and over the surface of our planet.

consistently blow east to west. Between latitudes of about 30° and 35°, precipitation amounts are low beneath the dry air masses in the descending limb of the Hadley cell. Earth's great deserts, like the Sahara, the Arabian, the Sonoran, and the Kalahari, are concentrated in these high-pressure subtropical belts. Poleward of the Hadley zone, the prevailing westerlies that consistently blow west to east give rise to the temperate-zone **Ferrel cell**, in which rising air masses produce another belt of high rainfall between 40° and 60° latitude. In polar regions, the descending air of the third, or **polar cell**, delivers little moisture, resulting in cold deserts at high latitudes. These broad latitudinal patterns not only shape regional climates but they influence individual weather events as well. The trajectories of storms in the Northern Hemisphere temperate zone track the unstable, constantly shifting jet stream at the boundary between the Ferrel and polar cells. The short-term variability of this atmospheric interface defines weather patterns, whereas the long-term position controls regional climates.

Temperature and precipitation change with elevation. Within a mountain belt, the local gradient in temperature and precipitation with elevation can be as great as the difference between latitudinal climate zones. Differences in temperature and precipitation define distinct climate zones that greatly influence the ecosystems and styles of geomorphic processes in landscapes at different latitudes or elevations [**Figure 1.6**]. Geomorphic processes involving ice are important in cold, high-latitude, and high-elevation regions; rainfall predominates in temperate and tropical regions; and both wind and water shape arid-region landforms. Some climates can produce distinctive landscapes such as those formed by glaciers; however, some landforms (such as sand dunes) occur in a wide range of climates [**Photograph 1.5**].

At a regional scale, the distribution and orientation of mountains relative to prevailing winds and moisture sources affect the delivery of precipitation. For example, as moisture-laden winds approach a mountain range, air masses flow up and over the high topography. As wet air ascends the windward (upwind) slopes of a range, it cools, loses some of its ability to hold moisture, and the resulting condensation generates precipitation that nourishes lush vegetation on the upwind side of the mountains. By the time an air mass reaches the leeward (downwind) side of a high mountain range, it has lost substantial moisture. Warming as it descends, this low-humidity air continues on to form arid regions and deserts downwind of major mountain ranges.

The **orographic effect** of topography wringing moisture out of the atmosphere results in the development of so-called **rain shadows** on the leeward sides of mountain ranges (and substantial oceanic islands like Hawaii) that tend to be drier than their windward sides. Continental interiors are also drier than coastal areas. Such differences profoundly affect the local climate, ecological communities, and erosion rates and processes that influence the development of topography.

Ocean circulation plays a large role in determining terrestrial climate because ocean currents move large amounts of heat and water from low to high latitudes. Cold currents reduce evaporation and thus contribute to aridity in locations downwind. For example, upwelling of cold water off the west coasts of South America and Africa is a critical factor maintaining the aridity of the Atacama (Chile) and Namibian deserts. In contrast, the warm Gulf of Mexico delivers large amounts of atmospheric moisture to southeastern North America; its warm waters and high humidity nourish hurricanes that can cause large amounts of geomorphic change.

Hydrologic Cycle

The movement and exchange of water among the oceans, land, and atmosphere is known as the **hydrologic cycle** [**Figure 1.7**]. Water evaporated from the ocean surface rises together with warm air to become clouds that move with winds that blow air masses over continents. Precipitation that falls as rain or snow eventually either infiltrates into the ground, runs off over the ground surface to join bodies of surface water, evaporates, or is transpired by plants back to the atmosphere. Whether it is slow-moving groundwater or quickly flowing surface and near-surface runoff, water eventually flows into stream systems that ultimately discharge into the sea. The distillation of freshwater from the oceans, its delivery to the continents, and subsequent return to the oceans drives key geomorphological processes. Most of the water on Earth (97 percent) is held in the oceans. About 2 percent is stored as ice in glaciers and polar ice sheets, and about 0.6 percent is stored as groundwater. Freshwater rivers, lakes, and wetlands account for <0.5 percent of the water on Earth. Humanity depends on the continuous movement of water through the hydrologic cycle to maintain the freshwater supplies that sustain us, irrigate our crops, and support the terrestrial ecosystems upon which we depend.

Biosphere

The **biosphere** defines the realm of life within, upon, and above Earth's crust, and includes organisms ranging from small, short-lived soil microbes that enhance the weathering of rock to gigantic millennia-old redwoods that when they fall over move large amounts of soil downslope. Living systems depend on their physical environments and, in turn, influence the soils, rocks, air, and water in which they live. This interdependence is well illustrated by the complex ecosystems that exist in the soils and fractured and weathered rock at the interface between the abiotic, sterile geology of our planet's deep interior and the biology that covers much of its surface.

The dynamics of Earth's surface processes control the frequency and size of disturbances like floods and landslides that alter biologic and human communities. Disturbances may act to maintain stable ecological systems when

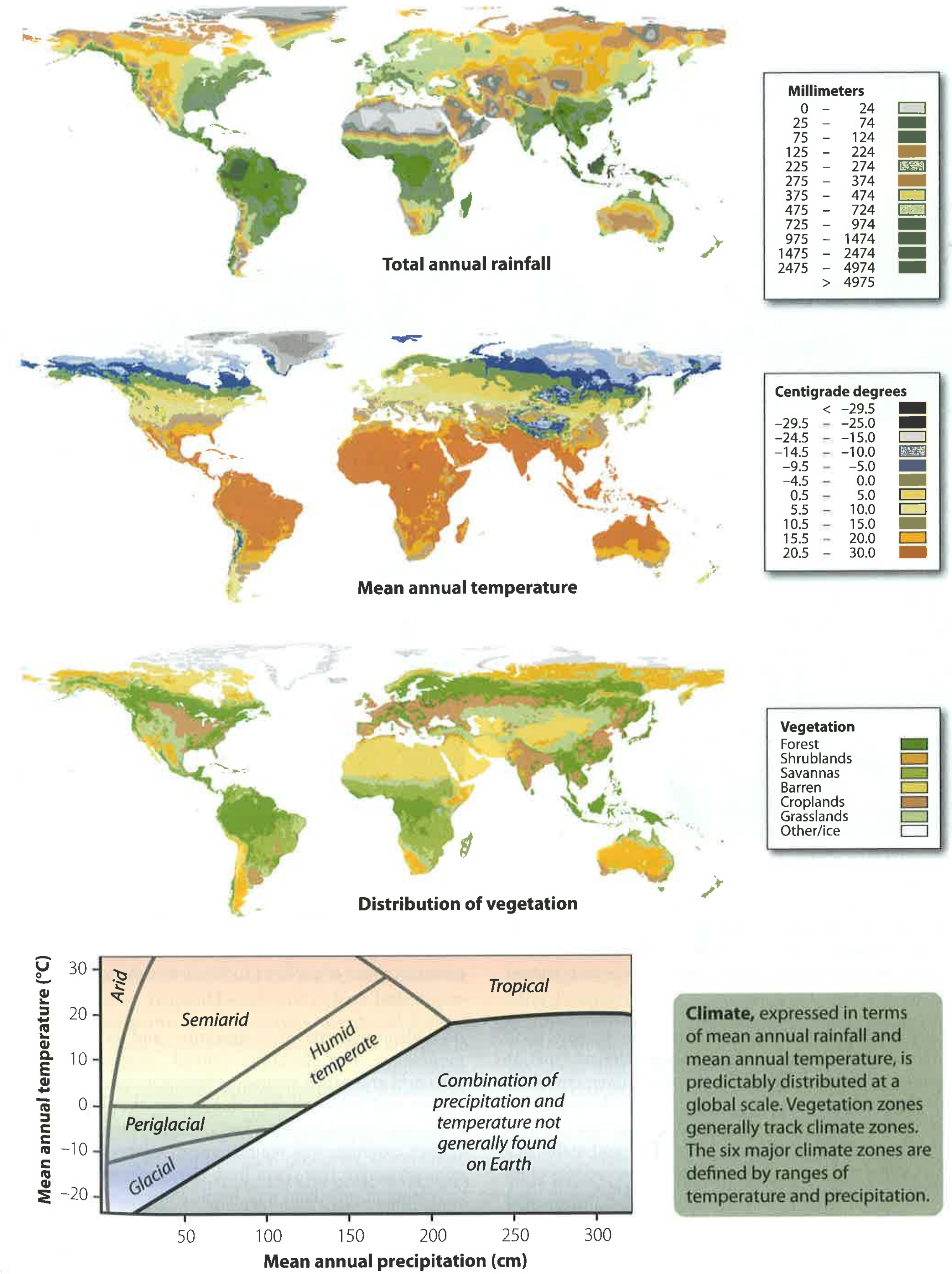


FIGURE 1.6 Global Temperature, Precipitation, Vegetation, and Climate. Earth has distinctive and predictable climate and vegetation zones determined by mean annual precipitation and temperature. These zones shift over geologic time as climate warms and cools. [Adapted from Wilson (1968).]

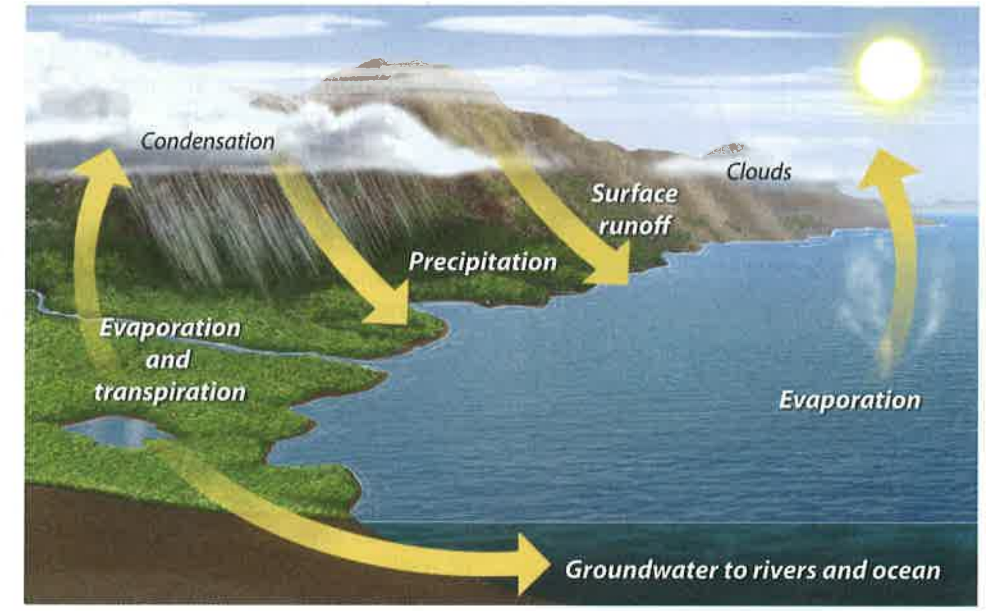
PHOTOGRAPH 1.5 Climate, Geomorphic Processes, and the Appearance of Landscapes. (a) Largely devoid of vegetation, hillslopes in the Atacama Desert of northern Chile are gullied by rare but intense rainfalls. (b) Arctic landscapes are often dominated by ice and diminutive vegetation, stunted by cold and the short growing season, such as here, in Greenland near a recently drained glacial-margin lake. (c) In humid temperate zones, where much of Earth's population lives, the landscape is often tree-covered, such as in Shenandoah National Park, central Appalachian Mountains, Virginia. (d) Alpine landscapes are often steep, rocky, and cold with little vegetation. Such landscapes are characterized by the persistent effects of glaciation such as here in the Austrian Alps.

they predictably recur in the same place. For example, regular inundation of floodplains leads to characteristic riparian vegetation that slows flood flows along river corridors. Conversely, disturbances that are unpredictable and do not occur in the same place (for example, landslides) favor weedy plants that specialize in colonizing and stabilizing freshly disturbed land. Understanding the relationships between ecological communities and the landscapes they inhabit informs our understanding of both.

Geographical Distribution of Ecosystems

The global distribution of plant communities generally tracks global latitudinal climate zones and the elevation-dependent patterns of temperature and precipitation in mountains. Five broadly defined vegetation zones—semi-arid grasslands, temperate forests, tropical forests, arid deserts, and polar regions—characterize the global distribution of plant communities. Each zone has distinctive ground surface coverage, root reinforcement, soil types, and weathering properties that result from its plant communities.

Plants in grassland and forest zones not only generate different types of soils, but their root systems reinforce soils differently so the landscapes differ in their resilience to environmental disturbance as well. Grasslands generally have more biomass below ground than above ground, most of it in roots. Removal of root reinforcement when grasslands are impacted by overgrazing and/or plowing leaves them



The **hydrologic cycle** drives many surface processes. Solar energy causes **evaporation** from lakes, rivers, wetlands, and the oceans as well as **transpiration** from plants. These processes move water vapor into the atmosphere where it condenses. Rainfall and snowmelt convert the **potential energy** of water vapor to the **kinetic energy** of raindrops and flowing water and do work, both as drops that impact the ground and as surface water runoff that collects and flows through channels. Groundwater, recharged by preciptation, weathers rock and destabilizes hillslopes.

FIGURE 1.7 Global Hydrologic Cycle. Water moves through the hydrosphere in vapor, liquid, and solid forms driving many geomorphic processes.

particularly vulnerable to erosion. In forests, extensive root networks form interlocking webs that mirror the extent of the forest canopy and reinforce hillside soils. Geomorphically important effects of forest type include the depth of root penetration, root strength, and the shape of fallen trees that enter rivers. In river channels, the difference between the long, pole shape typical of conifers and the branching structure typical of deciduous trees influences the stability and transportability of wood and thereby the propensity for logjam formation. Tropical forests tend to have little below-ground organic matter and extensively weathered mineral soils. Because most bio-available plant nutrients are held in the plants themselves, it can be hard to reestablish native forests after forest clearing, resulting in ongoing soil erosion.

In contrast to temperate and tropical regions where vegetation clearly plays a major role in the type, frequency, and intensity of geomorphological processes, the geomorphological role of vegetation in arid and polar landscapes can be more subtle. In desert landscapes where plant communities contain little biomass and plant cover is sparse, the presence or absence of even a little ground cover or a thin web of roots can greatly affect soil development and landscape stability. Fragile **cryptogamic crusts** made up of bacteria, mosses, and lichen hold together desert surfaces and prevent wind and water erosion. Biological respiration affects the deposition of impermeable, erosion-resistant calcium carbonate in desert soils—eventually changing subsurface water flow and influencing landform development.

In the arctic, plants, in particular small trees, influence the distribution of **permafrost**, the presence of ground that is frozen year-round. Areas with plants have deeper snow cover because the plants trap blowing snow. This snow insulates the ground beneath from frigid winter temperatures, limiting the freezing depth and keeping ground temperatures warmer over winter. Such areas are more likely to thaw in the summer and thawed permafrost tends to be weak and thus very active geomorphically.

The distribution of animal communities generally tracks climate zones, and these animals can influence the geomorphology of the landscapes they inhabit. For example, spawning salmon reshape bars and pools in Pacific Northwest rivers. Overgrazing by domestic animals accelerates soil erosion, leaves terracettes (small terraces) on hillslopes, and through soil compaction, can trigger gully development. Burrowing animals and mound-building ants and termites can displace and mix tremendous amounts of soil and weathered rock [Photograph 1.6]. Charles Darwin calculated that over the course of centuries, worms steadily plowed and thus mixed the hillside soils of England.

PHOTOGRAPH 1.6 Termite Mounds. Termite mounds in the Northern Territory of Australia indicate the amount of soil moved and stirred by insects.

Plants and animals influence geomorphological processes directly, as when burrowing activity and roots mechanically pry weathered rocks apart, and indirectly, as when plants protect soils from erosion during rainstorms, and roots mechanically reinforce slope-forming materials. Plants also are central to the chemical transformations that accompany the breakdown of rock-forming minerals into the clay minerals that hold nutrients essential to soil fertility. The size of an organism is not necessarily related to its importance or impact. Soil bacteria, for example, are important chemical weathering agents in many environments.

Humans

Humans move enough rock and soil to be counted among the primary geomorphic forces shaping Earth's modern surface. Coal and mineral mining operations move whole mountains and excavate great pits **[Photograph 1.7]**.

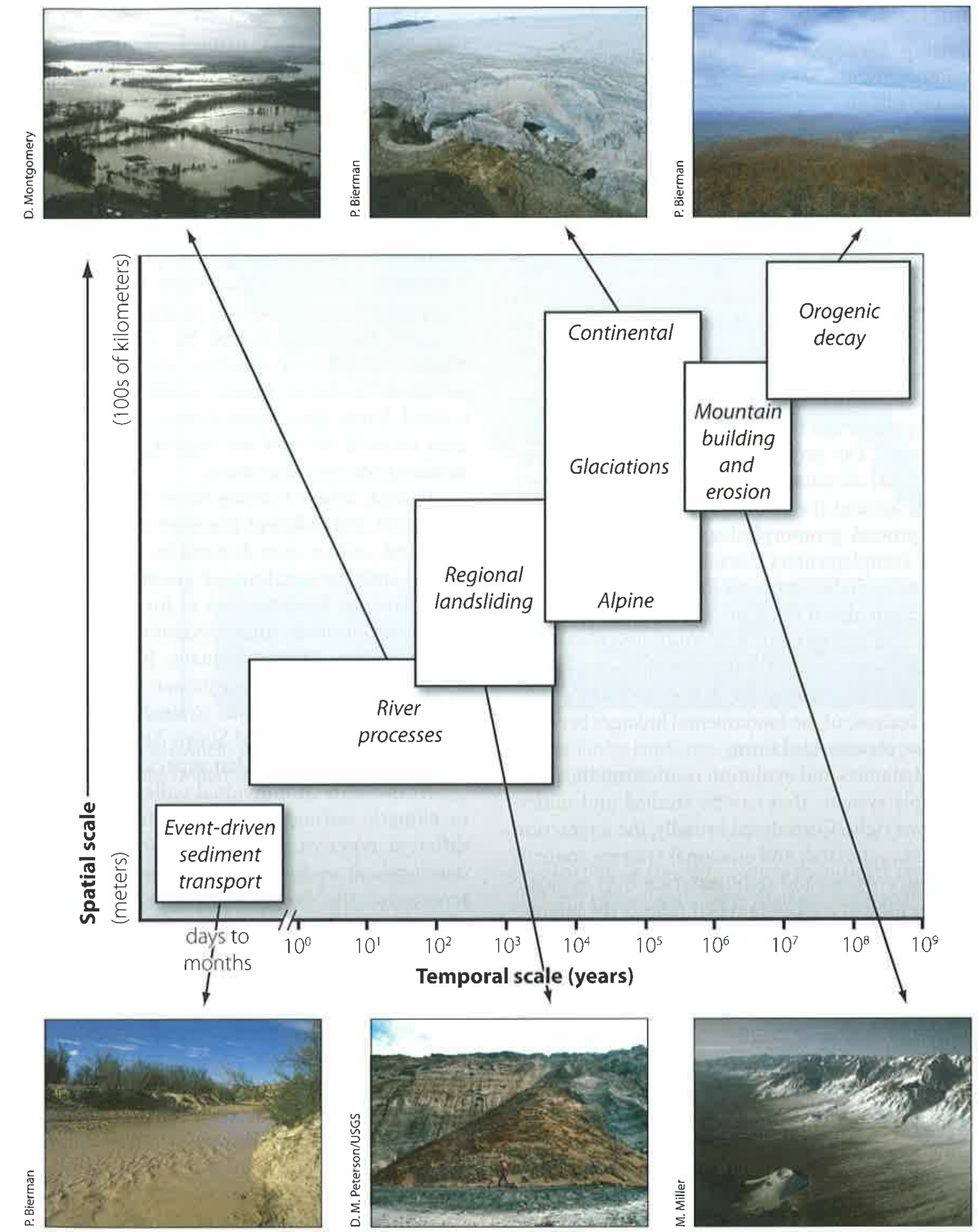
PHOTOGRAPH 1.7 Open Pit Mining. This face of an open pit mine in Brazil shows how tropical landscapes, dominated by extreme weathering, are mined for residual ores, such as aluminum and iron oxides. The depth of weathering is shown by the red iron oxidation in rock tens of meters below the surface. Trees above the mine provide scale.

Farmers' plows push soil gradually but persistently downhill, and construction crews cut or fill the land to facilitate building or to suit our aesthetic whims. Human activities further influence geomorphological processes through the indirect effects of our resource management and land-use practices. In manipulating our world, we alter hydrological processes by changing surface runoff, stream flow, and flood flows. Clearing vegetation and changing water fluxes in the landscape affect slope stability and erosion rates. Construction of dams and coastal jetties interrupts the transport and storage of sediment. Human-induced changes often have unintended consequences far downstream, such as when upriver dam construction starves beaches and deltas of sand and mud by trapping the sediment that formerly flowed to coastal environments. Learning to recognize and understand such connections is central to applied geomorphology, whether to aid in the design of resilient communities, develop more sustainable land-use practices, or construct measures to protect critical infrastructure.

Human activities have resulted in changes to a wide range of local and landscape-scale geomorphological processes. For example, at a local scale, clearing of forests has triggered the erosion of slopes and the accumulation of sediment in rivers. On a global scale, the influence of human activity is great enough that geologists have proposed that we are entering a new period of geologic time that they call the **Anthropocene Epoch** (the human era). Over the next century, human-induced changes in the global climate are predicted to cause increasingly variable weather, more frequent hurricanes, rising sea levels, and a host of related regional impacts, like the loss of winter snow pack critical for maintaining spring and summer stream flows in mountainous areas. Predicting the ways that landscapes respond to such changes will be central to planning societal adaptation and mitigation efforts.

Landscapes

Landscapes are suites of landforms that share a common genesis, contiguous location, and related history. The study of landscapes involves investigations over a tremendous range of spatial and temporal scales, from the movement of a sand dune or gravel bar on a riverbed in a single storm to the rise of the Himalaya and growth of the Tibetan Plateau over tens of millions of years **[Figure 1.8]**. Consequently, the approach, methods, and scale of analysis involved in any particular study need to be tailored to the questions the geomorphologist seeks to address. Landscapes can be divided into distinct units that can be studied over discrete periods of time; the relationships between processes and landforms are fundamental in the modern approach to geomorphology. In seeking to understand landscape evolution, it is important to match the types of measurements and the understanding of geomorphological processes to the spatial and temporal scales over which relevant processes act.



Geomorphically important processes occur on a variety of time and length scales, ranging from **event-driven** transport of sediment grains on a riverbed that happens in seconds and moves material meters, to the uplift and erosion of mountain ranges extending over hundreds of kilometers and taking millions to hundreds of millions of years.

FIGURE 1.8 Spatial-Temporal Range of Geomorphology. Scale is critical to understanding the geomorphology of Earth's surface. Some processes happen on short timescales and over small distances while others are imperceptibly slow and occur on the scale of continents.

Process and Form

The relationship between process and form lies at the heart of geomorphology. Stream flow, slope failure, moving glaciers, and blowing wind act to shape landscapes. At the same time, topography itself determines the style and rate of geomorphological processes. The shapes and orientations of large-scale landforms generally control the rates and distributions of the small-scale erosional and depositional processes that determine how landforms evolve over time. A geomorphologist can often read form to infer process, as in determining dominant wind directions from the shape and orientation of sand dunes. But in order to understand landforms and predict landscape response, we must understand the processes that form the landscape.

The geological and environmental history of a region can leave a lasting signature on landforms and on the processes operating on them. The physiographic signature of long-vanished glaciers still dominates the topography of formerly glaciated regions around the world. Thus, it should not be surprising that **process geomorphology** and **historical geomorphology** are complementary disciplines. Although many geomorphologists specialize in one or the other approach, no geomorphologist can afford to ignore either. Proposing testable hypotheses and interpreting field and laboratory data and the output of computer models in the evaluation of those hypotheses requires considering the action of surface processes over time because of the fundamental linkages between landscape history, process, and form.

Landscape dynamics and evolution result from the interaction of multiple systems that can be studied and understood in their own right. Considered broadly, the interaction of coupled tectonic, climatic, and erosional systems controls patterns of uplift, erosion, and sedimentation over geologic time. The topography of a mountain belt reflects the interaction of tectonic processes that raise rocks above sea level with the hydrologic and runoff processes that govern how erosion acts to shape slopes and incise valleys. At finer scales, many geomorphological processes reflect the interaction of ecological and hydrological systems, such as when the binding effect of tree roots helps to stabilize soils on landslide-prone slopes, or when logjams create dams that divert stream channels to new courses across their floodplains. Understanding landscapes often requires an appreciation of how processes interact in different regional contexts.

Spatial Scales

At global and continental scales, geomorphologists study major physiographic features like mountain belts, depositional basins, and great river systems like the Mississippi, Amazon, or Nile. At these scales, broad patterns in global climate and plate tectonics influence erosion and deposition that, in turn, influence the size and extent of mountains, plateaus, lowlands, coastal plains, and river basins. The resulting geomorphology reflects the relative importance of glacial, fluvial, aeolian (wind-driven), and coastal processes in shaping topography.

At a regional scale, tectonic forces have created distinct **physiographic provinces**, areas in which suites of geomorphological processes govern landscape formation and dynamics, producing similar landforms. In North America, examples of such provinces include mountain belts like the Sierra Nevada or Appalachian Mountains as well as features like the Great Plains, California's Central Valley, the Colorado Plateau in the Southwest, and the eastern Coastal Plain [**Figure 1.9**].

At more local scales, geomorphologists use a variety of techniques to define logical units for the analysis of landscape processes and history. In glaciated terrain, one might consider the area covered by an ice sheet or a valley glacier. Stretches of coastline with similar orientation or substrate (rocky or sandy) could be used for analysis of coastal landscapes. Sand source, wind direction, or the area covered in sand are logical units of analysis where aeolian processes dominate.

In areas where running water is the predominant agent of erosion and sediment transport on land, a **drainage basin** (the land surface area drained by a stream or river) is the logical unit for analysis of geomorphological processes. Small streams flow together to form larger rivers, so landscapes are naturally organized into smaller drainage basins nested within larger drainage basins. Drainage basins range in size from a headwater catchment that collects water from a single hillside to the Amazon River basin that drains more than half of South America. **Drainage divides** are topographic ridges that separate drainage basins.

At the scale of individual valley segments, the tectonic or climatic setting of a region often defines areas where different types of processes and/or histories have led to development of distinct landforms and dynamics. The difference in cross-sectional form between U-shaped valleys carved by glaciers and V-shaped valleys cut by streams is a classic example. There are systematic downstream changes in stream valley morphology, from erosional headwater streams with narrow valleys confined between bedrock walls, to the broad, unconfined valleys of depositional lowlands. Distinct suites of valley segment types are diagnostic of specific physiographic provinces.

At finer spatial scales, landscapes can be divided into distinct hillslopes, hollows, channels, floodplains, and estuaries. **Hillslopes** (including hilltops) are the undissected uplands between valleys that function as sources of sediment. **Hollows** are unchanneled valleys that typically occur at the head of channels in soil-mantled terrain. **Channels** are zones of concentrated water flow and sediment transport within well-defined banks. Valley bottoms are generally zones of sediment storage and include both active **floodplains** formed along river valleys by land that is inundated during times of high discharge under the present climate, and **terraces**, abandoned floodplains formed under conditions that differ from those at present. **Estuaries** are locations where streams entering coastal waters arrive at their ultimate destination—sea level. Each of these individual landscape

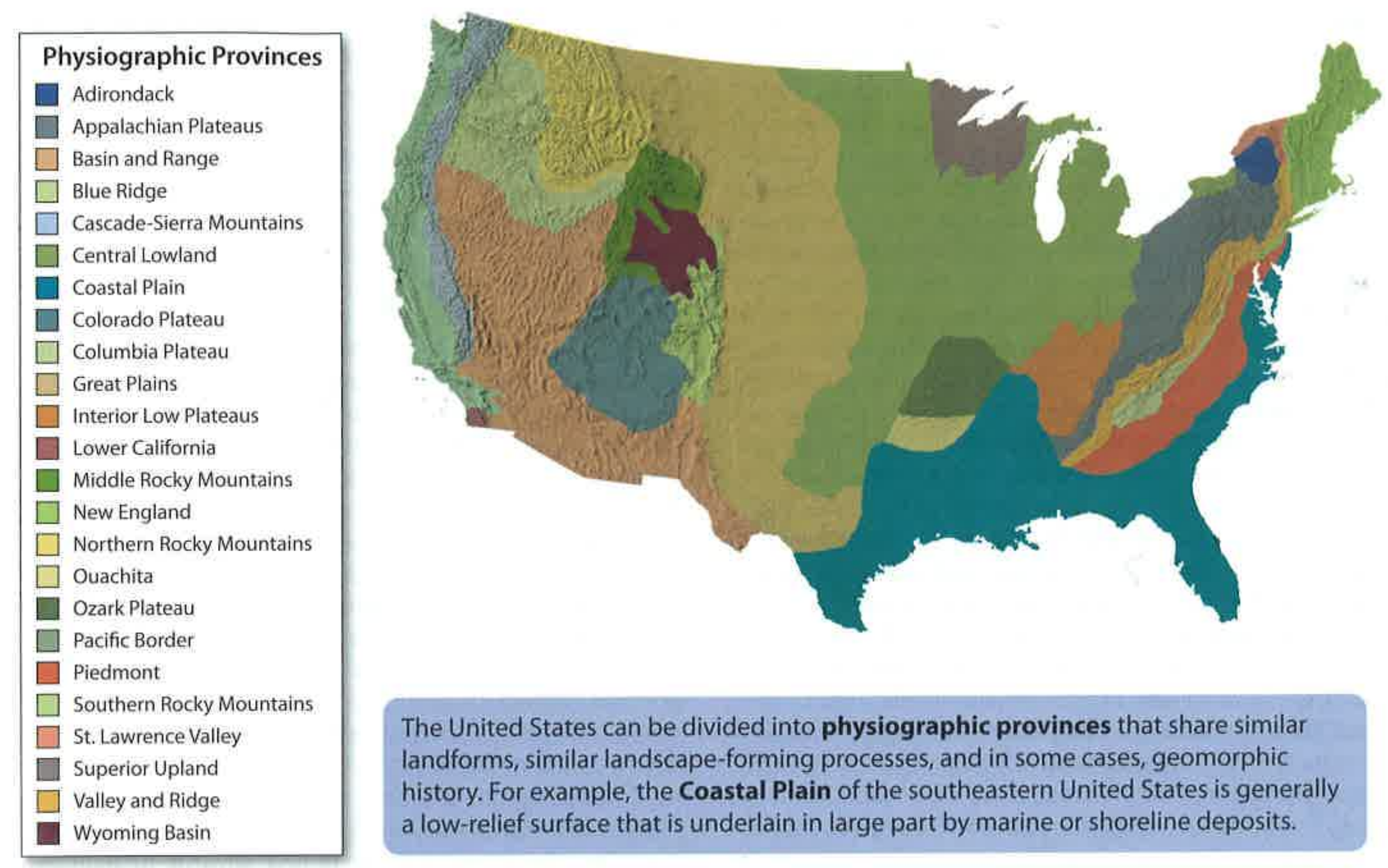


FIGURE 1.9 Physiographic Provinces of North America. Physiographic provinces of the United States are defined on the basis of similar landforms, geomorphic histories, and active surface processes.

units exhibits a variety of specific landforms that are discussed in later chapters.

Temporal Scales

Interesting changes in the landscape occur over a variety of timescales. For example, topography evolves over periods of time that range from the few seconds, minutes, or days it takes for an earthquake-driven fault displacement, landslide, or flood to disrupt the land surface to the tens of millions of years required to erode away mountain belts. Climate cycles influence landscapes over millennia as glaciers advance, retreat, and scour out alpine valleys. Likewise, river profiles adjust to the sea-level changes that accompany glaciations. Large disturbances, like hurricanes and volcanic eruptions, often affect landscapes for centuries; it can take decades for landslide scars to revegetate and for river channels to process the sediment shed from slopes during intense, long-duration storms. River flow exhibits annual and seasonal variability that controls the timing of sediment movement.

Geomorphologists deal with a wide variety of measurements that represent process rates over very different timescales. For example, erosion rates directly measured in the field might be representative of months to years of geomorphic activity. In contrast, indirect estimates of rates of long-term landscape change inferred from isotopic analyses, or constrained by the volume of sediment preserved in depositional basins, can represent the average erosion rate over hundreds of thousands of years. Because of the disproportionate influence on erosion and sediment transport of infrequent extreme events like storms, landslides, and floods, rates of processes measured over short time spans may be very different from those measured over longer timescales. Since erosion and deposition include both chronic and episodic contributions to mass transport and landscape change, it is necessary to use a measuring scheme that samples over the magnitude and frequency of both types of contributions.

It is important to use measurements and analyses relevant to the timescale of interest because the timescale of observations can strongly influence geomorphic interpretations. For example, in the Blue Mountains of Australia, near Sydney, and in the mountains of Idaho, short-term rates of sediment export by streams are much lower than isotopic estimates that represent thousands of years of surface erosion and estimates of rock removal that consider millions of years of change. Geomorphologists reconciled this apparent difference by considering the impact of very large but very rare storms that move large amounts of sediment out of drainage basins. Because such storms recur hundreds of years apart, they are unlikely to influence short records, but they matter greatly over the long term.

Unifying Concepts

A number of core scientific concepts are central to contemporary geomorphology and guide our understanding of Earth's dynamic surface. Among these are the conservation of mass and energy, the routing of material through landscapes, force balances and thresholds in natural systems, equilibrium and steady state, and the relationship between the magnitude and frequency of geomorphic events. These concepts are fundamental to the discipline of geomorphology, and you will encounter them throughout this book.

Landscapes are created by the movement of matter through space. Gravity pulls water and sediment downhill. Thus, the routes that material takes from sources in eroding uplands to sinks in depositional lowlands and marine environments provide a common framework within which to consider the action of geomorphological processes across landscapes. The balance between driving and resisting forces allows us to quantify the way that stable landscape features may change state or become destabilized. The frequency with which events of a given magnitude occur is as important as the magnitude of events in considering their geomorphic significance. Together, these unifying concepts help structure a general, systematic approach to studying how Earth's surface processes interact to shape landscapes.

Conservation of Mass

Landscapes are dynamic systems through which mass is continually moving. Individual landforms can lose or gain mass over time; for example, rocky outcrops disaggregate and erode over time as they weather, but mass is conserved as it moves downslope. Eroded material is transformed by chemical reactions or physical abrasion as it moves, but it always ends up somewhere else. For example, a delta system at the mouth of a river grows because of input of sediment from upstream sources. Deltas erode away when gravity and ocean currents remove more sediment than the river supplies. Similarly, a mountain range erodes down to gentle hills over geologic time after tectonic uplift ceases because erosion removes mass from the mountain system. Tracking the flow of mass through geomorphic systems gives us a powerful framework for understanding Earth's surface processes.

In geomorphic systems, a simple yet very useful concept is that the difference between inputs (I) and outputs (O) during some time period equals the change in storage (ST):

$$I - O = \Delta ST \qquad \text{eq. 1.1}$$

where the Greek symbol delta, Δ, stands for change. This idea is simple and familiar. If you continually deposit money in the bank, your balance (storage) increases. If all you do is spend, you deplete your savings. Do this for long enough and you eventually run out of money. The same concept holds for soil, rock, and sediment. A mountain range eroding faster than tectonics raises it loses elevation. A river that receives more sediment than it can transport fills its valley with alluvial deposits.

Conservation of Energy

Energy is neither created nor destroyed but only transformed. Potential energy, the energy of position and configuration, like that of a boulder perched high on a cliff, may be converted into kinetic energy. Imagine that same boulder rolling off the cliff and crashing to the ground below. Its initial potential energy is transformed into kinetic energy as it falls and picks up speed (with a small loss to heat by friction in the air). When the boulder strikes the ground, the kinetic energy gained in the fall might shatter the rock or be imparted to anything it dislodges.

Rain or snowfall that is delivered to the land surface has potential energy of position. As water sinks into, collects upon, and runs off over the land surface, that potential energy is converted to kinetic energy. The kinetic energy is used to transport sediment and generates heat through friction. Water flows downhill under the influence of gravity, providing the energy for rivers and streams to maintain channels, transport sediment, and incise valleys. The frequency and magnitude of precipitation across a landscape—how much water falls where—determines the potential energy that is converted to kinetic energy. Most of the kinetic energy of the flow is dissipated by friction and turbulence generated as water moves across the channel bed and banks, leaving just a fraction to do the geomorphic work of transporting sediment and eroding bedrock.

Topographic slope sets the erosive potential of a landscape. Steep landscapes in general erode more quickly because the potential energy gradient (slope) controls the rate and magnitude of energy conversion, thereby linking process and form. The rugged Himalaya is eroding rapidly; the flat plains of central Australia are not.

Material Routing

Geomorphic systems route material from eroding sources to depositional sinks. In coastal systems, sand may move from beaches offshore to deeper water. In eolian systems, dust may originate in barren windy areas and be deposited in more heavily vegetated regions downwind. However, the one-way flow of water down river networks, of ice down glacial valley systems, and of soil and rock down hillslopes are the predominant agents of mass transport on the continents. Material eroded from the headwaters of a drainage basin eventually makes its way down through the river network and becomes the sediment supply for downstream channels before finding its way to depositional basins.

Tracking material from upland sources to lowland depositional sinks is particularly useful for considering how geomorphological processes interact to form and shape most landscapes. Headwater areas are generally steep, erosional regions where rocks weather and break down into transportable material. Sediment mobilized from upland slopes is delivered to streams and rivers and then transported to lowland depositional environments, to the coast, and ultimately to the deep ocean plains **[Figure 1.10]**. Because they are zones of erosion, steep headwaters are rarely preserved in the geologic record. Thus, to reconstruct the erosional history of continental highlands, we rely mainly on the geologic record of depositional environments where material stripped from erosional source areas was deposited near or below sea level. A source-to-sink framework shows how the erosion, transport, deposition, and storage of sediment drive landscape evolution and dynamics.

Force Balances and Thresholds

Force balances are fundamental to our understanding of geomorphic processes, particularly the balance between driving forces imparted by gravity and resisting forces offered by Earth materials. Force balance calculations help geomorphologists analyze a diverse set of processes, including, but not limited to, slope stability, the movement of sediment along the bed of a river, and the flow of ice down glacial valleys **[Figure 1.11]**. Generally, the ratio between driving and resisting forces is determined using vectors to resolve gravitational driving forces in the downslope direction; **constitutive equations** are used to quantify how earth materials like rock, soil, and ice resist deformation or failure.

In considering the relationship between an applied force and the surface it acts upon, it is useful to resolve the force into normal and shear components that respectively act orthogonal to (normal) and parallel to (shear) the land surface. We use trigonometry to resolve forces arising from the unit weight (the product of density, ρ, and gravitational acceleration, g) of a column of rock, soil, water, or ice of thickness z, on a surface, like a hillside or riverbed that slopes at an angle θ, into normal and shear components. The **normal force** per unit area, the stress, is given by

$$\rho\, g\, z \cos\theta \qquad \text{eq. 1.2}$$

The normal stress acts into the surface to hold material in place on slopes and resist downhill movement on slopes through solid friction. The shear stress is given by

$$\rho\, g\, z \sin\theta \qquad \text{eq. 1.3}$$

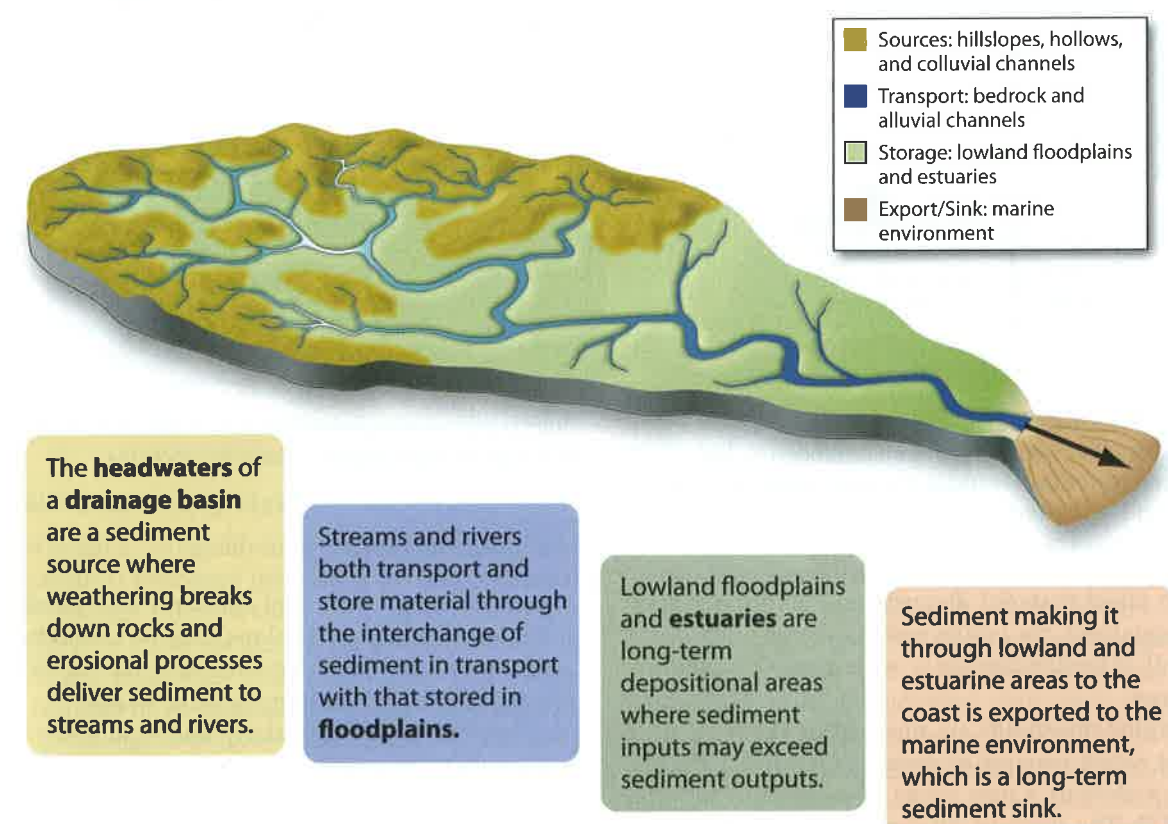
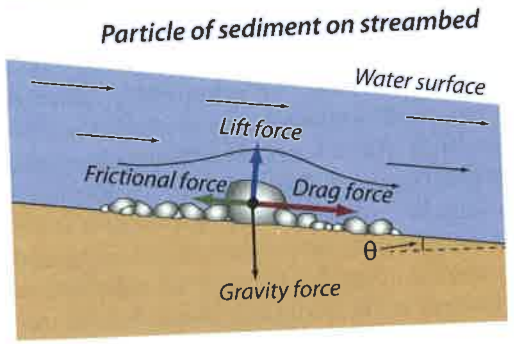
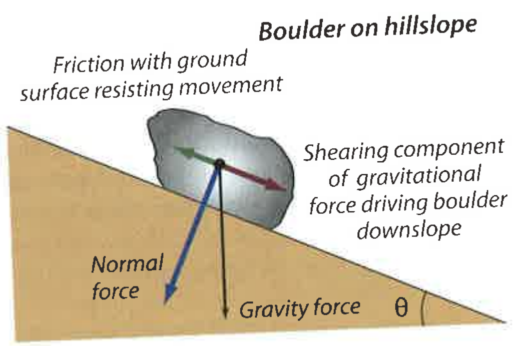


FIGURE 1.10 Drainage Basins: Source-to-Sink. It is useful to understand Earth's surface from the perspective of drainage basins—units of the landscape in which mass can be accounted and conserved. In general, sediment is sourced in the eroding uplands and deposited in lowland sinks, although it may be stored temporarily in floodplains along the way to long-term storage in marine environments.

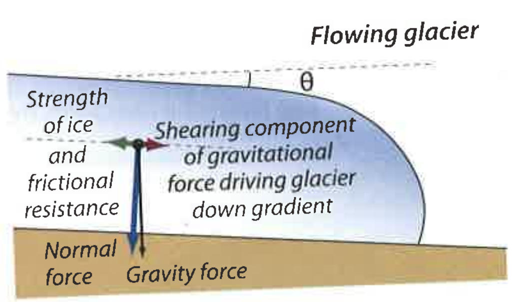
Many surface processes are driven by gravity. To calculate force balances and determine whether a landscape element will be stable, it is helpful to resolve the downslope force into the components resisting and driving movement, respectively oriented perpendicular to the slope (**normal force,** ⟶) and parallel to the slope (**shearing force,** ⟶).



Sediment on a stream bed is subject to a variety of forces. The **gravity force** holds the grain on the bed opposing the **lift force** generated by the current. The current also applies a **drag force** to the grain. The drag force is resisted both by **frictional forces** and by the resistance offered by neighboring grains if the clast is embedded. When the lift and drag forces exceed the forces of gravity and friction, the grain of sediment moves.



A boulder on a hillslope remains stable as long as the frictional force, holding the boulder in place, exceeds the **driving force,** in this case a **shearing force** parallel to the slope. Once the driving force exceeds the frictional force, down goes the boulder. Earthquakes, tectonic tilting, and slope undercutting can increase the driving force or reduce the normal force.



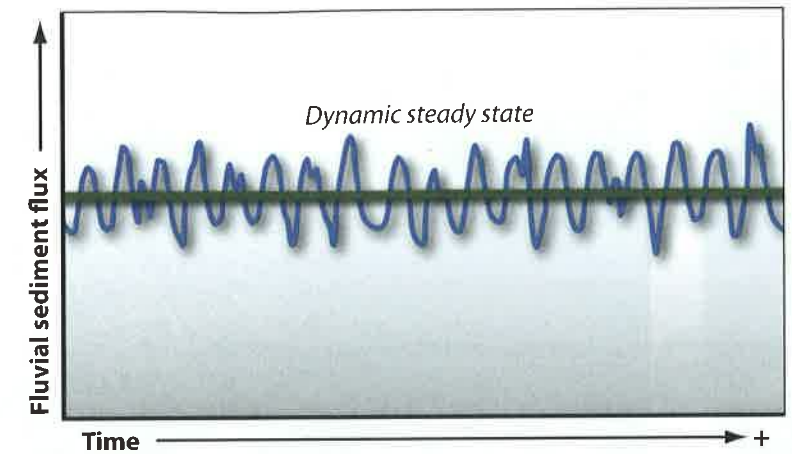
Glaciers flow by deforming and sliding along their bed. The driving force is the shear stress governed by the slope of the ice surface. The **resisting forces** include the strength of ice to resist internal deformation and the frictional resistance to sliding of material at the bed of the ice.

FIGURE 1.11 Force-Balance Diagrams. Force balances are a physical way of understanding Earth surface processes. The dynamic interaction between driving forces that tend to move objects and resisting forces that tend to prevent movement can be used to explain a diverse range of processes.

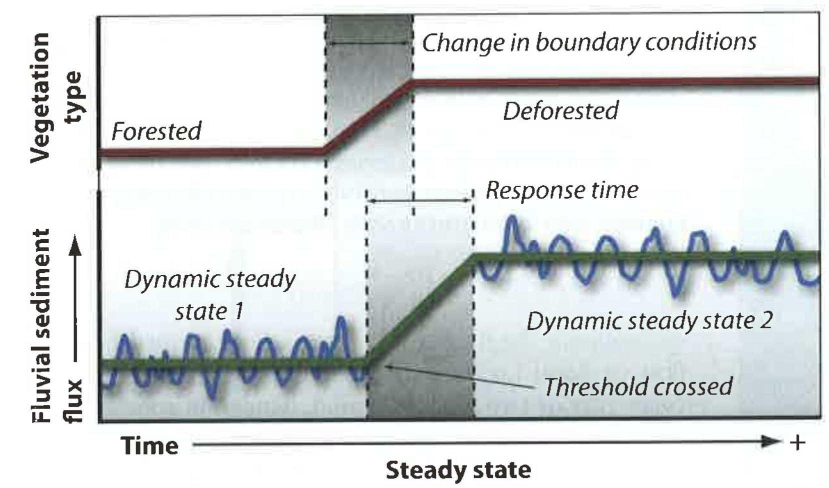
and acts to impel material downslope. The difference in these two equations, the cosine versus the sine function, is fundamental to understanding a wide range of geomorphic processes.

Geomorphic **thresholds** are physical or chemical conditions that, when reached or exceeded, trigger a change in state or a shift to a new range of average conditions (**Figure 1.12**). The concept of geomorphic thresholds is important because many landscape processes and landforms are prone to the influence of individual events. The idea is that a geomorphic system may remain stable until an event of sufficient strength tips the balance, causing the system to cross a threshold and settle into another steady state. For example, a hillslope may be stable for decades until a very large rainstorm saturates the soil, reducing the resisting force and causing the slope to slide.

Thresholds are particularly important when considering a variety of geomorphic environments and processes including mass movements, sediment transport, and volcanic eruptions. A central implication of the concept of geomorphic thresholds is that small changes can trigger large responses. Changes triggered by crossing geomorphic thresholds sometimes cause a cascade of responses, referred to as a **complex response**, in which different parts of a



The flux of sediment from an undisturbed drainage basin changes over the short term as rainstorms come and go, individual hillslopes fail in mass movements, and riverbanks collapse. Over the long term, the flux of sediment from a drainage basin oscillates around a mean value, producing a **dynamic steady state,** unless there are significant changes in **boundary conditions,** such as climate, vegetation cover, or uplift rate.



When boundary conditions change significantly, geomorphic systems adjust. Such adjustment does not happen instantaneously, rather it lags the change in boundary conditions, over a **response time.** In this case, deforestation and land conversion to agriculture increased the fluvial sediment flux to a new and higher dynamic steady state because soils are now disturbed by plowing and thus more vulnerable to erosion.

FIGURE 1.12 Steady State, Thresholds, and Response Time. Many geomorphic systems are in steady state, their central tendencies oscillating in equilibrium around a mean value. When external factors, such as climate or base level, change, the system can cross a threshold and, after a certain response time, change to a new and different state, in which the system may oscillate around a different mean.

system reach the threshold conditions at different times. The responses may be out of phase in different portions of the channel network, such as downstream channels that incise while upstream reaches remain sediment-choked.

Equilibrium and Steady State

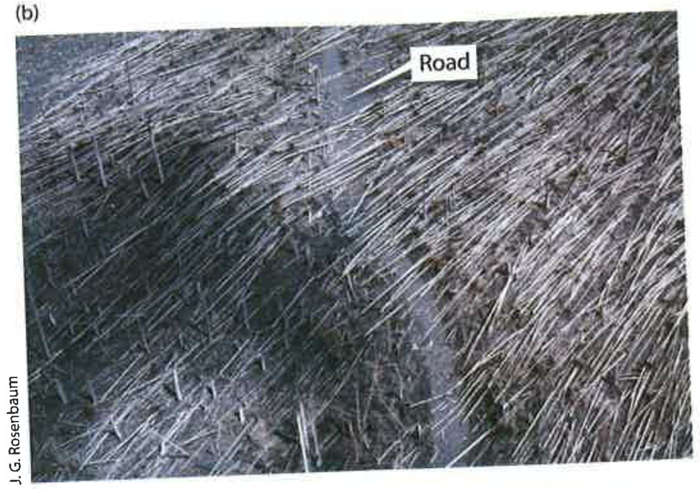
The idea of balance, or **equilibrium,** between landforms and geomorphological processes provides a useful conceptual framework through which to study landscape evolution, as well as a reference frame for identifying and understanding **nonequilibrium landforms and landscapes.** It is often useful or convenient to assume an equilibrium landscape that does not change over time—a condition referred to as **steady state.** Equilibrium is, however, often not static, but is rather a **dynamic steady state** (see Figure 1.12), with landscape characteristics that vary over time around a central tendency. Steady state is strongly scale-dependent. The average slope of a mountain range, for example, remains constant if erosion and rock uplift rates are equal over time, even if individual erosional events greatly change local slopes in the short term. The timescales over which topography equilibrates to changes in landscape-forming processes range from seasonal resurfacing of gravel streambeds following winter storms to the tens of millions of years it can take to erode mountain ranges.

Landscapes may appear unchanging, but considered geologically, topography is dynamic because material is constantly being entrained, transported, and deposited. Over centuries to millennia, such changes result in a **dynamic equilibrium** that maintains topographic forms in an average sense even as individual slopes experience landslides; coastal landforms shift with currents, tides, and storms; and rivers migrate across their floodplains. Over longer timescales, sometimes referred to as **cyclic time,** landforms evolve in concert with tectonic and climatic changes. For example, once tectonically driven rock uplift ceases, mountains slowly erode away and average slopes decline. The **response time** of a landscape or landform to changes in driving or resisting forces varies greatly

(a)

J. Stovall

(b)



J. G. Rosenbaum

PHOTOGRAPH 1.8 Disturbances Come in Many Different Length Scales. (a) Blowdown of a single tree in the Adirondack Mountains of New York State disturbs several tens of square meters. Two-meter-high student for scale. (b) When Mount St. Helens erupted on May 18, 1980, much of the volcanic edifice collapsed and many square kilometers of trees were blown down by the volcanic explosions. Aerial view of timber blown down by eruption, with forest road for scale (Skamania County, Washington).

depending on the type of change, the rates of landscape-forming processes, and the resistance of the landscape to a particular change. All landscapes reflect the shifting balance between driving and resisting forces, and the response time to changes in either.

Recurrence Intervals and Magnitude-Frequency Relationships

Most changes on Earth's surface happen in response to discrete events that disrupt the land surface, move mass, and change surface forms. Geomorphic disturbances come in a wide range of scales, from massive volcanic eruptions and hurricanes with 200 km/hr winds and storm surges several meters high to a lone tree falling over, mixing the soil held by its roots [**Photograph 1.8**]. Both the frequency of disturbances and the duration of geomorphic events vary over many orders of magnitude.

Geomorphic events, while randomly distributed in time, generally have a characteristic **recurrence interval**, the average time between events of a similar magnitude. Take, for example, a flood that is just barely capable of overtopping the banks of a river, a level termed **bankfull flow**. A flood of this magnitude occurs, on average, once every year or two in most humid, temperate zone streams, while the recurrence interval of such bankfull flow may exceed 50 years in arid-region channels. Likewise, landslides on hillslopes have typical recurrence intervals of centuries to millennia. Many events that are important in shaping landscapes, including earthquakes, floods, and hurricanes, have discrete **magnitude-frequency relationships** that quantify the relationship between the size of an event and the chance that it will occur in a given time period [**Figure 1.13**].

It is important to note that different environments can have different recurrence intervals for the same process, a result of differing climate and tectonic setting. Furthermore, sometimes it is an infrequent event that shapes the landscape (for example, glaciation) and sometimes it is a frequent event, such as the annual flood.

Applications

The relationship between geomorphological processes and landforms has applications across all aspects of the human endeavor, from feeding a growing population sustainably to disaster preparedness, land-use planning, ecological restoration, and planetary exploration. Fundamental understanding of geomorphological processes lays the foundation for applied geomorphology. The dynamic nature of Earth's surface means that geomorphology has

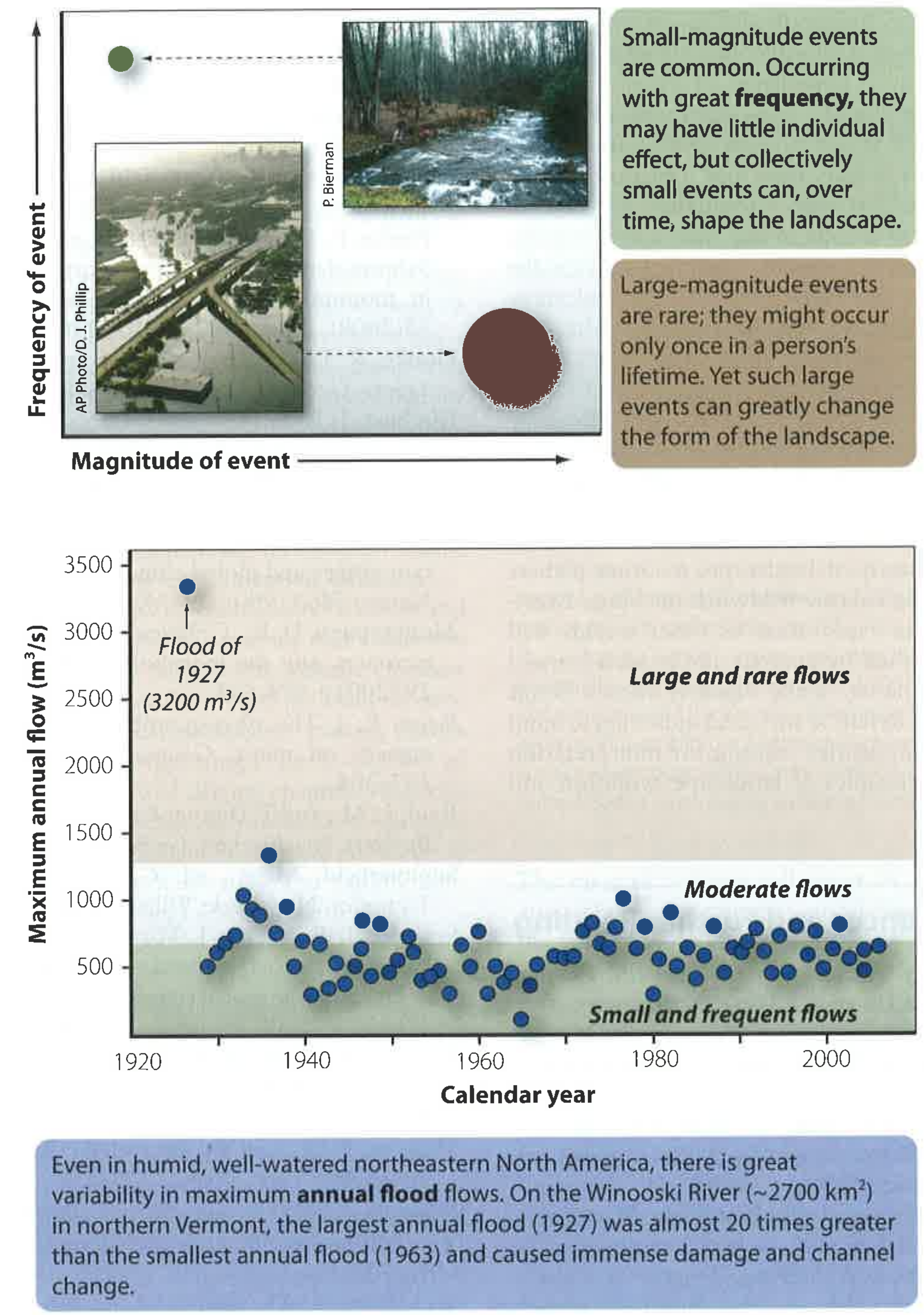


FIGURE 1.13 Magnitude-Frequency Relationships. At Earth's surface, small, low-intensity events are common, but rare, large-extent or high-intensity events may dramatically affect the landscape.

important ties to other disciplines, from civil engineering to agriculture and ecology.

Geomorphology plays a key role in natural hazard assessment, prevention, and recovery. Our ability to predict how landslides, floods, earthquakes, storms, and sinkholes will change Earth's surface is essential in efforts to minimize loss of life and property destruction, to mitigate or repair damage, and to modify our behavior to minimize future damage from these hazards. Geomorphology is an essential foundation for rational land-use planning and landscape management, particularly for landscape-scale natural resource management, like forestry and agriculture. In particular, understanding how natural processes shape landforms and river systems is a key part of developing strategies that mitigate human impacts and guide ecological restoration efforts.

The ability to read the landscape has proven invaluable for military planning for millennia. History is replete with examples of how knowledge of geomorphology led to military triumph, and how ignorance or neglect led to disaster. Thick layers of dust hidden just below rocky desert surfaces in Iran, Iraq, and Afghanistan have plagued helicopters that were originally designed to maneuver and deploy troops in the humid and muddy, but dust-free, jungles of Vietnam. Hannibal crossed the Alps in 218 BCE and lost thousands of troops and many of his elephants when they were overwhelmed by avalanches. History repeated itself during World War I, when many troops were buried by avalanches in northern Italy, some triggered intentionally on steep mountain slopes by the opposing army. Knowing what to expect from the terrain has proven invaluable time and again throughout history.

Spectacular advances in planetary geomorphology have extended the study of landscapes to other planets and moons, including robotic fieldwork on Mars. Exciting challenges in the exploration of other worlds will continue to be informed by analogs and lessons learned here on our home planet. While much is known about the nature of Earth's dynamic surface, landscapes around the world still harbor stories waiting for interpretation using the general principles of landscape evolution and dynamics.

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DIGGING DEEPER Why Is Earth Habitable?

Earth is the only planet we know of that harbors life. So far, our planet appears to be a special place where the interactions and feedbacks among the solid Earth, the hydrosphere, the biosphere, and the atmosphere provide conditions favorable for living organisms.

What makes Earth so special? Earth is habitable because liquid water is stable on its surface; it is large enough to retain an atmosphere and some internal heat; and it has a composition of long-lived **radioactive elements**, along with the original accretionary heat, to warm the planet's interior even after 4.5 billion years. This heat warms and softens interior rocks, sustains mantle flow, and thereby drives plate tectonics. The same heat keeps the core partially molten, allowing for the generation of a strong magnetic field. Without our magnetic field and thick atmosphere, Earth's surface would be bombarded by life-threatening levels of **cosmic radiation.**

Together, these characteristics enable active tectonic and volcanic processes to continue. **Tectonism** and **volcanism** are critical for life because they recycle **volatile elements** and compounds critical for carbon-based life from the geosphere to the atmosphere and hydrosphere—making Earth's surface dynamic and life-supporting. Life is capable of reducing **entropy** (disorder) and driving chemical reactions that are not thermodynamically favorable. For example, without life, atmospheric oxygen is unlikely to occur in Earth's atmosphere because it is easily and rapidly consumed in **oxidation** (weathering) reactions with rocks.

Life as we know it requires the presence of liquid water and is thus limited to average temperatures in the range of approximately −15°C to 115°C. The **habitable zone** around a star is defined as the range of distances at which surface temperatures on a planet could potentially support liquid water. For our solar system, the habitable zone extends from about 0.84 to 1.7 times Earth's distance from the Sun, a range that includes Earth and Mars but not Venus.

The presence of liquid water is not only important for life itself, but it is also important for the **differentiation** of **continental crust** through the formation of granitoid rocks (Campbell and Taylor, 1983). In our solar system, Earth is the only inner planet with abundant water and the only known planet with continents. The formation of continents occurred as partial melting of oceanic crust released silicon- and potassium-rich, felsic magmas, a process that depends on water being carried (by **subduction**) into the mantle to initiate **partial melting.** Creation of extensive continents with a density low enough to stand above sea level requires the transport of large amounts of water into the upper mantle and thus requires tectonics. Continental rocks weather subaerially (under the atmosphere), consuming carbon dioxide (CO_2) and water, and thus in part control the composition of Earth's atmosphere [**Figure DD1.1**].

Planetary atmospheres are a key part of the habitability puzzle, in part because they buffer thermal swings that would otherwise occur between night and day and between seasons.

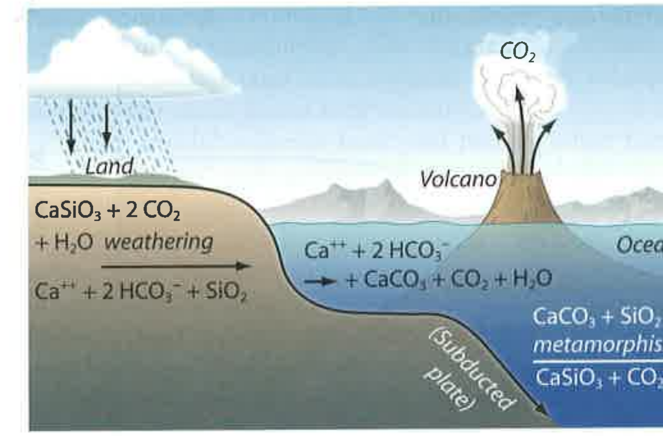

FIGURE DD1.1 This diagram shows the global cycle of carbonate and silicate, which is driven by surface weathering and plate tectonics. Silicate rocks exposed on land weather as they combine with water and carbon dioxide (CO_2). The weathering products, those that are not left on the land, enter the ocean and are eventually subducted by plate tectonics. Once subducted, CO_2 and water are released back to the atmosphere by volcanism and the cycle continues. Without plate tectonics, weathering on Earth's surface would slow and the atmospheric levels of CO_2 would be quite different. [From Kasting and Catling (2003).]

The mass of a planet influences its potential to retain an atmosphere, a seemingly critical ingredient for life; small planets and moons have insufficient gravity to hold an atmosphere. For example, the atmospheric density of Mars, which is one-third the size of Earth, is 1/100th that of Earth and does not provide much insulation (it gets very cold on Mars); nor does the Martian atmosphere provide much radiation shielding. In contrast, the atmosphere of Venus is 100 times thicker than that of Earth but is made of greenhouse gases, primarily CO_2, that make it too hot there for life. On Earth, the weathering of rocks and tectonic cycling of crustal materials absorb the greenhouse gas carbon dioxide from the atmosphere and thus stabilize global climate (Kasting and Catling, 2003; see Figure DD1.1), keeping Earth cooler than Venus. Most of the carbon on Earth is sequestered in limestones and organic fuels including coal and oil. Early life made Earth more habitable for later organisms by sequestering carbon and reducing atmospheric CO_2 content.

Humans have been inadvertently tinkering with the systems that stabilize our planet's environment for millennia. The dramatic rise of many different human civilizations occurred over the past 11,500 years, the **Holocene Epoch**, a period of generally stable climate and atmospheric composition [**Figure DD1.2**]. After sea level stabilized about 6000 years ago, agriculture spread into highly productive river deltas and preindustrial, human-induced changes to Earth's surface included regional deforestation and the erosion of soils that followed. Studying the record of gases preserved in ice cores and compiling historic data,

DIGGING DEEPER Why Is Earth Habitable? *(continued)*

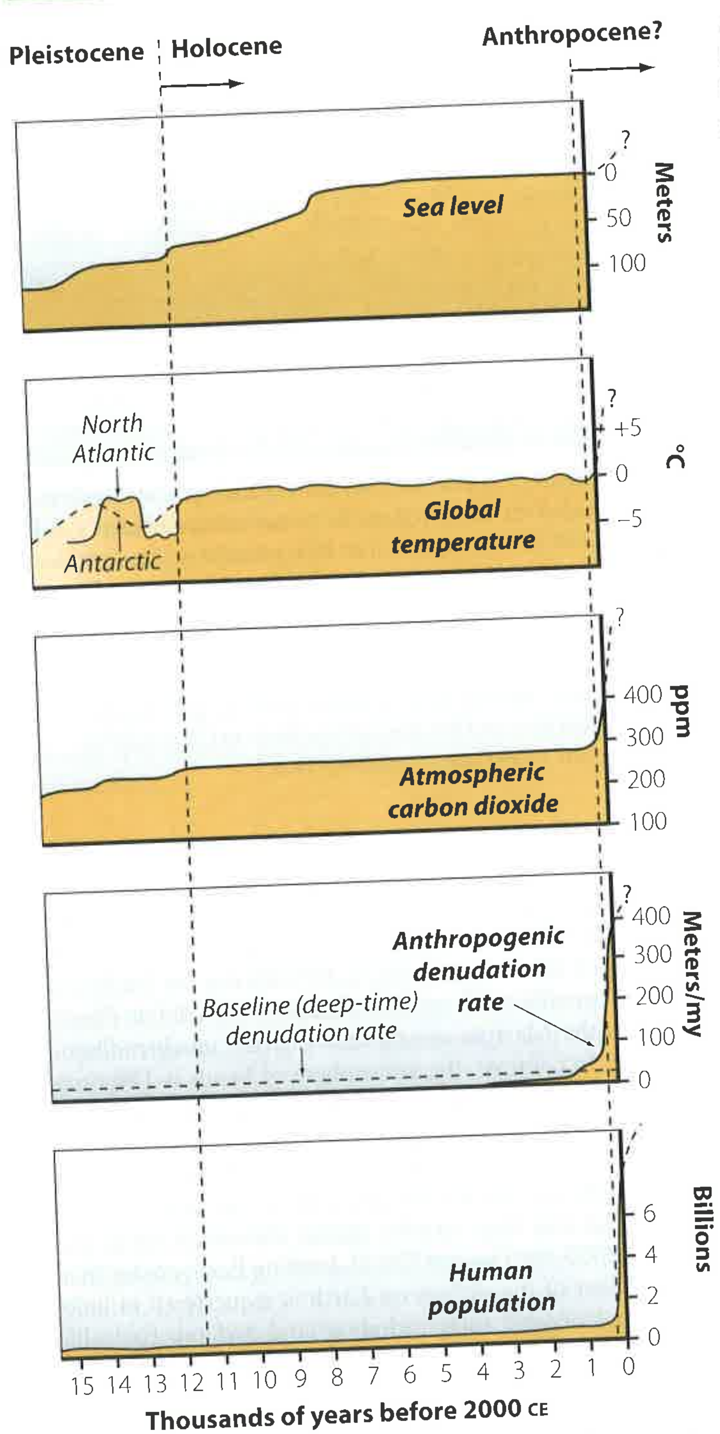

FIGURE DD1.2 The Holocene Epoch, the past 11,500 years, has until recently been a period of great stability on Earth. Global temperatures and atmospheric carbon dioxide levels have changed relatively little since the end of the last glaciation. Human population and global erosion rates were also steady and low until the last few thousand years, when both began to rise. During the twentieth century, after the Industrial Revolution, human population increased explosively and erosion rates have skyrocketed as people rapidly change our planet's surface. [From Zalasiewicz et al. (2008).]

Ruddiman et al. (2008) and Ruddiman and Ellis (2009) hypothesized that flooding of rice paddies and domestication of livestock may have led to subtle changes in atmospheric composition thousands of years before the Industrial Revolution **[Figure DD1.3]**. Today, changes in atmospheric composition (primarily increases in CO_2 and CH_4) are directly tied to human activities, and the result is clear—unmistakable changes in global temperature, the intensity of the hydrologic cycle, and the distribution and intensity of storms such as hurricanes.

Over the past century, with the advent of mechanized agriculture, irrigation, and industrial fertilization, the human impact on global systems became more substantial and readily detectable. Compiling data about the rate at which humans, now powered by fossil fuels, move soil and sediment, Hooke (1994) suggested that humans are a major geomorphic agent on the planet, moving huge amounts of mass on and from uplands. At the same time, people have littered the planet with dams that are trapping much of this sediment. Compiling sediment yield data and land-use data, Syvitski and Milliman (2007) argued that more than one-quarter of the sediment coming off the continents is trapped in dams and not reaching the oceans. The consequences include sediment starvation for some of the world's deltas and beaches.

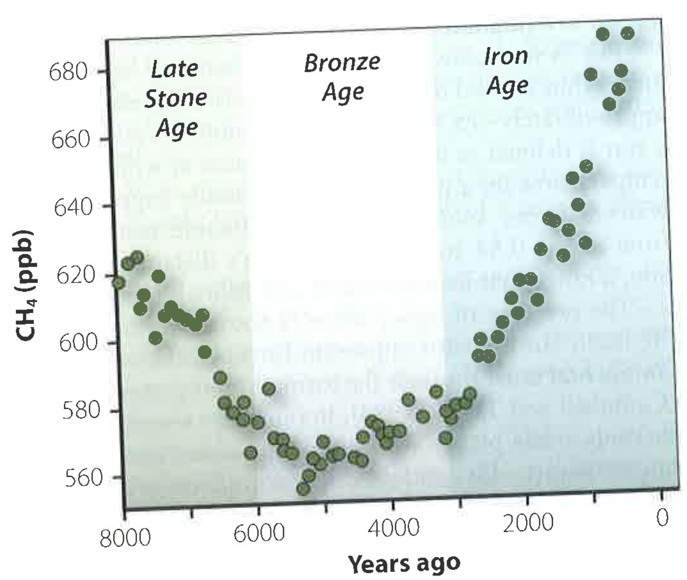

FIGURE DD1.3 Ancient glacial ice in Antarctica and Greenland preserves a long record of Earth's atmospheric composition. Here, Ruddiman et al. (2008) present the trend of methane gas (CH_4) composition in the Dome C ice core from Antarctica. They suggest that the decline from 8000 to 5000 years ago represents a natural trend and that the reversal of this trend about 5000 years ago represents the addition of methane to the atmosphere coinciding with human activities, primarily agriculture, during the Bronze and Iron ages. If Ruddiman is right, humans have been affecting Earth's climate for several thousand years. [From Ruddiman et al. (2008).]

The impact of more than 7 billion people on Earth's surface, atmosphere, and geochemical systems threatens to destabilize the linked planetary systems and cycles on which society critically depends (Rockström et al., 2009). How much is too much impact on our planet? Rockström et al. proposed that there is a "safe operating space for humanity" on planet Earth **[Figure DD1.4]**. To define this safe space, they identified nine planetary systems and associated thresholds, which include geochemical cycles, the climate, the biosphere, the hydrosphere, and the atmosphere. If human impacts to Earth exceed reasonable limits, they argue that the stable, habitable planet on which humans evolved and societies have flourished may become unstable. In other words, the planet on which we depend may no longer be able to support us. In their view, we have already exceeded three boundaries: climate change, nutrient cycling, and losses from the biosphere. We are fast approaching other boundaries through acidification of the oceans, land-use changes, and freshwater use. Given that many Earth systems react abruptly to external changes, crossing thresholds could result in unexpected and potentially painful consequences like the rearrangement of ocean circulation (and thus regional climates) or rapid sea-level rise as ice sheets melt catastrophically.

There is solid evidence from past periods when Earth systems changed state radically that such thresholds exist. Probably the best known manifestation of a climate threshold in the recent geologic past is the abrupt Northern Hemisphere cooling that occurred just as the Earth was warming from the last glacial period. In this period, called the **Younger Dryas**, at least the area around the North Atlantic plunged back into near-glacial conditions for more than a millennium. The driving force may have been a change in ocean circulation, last triggered at the end of the Pleistocene Epoch by rapidly melting ice sheets (Alley, 2004).

Earth did not come with a user's manual. Yet to keep our planet habitable, we need to understand how surface processes act, and interact, to sustain or limit critical ecological, climatological, and hydrological systems on which we all depend. However one looks at it, a deeper and broader understanding of the linked processes, feedbacks, and history of Earth's dynamic surface is a useful prerequisite to learning how to live within our planetary means.

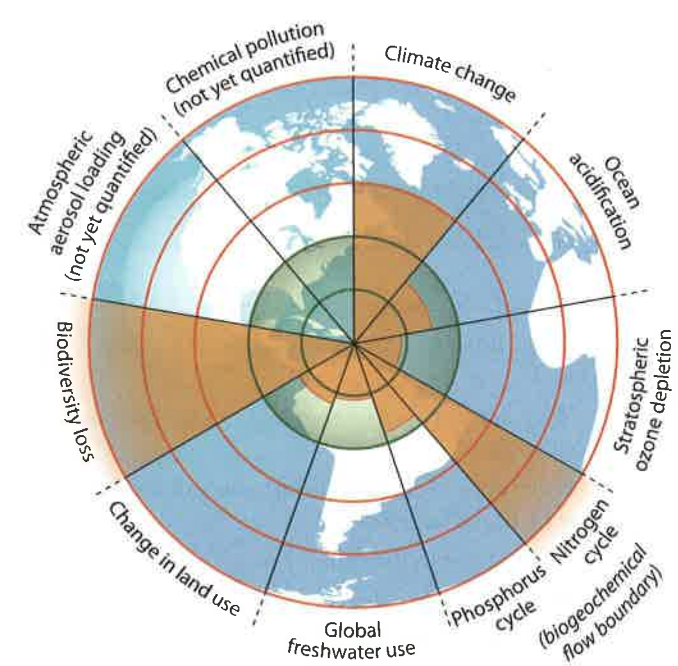

FIGURE DD1.4 Humans have changed the planet we inhabit. How do we know if this impact is significant and when it might become hazardous to the world's societies? Rockström et al. (2009) identified nine major effects that humans have on planetary systems and then sought consensus on the level of impact we could have without significantly disturbing the operation of our planet (the green zone). The orange shaded slices represent the current position of each system. Look carefully and you will see that human impact has taken the planet out of the safe operating zone for biodiversity, nitrogen cycling, and climate change. [From Rockström et al. (2009).]

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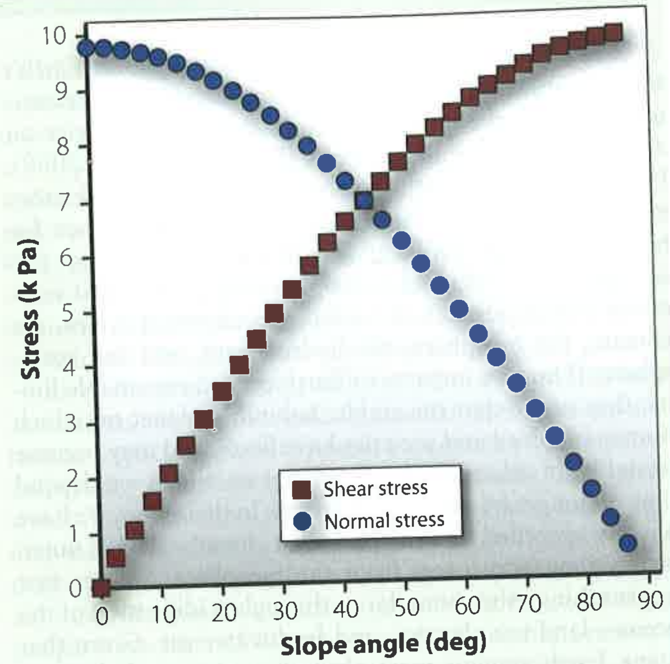
WORKED PROBLEM

Question: Calculate and then describe how the normal force and the shear force per unit area (stress) vary as hillslope angle increases. Make two graphs that show the change in normal and shear stress as a function of slope angle.

Answer: The normal and shear stresses on a hillslope vary inversely. When one goes up, the other goes down. Equations 1.2 and 1.3 describe the change in shear and normal stresses as a function of slope angle. As slope increases, the normal stress declines and the shear stress increases. Eventually, this increase in shear stress and decrease in normal stress lead to hillslope failure in what could be a dramatic landslide or rock fall. The normal and shear stresses are the same on a 45° slope.



Shear and normal stresses calculated using equations 1.2 and 1.3 and assuming a 1-m-thick slab, a soil bulk density of 1000 kg/m^3, and an acceleration of 9.8 m/s^2.

KNOWLEDGE ASSESSMENT Chapter 1

- 1. Define geomorphology.
- 2. Geomorphology draws on four disciplines to explain the behavior and history of Earth's surface. Name them.
- 3. What two contrasting forces does topography reflect?
- 4. Define the geosphere.
- 5. What controls the location of the first-order features of Earth's surface?
- 6. What are the most common elevations of Earth's topography?
- 7. What controls the location of mountain systems?
- 8. Define isostasy, explain how it works, and consider why it is important to geomorphology.
- 9. How thick are the roots of some large mountain ranges?
- 10. Explain how erosion causes uplift of rocks.
- 11. Why are mountain ranges long-lasting topographic features?
- 12. Compare and contrast the rate of erosion and the rate of land surface elevation change.
- 13. Describe a cratonic landscape.
- 14. What does a rift zone look like at Earth's surface?
- 15. Why are hot spots geomorphic agents, shaping topography?
- 16. How does rock type (lithology) influence the shape of Earth's surface?
- 17. What is the hydrosphere?
- 18. Sketch the hydrologic cycle.
- 19. How do plants influence overland flow?
- 20. How does the distribution of precipitation help to determine the shape of Earth's surface?
- 21. What is the primary driver of Earth's climate?
- 22. Describe a convective cell and predict how such cells affect Earth's large-scale climate and geomorphology.
- 23. Predict the distribution of rainfall across a mountain range.
- 24. Where do you find the biosphere?
- 25. What does the biosphere contain?

- 26. Give three examples showing how the biosphere influences Earth's surface processes.
- 27. In what ways have humans become geomorphic agents?
- 28. Give an example of how geomorphic processes and landforms are related.
- 29. At what temporal and spatial scales do geomorphologists work?
- 30. How is the concept of steady state applied to landscapes?
- 31. List the unifying concepts underlying modern geomorphology.
- 32. Define a drainage basin.
- 33. Describe the conservation of mass and why it is important for understanding Earth's surface processes.
- 34. Why are thresholds important in geomorphology? Provide an example.
- 35. Explain the idea of "source-to-sink."
- 36. What is a force balance and why is the concept useful in geomorphology? Give an example.

A Brief History of Geomorphology

Since the establishment of geomorphology as a distinct scientific discipline in the late nineteenth century, geomorphic thinking has evolved from broad conceptual ideas ("conceptual models") of the origins and dynamics of landscapes and how fluvial and glacial processes shaped landforms to mathematical models of landscape evolution that allow formal evaluation of how day-to-day and rare extreme events can shape landscapes. Field observations, mapping of surficial deposits, and the evolution of measurement technology drove thinking and provided both a foundation for and a means to test theoretical models.

Since the 1950s, geomorphologists extended the qualitative insights of prior workers to develop a quantitative, physics-based understanding of how geomorphological processes erode, transport, and deposit sediment and in so doing shape landforms. Today, prediction of landscape response is now a common goal, although the push to develop predictive models faces significant challenges because of the number of underconstrained but important variables in many geomorphic systems. Since the time of the ancient Greeks, our view of landscapes has shifted from descriptions and imaginative theories regarding the origin of topography to the analysis of topographic contours, usually focusing on the profiles of individual hillslopes and rivers, to fully three-dimensional investigations and simulation models of topographic change over entire landscapes. Today, geomorphologists explore the interactions among climate, tectonics, and erosion in shaping Earth's dynamic surface.

Classical Knowledge

We recognize the geographers and philosophers of classical Greece as the first geomorphologists. They realized that Earth was a globe and that its surface evolved over unimaginably long time spans. For example, the historian and geographer Herodotus (c. 484 BCE–c. 430 BCE) described the striking contrast between the rich, black alluvial soils of the Nile River delta and the bare rocky soils of Libya and Syria. He concluded that the Egyptian coast advanced out into the Mediterranean Sea as the Nile deposited its load of silt, and calculated the age of the Nile delta from his estimated rate of sediment deposition. The annual flood of the Nile was so important to the prosperity of ancient Egypt that the rise and fall of the river was carefully monitored and recorded [**Figure A**]. The great philosopher Aristotle (384 BCE–322 BCE) argued that the land and sea constantly swapped places as rivers carried silt and sand to the sea, gradually filling it in, causing sea level to rise and submerge coastal land. Aristotle thought that an endless cycle in which land became sea, and then land again, happened so slowly as to escape observation as civilizations rose and fell in a world without beginning or end. His view of an ancient, eternally changing world did not appeal to those convinced that God created the world just a few thousand years ago.

FIGURE A Nilometer used to measure the stage of the Nile River in ancient Egypt. The chamber was connected to the river. As the river level rose, so would the level of water, covering stairs one by one as the flood crested. Flood heights were quantified by the number of stairs that were under water.

Nicolaus Steno (1638–1686)

In the late seventeenth century, Danish physician Niels Stensen, better known by his Latinized name Nicolaus Steno, laid the foundation for modern geology, including geomorphology, while working for the Grand Duke of Tuscany in Florence. Steno recognized the organic nature of fossils and proposed a foundational principle of modern geology known as **Steno's law of superposition**, the idea that the oldest sedimentary layers are on the bottom and the youngest are on top. He also recognized that sedimentary rocks are deposited horizontally and used these principles to infer the geologic and physiographic history of the landscape of northern Italy, proposing a conceptual landscape-evolution model based, in part, on the biblical flood (Steno, 1669). Steno saw how layered rock containing marine fossils lay high above sea level, and that while some layers lay flat, others were contorted or lay pitched at steep angles.

His conceptual model to explain the modern geology and topography of the region involved two rounds of collapse in which continents fell into great subterranean caverns [**Figure B**]. Geologists respect Steno because he began an ongoing process of formalizing geological observations and interpreting evidence of Earth history through a set of guiding principles. Likewise, geomorphologists recognize Steno as an intellectual forerunner because he attempted to explain the history and dynamic, changing nature of landforms based on a combination of field observations and general principles.

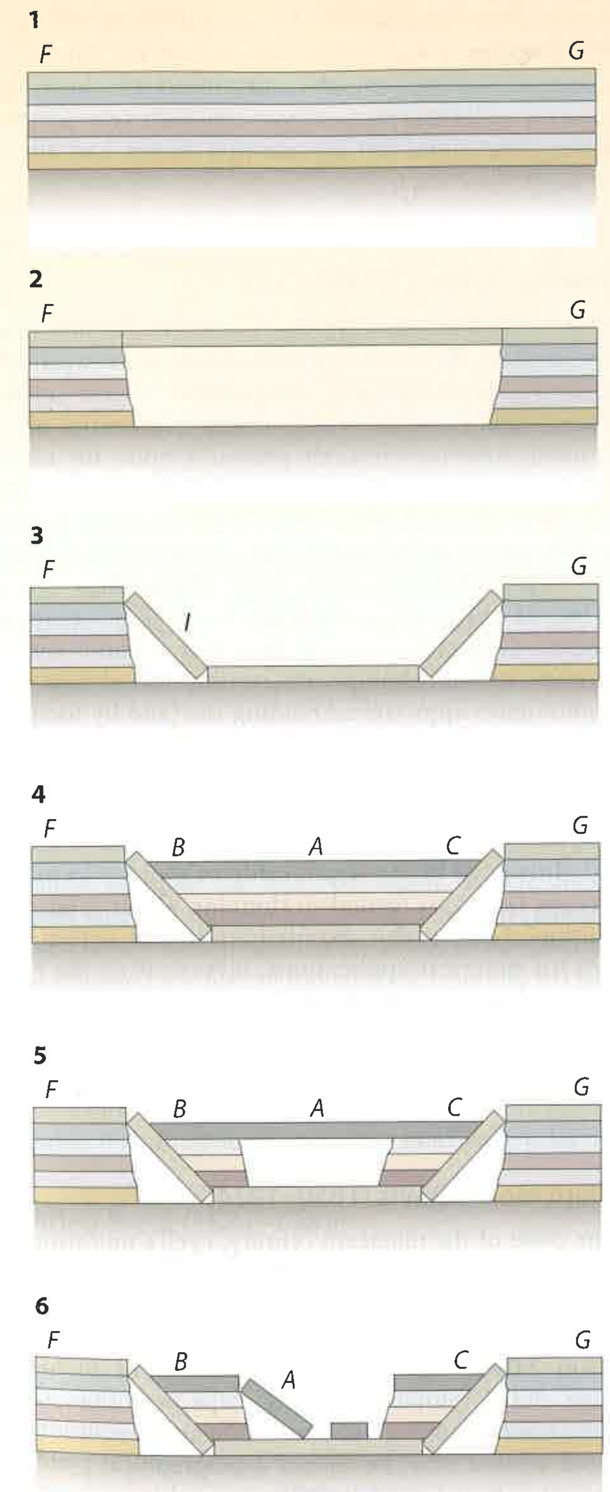


FIGURE B Steno's conceptual model for the geologic and physiographic history of northern Italy: (1) precipitation of fossil-free sedimentary rocks beneath a planetwide ocean; (2) the creation of subterranean caverns; (3) collapse of undermined continents and creation of drowned valleys by a great flood (Noah's flood); (4) new layered (sedimentary) rocks containing fossils form in inundated valleys; (5) continued undermining destabilizes younger rocks in valleys, resulting in (6) another round of collapse that created modern topography (from Steno, 1669).

Charles Lyell (1797–1875)

In the early nineteenth century, it was well established that the world was significantly older than the 6000 years suggested by biblical chronology, but conventional wisdom still held that evidence for the biblical flood was preserved in the world's surficial deposits and in the incision of valleys. The creation of modern topography during the most recent of many grand catastrophes was thought to have ushered in the most recent era of geologic time.

Lyell hypothesized that today's surface processes, if they had acted over vast expanses of time, could shape landscapes. Touring the Auvergne region of France, he was intrigued by deep valleys carved into stacked lava flows topped by delicate cinder cones. A global flood powerful enough to have carved the rivers down through solid basalt would surely have swept away the loose cinder cones. Lyell recognized how explaining deposits of river gravel buried beneath lava flows required multiple episodes of valley incision, gravel deposition, and burial by lava flows [**Figure C**]. A single flood did not carve modern topography; rather, over time, rivers gradually carved their own valleys. Lyell's *Principles of Geology* (1830–1833) made the case for how the laws of nature governing geological processes remain constant, even though their effects vary through time. His view that present processes were the key to understanding processes in the geological past became known as **uniformitarianism** and stood in contrast to prior belief that Earth's surface was shaped by one or more grand catastrophes, a view known as **catastrophism**.

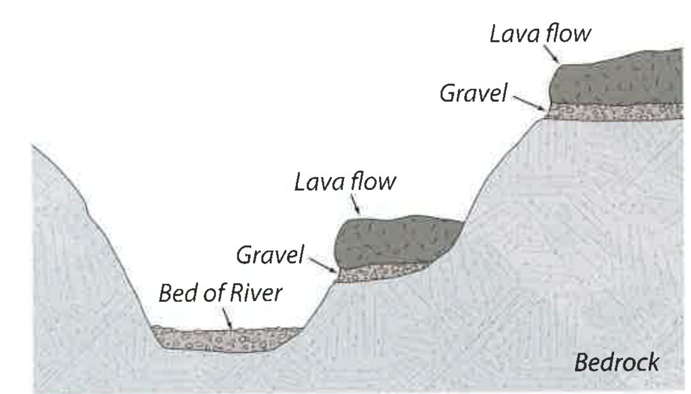


FIGURE C Lyell's illustration of river gravels buried by basaltic lava flows on the walls of valleys in the Auvergne region of France (from Lyell, 1830–1833).

Louis Agassiz (1807–1873)

In the 1830s, the origin of the great deposits of surficial gravel and debris that covered much of northern Europe remained enigmatic. What could have deposited the great blanket of geologic detritus that covered the lowlands across much of the continent? Contemporary processes active in the landscape were not doing so; there was no evidence of similar deposits forming anywhere at the time. Agassiz recognized the geomorphic role of glaciation and showed how different climates in the past changed the mix of geomorphic processes that shaped topography. Living in Neuchâtel in the Swiss Alps, he began to see how the landforms found around modern glaciers also occurred farther downvalley. Glaciers had been more extensive in the past, during an age of ice (Agassiz, 1840). Noting the stray, exotic boulders carried far from potential sources and the extent of ice-shaped landforms **[Figure D]** beyond the Swiss Alps, Agassiz established that glaciers had advanced not just short distances down their valleys but had overrun much of Europe in the past.

After emigrating to North America, he documented evidence for extensive continental glaciation in the surficial deposits and landforms of New England and the northern continental interior. His glacial theory was hotly debated before it was widely accepted in the 1860s; the discovery of glacial epochs introduced the idea that landforms could be relicts of past eras with very different climates. One could not assume that things had always been as they are today.

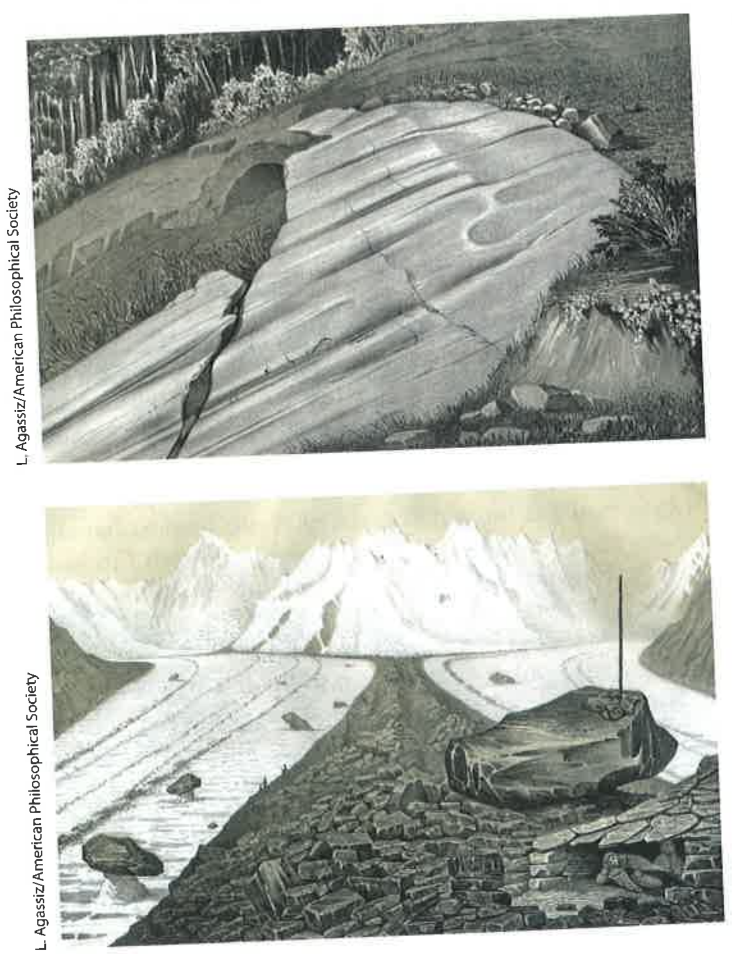


FIGURE D Agassiz's illustrations of glacially polished and striated bedrock and boulders moved by glacier transport (from Agassiz, 1840).

Grove Karl Gilbert (1843–1918)

Exploration of western North America in the late nineteenth century illuminated the connection between the landscape and the geology below. The federal surveys commissioned to inventory the resource potential of the expanding American frontier proved a boon for understanding the relationship of topography to the type and structure of the underlying rocks. Such connections were apparent across grand vistas due to the excellent exposures in the arid west (Gilbert, 1877) **[Figure E]**.

One of the most influential of these government scientists, Gilbert introduced ideas and methods central to **process geomorphology**. He revolutionized how geomorphologists approached reading the land by focusing on the morphologic implications of erosion, transport, and deposition processes. Gilbert also recognized the role of past climates in forming the now-vanished but once extensive lakes in the arid American West (Gilbert, 1890). Intrigued by the relationship of geology to topography, he began to formalize thinking about landscape evolution. Gilbert also initiated studies of active processes for practical applications, investigating the routing of sediment through drainage basins affected by hydraulic mining in California's gold rush, and conducting experimental studies of sediment transport in flumes (Gilbert, 1914).

William Morris Davis (1850–1934)

At the close of the nineteeth century, Lyell's uniformitarianism had become well established and the biological sciences were being revolutionized by Darwin's idea of natural selection. Evolutionary thinking was in vogue, and William Morris Davis adapted concepts of biological change and development to landscape evolution. Davis systematized thinking about landscape evolution as ordered around what he termed a **geographical cycle**. He proposed a broad model of physiographic evolution in which topography progressed in stages from youthful to mature to old age after an initial pulse of uplift (Davis, 1899, 1909). Relief increased during uplift, and then gradually decreased, ultimately approaching a beveled-off surface he termed a **peneplain [Figure F]**.

Davis also wrote influential papers on the relation between geomorphic processes and landforms and the evolution of river systems, but it was his geographical cycle that dominated geomorphological thinking for the first half of the twentieth century. His ideas promoted qualitative interpretation of landscape history from broad aspects of landscape form. Davis's conception of peneplains became central to thinking about landscape evolution and motivated extensive searches for, and speculation about, suspected **erosion surfaces** thought to represent ancient peneplains. While Davis's conception of a life cycle of topography has been sidelined, the idea of topographic response to changes in rock uplift rate and the long time required to reduce the elevation of a mountain range remain pertinent in thinking about landscape evolution. Indeed, his thinking about general models of hillslope and river valley evolution led to modern mathematical models of landscape behavior.

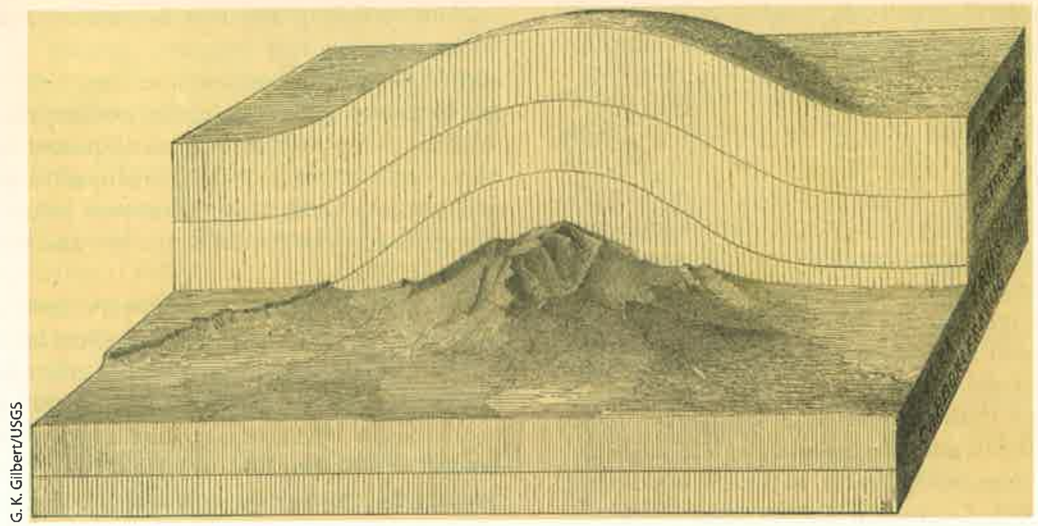


FIGURE E Frontispiece from *The Geology of the Henry Mountains* (Gilbert, 1877), showing the relationship between modern topography and the domal uplift inferred from the geologic structure of the range, in particular, the dip of the beds away from the core of the uplift. The mass of rock eroded off the landscape in the geologic past is shown above the current rugged landscape.

J Harlen Bretz (1882–1981)

For the first half of the twentieth century, uniformitarianism dominated geological thinking to such an extent that few in the geologic establishment were comfortable entertaining the idea of grand catastrophes. In the 1920s, J Harlen Bretz, then a young geologist, uncovered evidence for an enormous ancient flood in eastern Washington State (Bretz, 1923, 1925). Through extensive fieldwork, Bretz pieced together the story of how a surging wave of water hundreds of meters high roared across eastern Washington, carving deep channels where today no rivers flow. It took most of the twentieth century for geologists to accept his radical hypothesis.

Bretz reintroduced the idea of grand catastrophes as effective geomorphic events. His work showed how ancient events and processes no longer active today could catastrophically affect landscapes. Over time, the intensity as well as type of geomorphic processes affecting an area could change greatly and leave a lasting impression on the landscape. In establishing that landforms could be the result of catastrophic floods, Bretz opened the door for recognizing the topographic signature of catastrophic events of many different kinds.

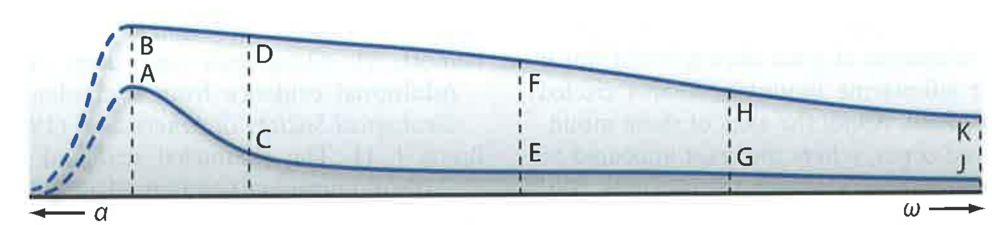


FIGURE F Davis's schematic diagram of the change in relief through time of the idealized cycle of erosion. Vertical dashed lines represent particular times; B-D-F-H-K represent the elevation of the ridge crest through time, whereas A-C-E-G-J represent the elevation of the valley bottom through time. The horizontal scale, α to ω, indicates the passage of time from the beginning (α) to the end (ω) of a geographical cycle (modified from Davis, 1899).

Ralph A. Bagnold (1896–1990) and Luna B. Leopold (1915–2006)

In the mid-twentieth century, most geomorphic studies were dominated by map analysis or Davisian thinking about grand cycles of uplift and response. But, by mid-century, things began to change as Bagnold and Leopold pioneered the application of physics to studies of landscape-forming processes and promoted the application of quantitative field measurements to test theories of aeolian and fluvial processes, respectively (Bagnold, 1941; Leopold et al., 1964). Bagnold explored the North African desert, where he studied the physics of blowing sand and the processes involved in the formation of sand dunes before putting his expertise to practical use as a major in the British army in Libya during World War II. In the 1950s, Leopold led a group of U.S. Geological Survey researchers who ushered in the modern era of process geomorphology with an aggressive campaign to quantify studies of river channels and explain the physics underlying fluvial processes.

Bagnold and Leopold introduced the practice of relating process to form. They did this by making rigorous field and laboratory measurements of geomorphological processes and the forms that resulted. Their approach to understanding the basic physics of aeolian and fluvial erosion, transport, and deposition began the quantification of landscape form, evolution, and response. The approach that Bagnold and Leopold adopted—coupling field and experimental observations and measurements with theoretical models to explain geomorphological processes—professionalized the practice of geomorphology and opened the door for development of process-oriented geomorphology in the late twentieth century.

Plate Tectonics

The gradual development of the concept of plate tectonics in the 1950s and 1960s revolutionized geology and elegantly tied Earth history together in a unifying framework that provides the basis for understanding the forces shaping Earth's dynamic surface. Plate tectonics was not the discovery of a single individual; its development was driven by data from many sources.

The theory of plate tectonics explained three independent mysteries that made sense only when considered together—magnetic stripes on the seafloor, high heat flow over the mid-ocean ridges, and the global distribution of earthquakes. The development of sonar during World War II revealed that linear submarine mountain chains circled the world (Heezen, 1960). Along the axes of these mountains were extensional zones, where the crust appeared to be pulling apart or extending. Mapping the magnetic field of the seafloor, to provide background values against which to hunt for submarines, revealed that away from these mid-ocean mountain chains the oceanic crust had alternating bands of normal and reverse magnetic polarity (Mason & Raff, 1961)—a natural strip-chart recorder of seafloor spreading over time because oceanic crust locked in the contemporary magnetic polarity as it cooled and moved away from seafloor spreading centers. Seismological networks set up to verify nuclear test ban treaties revealed that although most earthquakes occurred in the upper crust, mysterious deep earthquakes defined slabs of crust sinking hundreds of kilometers below ground, deep enough that rocks should be too hot and too soft to break (Benioff, 1954).

Considered together, these observations defined a cycle in which new crust formed from molten lava at mid-ocean ridges, moved away from the axial ridge, and dove back down to be recycled in the deep trenches at the edge of ocean basins. Here was a single, grand mechanism to explain the shapes of continents; how they moved and how mountains formed; why different rock types occur in different regions; and why earthquakes, volcanoes, and mountains all line up where plates split apart, collide, or slide past one another. Plate tectonics provided a unifying framework within which to understand the evolution of Earth's landscapes (e.g., Summerfield, 1991).

Modern Geomorphology

Today, geomorphologists work on a wide range of problems, using diverse methods and tools to understand the processes shaping individual landforms, and the history and evolution of global topography. Studies of the interactions of climate, tectonics, and surface processes of erosion and deposition frame new questions about the evolution of Earth's dynamic surface. Although rapid advances in the resolution, quality, and availability of digital topographic data have contributed to the quantification of geomorphology over the past several decades, there is still a significant role for insightful observation and fieldwork to advance our understanding of landscape processes and evolution, the geomorphology of particular regions, and the role of human actions in shaping the world we live on and the nature of the one our descendents will inherit. In addition, studies of Earth's landscapes provide the basis for interpreting evidence, gathered remotely, of the processes acting to shape surfaces of other planets and their moons.

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