23 Tectonics and Landscapes

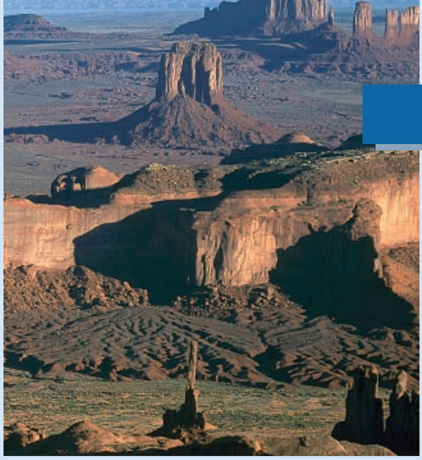
In the preceding chapters, we have seen that the landscape is shaped by Earth's geologic processes and evolves systematically. The processes of landscape development, however, are complex because tectonism produces a variety of structural settings upon which erosion occurs. The geologic structures of the shields are different from those of the stable platforms, folded mountain belts, or island arcs. Consequently, the landforms that develop in each tectonic setting have many distinctive characteristics. Moreover, climate influences the types of processes that operate within a region. Nonetheless, a landscape has many distinctive characteristics that reveal its history.

This panoramic photograph of Monument Valley of the Colorado Plateau illustrates this point very nicely. At first glance, this image appears to show the intricate details of a "lost world" with mesas, buttes, sheer cliffs, gentle slopes, complex spires and towering pinnacles. This landscape has fascinated humans since before historic times and many myths and

legends are associated with it. Indeed, this landscape may appear to be incomprehensible. However, there is a system and a beauty in the evolution of the land that promises an intellectual reward for those who take time to understand and appreciate it.

The landscape of Monument Valley, like any other, can be explained in light of Earth's tectonic and hydrologic systems. The events that produced this unique landscape began hundreds of millions of years ago when the colorful sedimentary rocks were deposited on the continent and in shallow marine waters. Gradually, the sediment lithified and turned to rock as it was buried. Joints broke through the rocks. Sometime in the last few tens of millions of years the region was uplifted above sea level and streams carved intricate systems of valleys. Weathering ate away at the cliffs and slopes, enlarging fractures and isolating columns of sandstone. Eventually, the details of the landscape were sculpted out by differential erosion of once continuous layers of sedimentary rock. Resistant formations eroded to form the pinnacles, steep cliffs, and mesa walls. Easily eroded shales form the gentler slopes.

You can see from the photograph that the landscape has much to tell about its history, but to read this history, you must learn a new language—a language written in the mesas, canyons, and rocks.



MAJOR CONCEPTS

1. The most important factors in the evolution of continental landscapes are tectonic setting, climate, and differential erosion.
2. The surface of a continental shield evolves through erosion and isostatic adjustment of a mountain belt. Ultimately, a surface of low relief near sea level is produced and equilibrium is reached. Local relief on a shield is largely the result of differential erosion on complexly deformed metamorphic and igneous rocks and is usually less than 100 m.
3. Stable platforms result from deposition of sediment in shallow seas that transgress and regress across the shields. The rocks are nearly horizontal or are warped into broad domes and basins. Erosional features on stable platforms are circular or elliptical cuestas and strike valleys and rolling hills developed by dendritic drainage patterns.
4. Landscapes developed on folded mountain belts are typically controlled by deformational structures, such as folds and thrust faults. Ridges and valleys carved on plunging folds are the most common landform.
5. Horsts and grabens are the major structural features formed in rift systems. The landscapes developed on these structures are eroded mountain ranges and basins partly filled with sediment.
6. Flood basalts formed at hotspots and rifts bury the previous landscape and form a completely new surface that is subsequently modified by weathering and erosion. Uplift and erosion of this surface commonly produce basaltic plateaus.
7. Landforms developed in magmatic arcs are dominated by volcanic features, such as composite cones and andesitic lava flows. These disrupt the drainage and create temporary lakes. Ultimately the original volcanic features are eroded away and deeper granitic intrusions are exposed and etched out by differential erosion.

FACTORS INFLUENCING CONTINENTAL LANDSCAPES

Tectonic setting, climate, and differential erosion are the most important controls on the evolution of continental landscapes on Earth.

Compared with other planets in the solar system, Earth is unique because of its consistently changing landscapes. The surfaces of the Moon, Mercury, Mars, and other planetary bodies are dominated by meteorite impact structures formed more than 4 billion years ago. But mountain building, volcanism, erosion, and sedimentation constantly change the surface of Earth. Indeed, most of Earth's continental landforms are very young and formed during the last 2 million years.

The constant resurfacing of our planet by both erosion and deposition results in a changing landscape that may seem at first to be unorganized and chaotic, but if you study Earth's surface from a variety of perspectives, you will find system and order in every feature of the landscape (Figure 23.1). Nothing is random. Every valley, plateau, volcano, and sand dune was produced by a geologic system, and every landscape preserves some record of its history and how it was formed.

We have emphasized in previous chapters how the hydrologic system operates and how each agent, including running water, glaciers, and wind, produces distinctive landforms. However, to read the stories told by the landscape more effectively, we must consider how the hydrologic system operates in different tectonic settings and how erosion on different rock sequences and structural features develops distinctive

FIGURE 23.1 **The major geologic provinces of North America** are shown on this map. The tectonic setting or structure of the rocks just below the surface is a major control on the character of the landscape. Most other continents also have shields, stable platforms, and folded mountain belts. *(Courtesy of WorldSat International Inc.)*

features. In every region, tectonism is important in determining the underlying foundation of Earth's surface features. The main focus in this chapter is on how tectonism influences the evolution of the landscape by providing several fundamental structural settings upon which the agents of the hydrologic system operate to produce their distinctive landforms.

Let us emphasize a few important facts about the continents first discussed in Chapter 1. Although the various continents may appear to be unique in size, shape, What are the three major structural components of all continents?

and surface features, they all have three basic components: (1) a large, relatively flat area of ancient complex igneous and metamorphic rocks known as a **shield,** (2) a broad, low platform or plain where the shield is covered with a veneer of sedimentary rocks known as the **stable platform,** and (3) **folded mountain belts** formed above a subduction zone or where two continental segments have been sutured together during continental collision (Figure 23.1). The geologic differences between continents are mostly in the size, shape, and proportions of these three components. In addition, some continents may be split by a rift system and some may be involved with a magmatic arc produced at a subduction zone. The important underlying theme in this chapter is that each of these major tectonic elements provides a different substructure on which the hydrologic system operates. Shields, platforms, mountain belts, and continental rifts, with their distinctive rock types and structure, will each tend to develop a distinctive type of landscape. Details of the landforms formed on each major tectonic setting will of course be determined by climatic factors that govern the type and intensity of the processes operating in the hydrologic system.

Climate

Climate is a major factor in landscape development because it controls the action of the hydrologic system and, therefore, of many types of geologic processes in a given region. Weathering, slope stability, river erosion, groundwater, glaciers, and wind are all subject to climatic conditions. A continent's climate is controlled mostly by latitude, but also by topography. For example, high mountains have low temperatures and create rain shadows downwind from them. Although the structural components of the continents are fundamentally the same, details of the landforms developed on them depend to a considerable degree upon climate. The landscape of the Canadian shield is modified by glaciation, the Brazilian shield is covered by a thick soil developed by tropical weathering, and the landforms of the shield of the Sinai Peninsula are different still because this shield is in an arid climate that imposes distinctive processes of weathering and erosion.

How does climate influence landscape?

The topography of the stable platforms and mountain ranges are likewise affected by climate. Limestone regions in humid climates develop karst topography, but in arid regions they are resistant to erosion and form ridges, ledges, and cliffs (Figure 23.2). In the tropics the high rainfall accelerates weathering, and thick soils (some more than 100 m thick) may develop. These soils mask structural details in the underlying rock that would be etched out in relief in arid regions. The complete disruption of river systems by glaciation results in many distinctive landforms produced both by glacial erosion and glacial deposition. Many landforms in arid regions may be dominated by eolian processes, and sand seas may cover extensive areas.

Differential Erosion

Differential erosion occurs on all scales, from a mountain range, to cliffs and slopes formed on alternating hard and soft rock bodies, down to thin laminae within a rock. Differential erosion is thus responsible for much of the beauty and the spectacular scenery of Earth. Differential erosion generally is well expressed in arid regions, where differences in rock type, jointing, and the availability of surface water and groundwater combine to produce fascinating details of the landscape.

Probably the most widespread examples of differential erosion on a stable platform are the alternating cliffs and slopes that develop on sequences of alternating hard and soft sedimentary rocks. Soft shales typically form slopes, and the more-resistant sandstones and limestones produce cliffs. The height of a cliff and the width of a slope are largely functions of the thickness of the layers involved.

(A) In humid environments, such as southeast China, limestone is nonresistant to erosion and weathers to form karst terranes.

(B) In an arid environment, such as the western United States, limestone is resistant to weathering and erosion and forms cliffs or ledges.

FIGURE 23.2 **Climate plays a major role** in the evolution of all landscapes. The same rocks in different climates will erode and weather very differently.

Similarly, if the series of resistant and nonresistant rocks are tilted, the nonresistant rocks are quickly eroded to form lowlands or valleys, leaving the resistant rocks as hills or ridges (Figure 23.3).

The main point here is that erosion is a selective process. It rapidly removes weak rock to form valleys or depressions in the landscape and leaves resistant rock bodies standing in relief as mountains, hills, and ridges. In this way, landscapes commonly reflect the structure of the rocks exposed at the surface.

How is differential erosion expressed on a sequence of tilted strata?

FIGURE 23.3 Differential erosion of a sequence of tilted strata produces ridges called hogbacks on resistant formations and long, narrow valleys in nonresistant rocks.

EVOLUTION OF SHIELDS

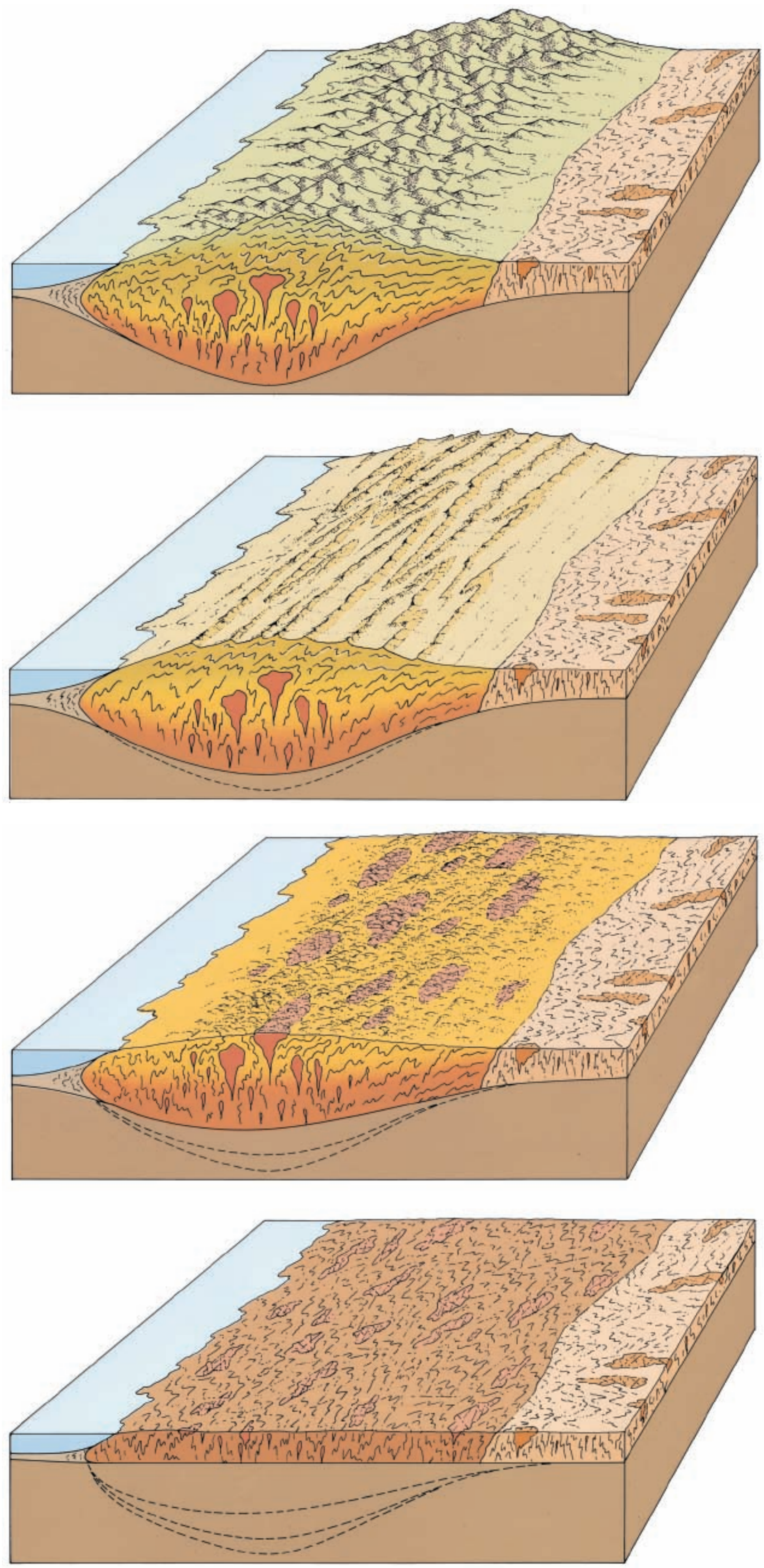
A continental shield results from the formation of mountain belts at convergent plate margins and from the subsequent erosion and isostatic adjustment, which reduce the mountain to a broad, flat surface near sea level. Local relief is usually less than 100 m and depends upon differential erosion on the igneous and metamorphic rocks.

Continental shields are distinctive in that their surface features are formed on ancient and complex metamorphic rocks—gneisses, schist, slates, quartzites, and marbles—all of which have been intruded by granitic batholiths, stocks, and dikes. In most regions, the shields have been eroded down to near sea level and differential erosion has etched out the nonresistant structural features of the various rock units. Thus, shields have a very distinctive landscape, although climatic influences (glaciation, desert, tropical forests, and so on) may leave their particular imprint upon the surface.

How does a mountain belt evolve into a segment of a shield?

Shields and their associated stable platforms are the fundamental tectonic components of continents, so an understanding of how they developed is essential in understanding the origin of the surface features of our planet. A general model showing how the basement rock evolves from mountain building is shown in Figure 23.4. Two major factors control this process: (1) erosion of the mountain belt by running water and (2) contemporaneous isostatic adjustment of the mountain belt as a result of the removal of material by erosion. Both erosion and isostatic adjustment continue until equilibrium is reached—a condition in which the topographic relief is eroded down to sea level and the mountain root has rebounded to a state of gravitational equilibrium. Under these conditions, large-scale erosion cannot occur because the surface is at sea level and uplift does not occur because of isostatic equilibrium.

In Figure 23.4A a new mountain belt has been formed by plate convergence. It is important to note that there are significant changes in the dominant structural features of the mountain belt, from the surface down to the deep roots. Andesitic volcanism occurs at the surface. At shallow depths, where the confining pressure



(A) In the early stages of development, there is maximum relief. Some andesitic volcanoes may still remain at the surface. Thrust faults and folds are the dominant structures exposed at the surface, and headward erosion of tributary streams begins to adjust the stream pattern to the major structural trends. The Andes of South America are in this stage of their development.

(B) As erosion removes material from the mountain belt, isostatic adjustment causes the mountain root to rebound. Tight folds formed in the deeper part of the mountain system are exposed at the surface, and headward erosion adjusts the stream pattern to the folded rocks. Many tributaries flow parallel to the structural grain of the mountain belt. The central Appalachian Mountains of eastern North America are similar to this.

(C) Continued erosion and isostatic adjustment reduce the topographic relief and the size of the root of the mountain belt below. Complex folds and granitic igneous intrusions, originally formed deep in the mountain belt, are now exposed at the surface. The stream patterns adjust to the new structure and rock types. Local relief and rates of erosion are greatly reduced. The eroded mountain belts of Scotland and Norway have structures like these.

(D) Isostatic equilibrium is ultimately reestablished. The rocks formed deep in the mountain root are exposed to the surface, and local relief is only a few meters. Stream patterns adjust to the structural trends in the metamorphic terrain. At this stage, the mountain belt constitutes a new segment of the shield. The Canadian shield has developed by the processes outlined here.

FIGURE 23.4 **A continental shield develops** from a folded mountain belt. Erosion occurs during crustal deformation, so by the time mountain building terminates, the mountain range is already carved into a rugged terrain. After deformation, a mountain root extends down into the mantle to compensate for the high topography. Note that the style of structure in a mountain belt changes with depth. Andesitic volcanic features may dominate at the surface. Thrust faults and folds occur at shallow depths. Tight folds and granitic intrusions occur at intermediate depths. In the deeper roots, metamorphic rocks intruded by small granitic bodies dominate.

is low, the rocks are relatively brittle, and the compression that formed the mountain belt has developed thrust faults (green). At greater depth, the rocks are under greater confining pressure, and they yield to plastic flow, which produces tight folds (tan). At still greater depths, complex folds are formed. Silicic magma, generated in the lower crust and involving magmas from the subduction zone, rises because it is less dense than the surrounding rock and reaches a level where it spreads out to form large plutons. In the deeper roots of the mountain belt, metamorphic rocks, including granulites and migmatites, dominate and are intruded by smaller bodies of granite (reddish brown). The topography in Figure 23.4A is young. It is controlled by andesitic volcanism, thrust faulting, and folds. The topographic relief is high, and headward erosion is beginning to adjust the drainage pattern to the structural trends of the mountain belt.

How does isostasy influence the development of a shield?

In the second stage (Figure 23.4B) the upper segment of the mountain belt has been removed by erosion, but isostatic rebound causes the mountain belt to rise continually. The dominant structure, now exposed at the surface, is a series of tight folds (tan) etched into relief. Erosion on the folds produces a series of ridges on resistant rocks that zigzag across the landscape. Long strike valleys erode on less resistant strata such as shales. The result is a "valley-and-ridge" type of topography.

At a later stage (Figure 23.4C) erosion has removed the zone of folded strata, but isostatic adjustment continues to elevate the mountain belt. Note the position of the root, or base, of the mountain belt in (C), compared to its former position in (A) and (B), shown in dashed lines. Isostatic rebound is less because the mountain root is not so deep, and topographic relief is consequently not as great as before. Complex folds and granitic intrusions, which formed deep in the mountain belt, are now exposed at the surface, and the landforms are controlled by these features. Resistant granitic rock bodies typically form elliptical low mountains surrounded by lowlands of metamorphic rock. Small-scale structural features in the metamorphic terrain may be eroded into relief, forming a complex of low ridges and lowlands. At this stage, the topographic relief and rate of erosion are much less than in stages A and B.

In Figure 23.4D erosion and isostatic adjustments have reached a state of equilibrium. There is no mountain root extending down as a bulge below the mountain topography, and as a result there is no isostatic uplift. Metamorphic rocks and igneous intrusions (reddish brown), which were formed in the deep mountain root, are now at the surface, and their structure and distinctive rock types control the topographic features to be developed. The entire surface is eroded close to sea level. The mountain root is now in isostatic equilibrium. The area is tectonically stable, and a new segment of the basement complex is formed. The most significant event in the subsequent history of the region is that slight changes in sea level may cause the sea to spread across the region and deposit shallow-marine rocks over the shield to form a stable platform.

Rates of Uplift and Erosion

The rate of uplift during mountain building is variable and difficult to measure. However, estimates can be made on the basis of the age of strata that were originally deposited in the sea but are now found high in mountain ranges, together with data obtained from precise geodetic surveys across active mountain belts. A number of such observations give a general rate of uplift of 6 mm/yr. If erosion did not occur contemporaneously with uplift, a mountain summit could rise 6 km in 1 million years. If these measurements are correct, a full-size mountain belt could be created in a relatively short time (5 to 10 million years).

Current estimates of rates of erosion are based on extensive measurements of the volume of sediment carried by the major rivers of the world. In mountainous areas, rates of erosion range from 1 to 1.5 m/1000 yr. From these data we can draw a generalized graph showing rates of uplift and the relation of rates of erosion to elevation (Figure 23.5). The rate of uplift is roughly 5 to 10 times faster than the

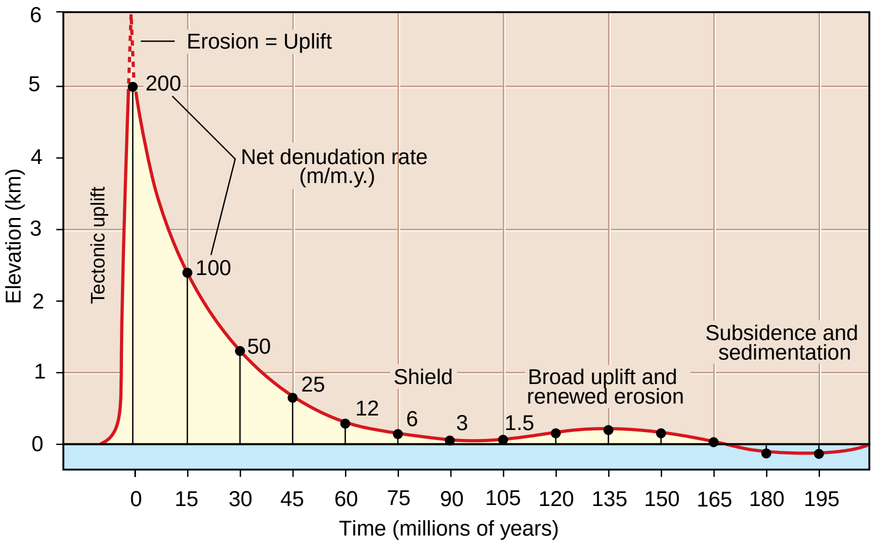


FIGURE 23.5 Rates of erosion of a mountain belt decrease exponentially with time. The period of mountain building is shown by the steep line at the beginning of the graph. The tectonic deformation is shown to last 5 million years, but most of the uplift may occur within 2 million years. Erosion proceeds contemporaneously with uplift, increasing in intensity with increasing elevation. By the time deformation ends, uplift of 6 km has occurred, but the surface is already eroded down to 5 km. The initial rate of erosion is 1 m/100 yr, but isostatic adjustment occurs at a ratio of 4:5. The initial rate of new lowering of the surface is thus 200 m per 1 million years (200 m/m.y.). In 15 million years, one-half of the mass is removed, and the net rate at which the surface is lowered is reduced to 100 m/m.y. After 30 million years, only one-quarter of the mass remains, and the average altitude is 1.25 km. In 75 million years, the mountain belt may be reduced to a new segment of the shield. *(Modified from A. N. Strahler)*

maximum rate of erosion. The relatively rapid rate of deformation and uplift is shown by the steep line on the graph and can occur in a time span of 5 million years. Erosion would occur during uplift, so by the time deformation and uplift terminate, the mountain range would already be carved into a rugged terrain, and perhaps as much as 1 km of rock would have been removed. The main idea that this graph emphasizes is not the absolute rate of erosion but the rapid decrease in the rate with a decrease in elevation. From the regional viewpoint, the rate of erosion depends on the height of the landmass above sea level.

As erosion removes material from the mountain belt, the mountain root rebounds in an attempt to reestablish the balance. In the early stages of erosion, the removal of 500 m of rock is generally compensated for by an isostatic uplift of about 400 m, so there is a net lowering of only 100 m of the mountain surface. If we assume that isostatic adjustment occurs constantly at a ratio of 4:5, the initial rate of net lowering of the surface will be 0.2 m/1000 yr or 200 m/m.y., as shown at the top of the curve in Figure 23.5. In contrast, at the end of 15 million years, the net rate of lowering of the surface has been reduced to approximately 100 m/m.y.

Erosion and isostatic adjustment continue to reduce the topographic relief. By the end of 30 million years, the elevation and rate of erosion are again halved, to one-quarter of the initial value. Approximately three-quarters of the original landmass has now been removed, and the structures of the deep mountain roots are exposed. The regional surface is a broad, nearly flat plain. Local relief of a few tens of meters is produced by differential erosion of belts of different metamorphic and igneous rock types. Erosion of the surface and the associated isostatic adjustment have declined at a rapid rate, probably exponential, so that a near balance is reached. Once the original mountains are eroded almost to sea level, the exposed roots of the mountain belt are a new segment of the continental shield.

The subsequent evolutionary history of the landscape is intimately related to broad uplift and subsidence and to changes in sea level. Sea level is important in

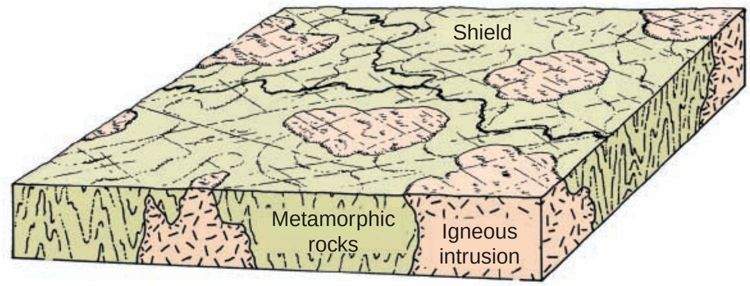


FIGURE 23.6 **The Canadian shield** is a broad, flat surface carved on a complex of igneous and metamorphic rocks that were originally formed deep in the roots of a mountain belt. This view shows that many structural features are eroded into relief. Erosion by a continental ice sheet during the last glacial advance is responsible for most of the small landscape features. Linear faults and zones of nonresistant rock are occupied by lakes. *(Courtesy of Canadian Government Dept. of Energy, Mines, and Resources)*

our model of erosion because it is the ultimate level to which stream erosion can effectively lower the continental surface. Both erosion and isostatic adjustment combine to produce a flat slab of continental crust, the upper surface of which is eroded to near sea level. There are, however, several reasons why the continental lithospheric plate can be expected to move both up and down with respect to sea level even though it is in a state of near isostatic equilibrium. For example, the top of the asthenosphere is not a perfectly smooth surface but undulates in swells and depressions. Bulges in the upper surface of the asthenosphere may also result from hotspots in the mantle. As the plate moves over these highs and lows, the continental crust may be upwarped or depressed with respect to sea level. This change would cause the sea to expand or contract across the stable platform.

Changes in sea level can also result from changes in the rate of spreading at midocean ridges. If spreading is rapid, the oceanic ridge swells and is arched upward, reducing the volume of the ocean basins and causing expansion of the sea over the flat continental surface. Slow spreading deflates the oceanic ridge, causing the sea to withdraw from the continents. Transgressions and regressions of the sea may thus be related to plate tectonics.

Another important point is that any change in sea level, regardless of the cause, may affect the erosional processes on the continent. If sea level is lowered (or the continent is upwarped), the processes of erosion will be rejuvenated. An increase in elevation of the land brings a rapid increase in the rate of erosion. An uplift of 1 km will be followed by accelerated erosion lasting probably 5 to 10 million years. If sea level rises (or a continent is depressed), the sea will advance over the land. Erosion terminates, and shallow-marine sediments are deposited on the eroded surface of the shield. Transgressions and regressions of the sea over the continental platform have been the major recurring events in this area through most of geologic time.

The Canadian Shield. The Canadian shield covers about one-fourth of the North American continent, more than 3 million square kilometers. Although it has been glaciated, the basic structural and topographic features are well expressed. On a regional basis, the surface of the shield resembles a vast saucer with the center in Hudson Bay. The shield extends northward to Baffin Island, eastward to Labrador and Newfoundland, southward to the Great Lakes, and westward to the interior plains of Canada. The landscape of this vast area is truly remarkable. As can be seen in Figure 23.6, the most striking characteristic is the vast expanse of the low flat surface, and throughout thousands of square kilometers the shield is barely above sea level. The only surface features that stand out in relief are the resistant rock formations that rise 30 to 100 m above the adjacent surface. The structural complexity of the shield (Figure 23.7) is shown by the complex patterns of erosion, alignment of lakes, and differences in tone and texture of the landscape. The major structural elements of the Canadian shield have been mapped, and several distinct geologic provinces were discovered. Each represents a different mountain system of a different age, and each has its own characteristics of rock type and structure.

The basic elements of the shields of other continents are quite similar to those of the Canadian shield. Conditions of the local climate, however, impart distinctive characteristics to the landscape. In the shields of desert regions, such as North Africa, Arabia, and Australia, the structural trends and local landforms are partly covered by desert features such as wind-blown sand, alluvial fans, and lag gravels. Shields in the tropics are commonly covered with thick soil and tropical vegetation. Those in the polar regions, such as Scandinavia's Baltic shield, carry the strong imprint of glaciation. Yet the fundamental topographies of all shields are remarkably similar.

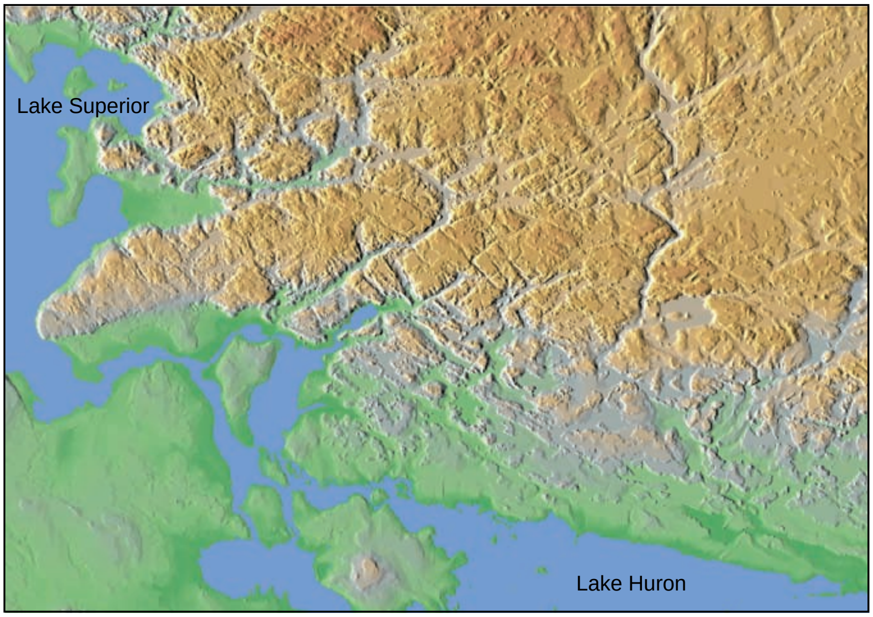


FIGURE 23.7 The complex structures of the shield are etched out by differential erosion of the igneous and metamorphic rocks, as shown in this topographic map of the Canadian shield in southern Ontario. The major fracture systems are eroded into narrow valleys, although the regional topography is eroded to within a few hundred meters of sea level. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

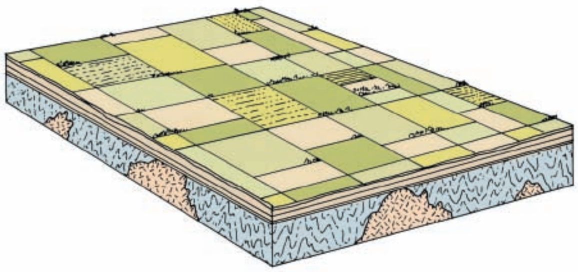


FIGURE 23.8 **The stable platform** is an area in which the basement complex is covered with a veneer of sedimentary rocks that are gently inclined or essentially horizontal. Stable platforms constitute much of the world's flat lowlands and are known locally as plains, low plateaus, and steppes. *(Tom Bean/Tom & Susan Bean, Inc.)*

STABLE PLATFORMS

Landforms developed on stable platforms result from differential erosion on horizontal to gently dipping sedimentary rocks. Dendritic drainage is common on horizontal strata and produces rolling hills. Cuestas and strike valleys typically form on the low dipping strata on the flanks of structural domes and basins.

The stable platform is simply that part of the basement complex covered with sedimentary strata. As we have seen, erosion and isostatic adjustment combine to produce a flat slab of continental crust that is very near sea level. Thus, any change in sea level causes the sea to expand or recede far across the surface of the low, flat continent. The history of the stable platform over hundreds of millions of years has been that of repeated transgression and regression of shallow seas in which were deposited cycles of sandstone, shale, and limestone (see Chapter 5). Each of these sedimentary sequences is bounded by an erosional unconformity. The total thickness of sedimentary strata on a stable platform rarely exceeds 2000 to 3000 m, so the sedimentary rocks form only a thin veneer covering the underlying igneous and metamorphic basement. Earth movements on the stable platform are mostly broad regional undulations that produce gentle domes (upwarps) and basins (downwarps) in the otherwise nearly horizontal strata. Thus, the landscapes on all stable platforms throughout the world consist of landforms developed on horizontal or gently inclined sedimentary rocks (Figure 23.8). These form the vast plains of the interior of North America, the great steppes of the Ukraine, the central lowlands of China, and the vast flat interior of Australia.

Major Landforms of the Stable Platform

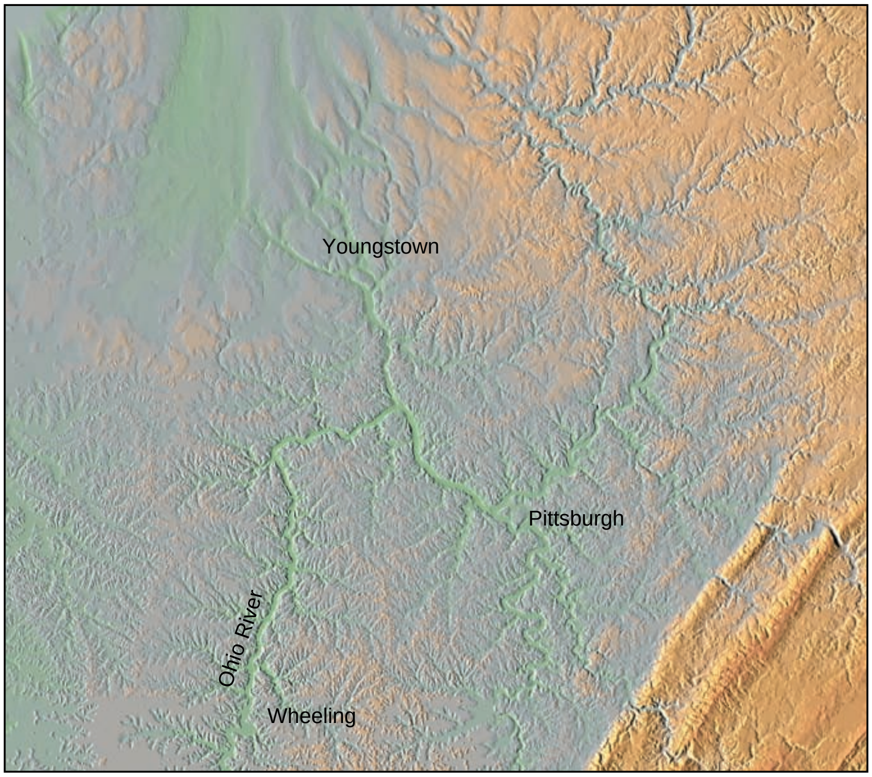
One of the most fundamental characteristics of a stable platform is the distinctive stream drainage pattern that develops on horizontal strata. A given layer of sedimentary rock forms a large area that is essentially homogeneous in all directions. Such a surface presents no appreciable structural control over the development of the drainage systems. Tributaries are free to develop and grow with equal ease in all directions so that **dendritic drainages** typically develop on horizontal rocks (Figure 23.9). Seen from the ground, the landscape seems to be a broad expanse of low "rolling hills."

Another important factor in the development of the major landscapes of the stable platform is differential erosion on the horizontal layers of sedimentary rock. Sedimentary strata deposited by the expanding and contracting seas consist of sequences of sandstone, shale, and limestone formations. Of these, shale is by far the most abundant and the least resistant. Layers of sandstone and limestone are thinner but are much more resistant in most climates. Differential erosion on these rocks is responsible for much of the landscape of the stable platform.

How does the landscape of a stable platform differ from that of a shield?

Resistant rock layers such as sandstone and limestone commonly form a resistant cap rock where interbedded with shale. The cap rock forms a low **plateau.** Erosion and slope retreat along the edges of the plateau create alternating cliffs (on the resistant unit) and slopes (on the nonresistant layers). As stream erosion eats headward, a large portion of the plateau can be detached from the main plateau to form a small **mesa** (Figure 23.10).

Where a sequence of alternating resistant and nonresistant strata is tilted, the nonresistant units are eroded into long **strike valleys** or lowlands trending parallel to the strike, or trend, of the rock layers. The resistant layers are left standing as



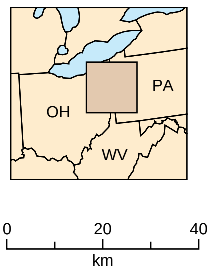


FIGURE 23.9 The stable platform of the east-central United States, shown on this shaded relief map, is underlain by flat-lying sedimentary rock layers dissected by dendritic drainage systems. Seen from the ground, this area appears as low rolling hills. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

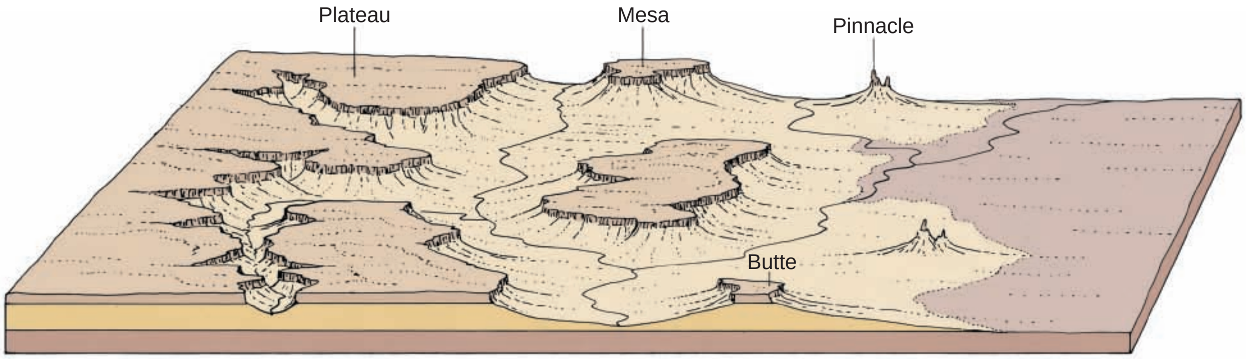


FIGURE 23.10 **Differential erosion of horizontal strata** is characteristic of a continent's stable platform and forms plateaus, mesas, buttes, and pinnacles. Resistant beds of jointed sandstone commonly cap plateaus and control the erosion patterns.

long, asymmetrical ridges. Ridges formed on gently inclined strata are known as **cuestas.** Sharp ridges formed on steeply inclined layers are **hogbacks** (Figure 23.3).

The major structural features of the stable platform are broad upwarps and swells that form structural **domes,** and downward movements that create **basins.** These warps in the crust are large, ranging from a few hundred to thousands of kilometers across. They may form while shallow seas cover the area so that sedimentary rocks may be thicker in the basins and thinner across the crest of the domes.

On the flanks of these structures, the strata may dip at angles of 20° or 30° or more. As stream erosion proceeds, strata are removed from the top of a dome, which is eroded outward to form a concentric series of sharp-crested cuestas or hogbacks with intervening strike valleys (Figure 23.11). The drainage pattern developed by erosion along strike valleys is commonly circular. If the older rocks in the center of the dome are nonresistant, the center of the uplift may be eroded into a topographic lowland bordered by inward-facing cliffs formed on the younger, resistant units. If the older rocks are more resistant, the center of the dome remains high, forming a dome-shaped hill or ridge. Large structural domes have inward-facing cliffs, whereas large basins have outward-facing cliffs.

Domes and basins in the stable platform may form in a variety of ways. They may result from mild compression associated with a mountain-building event at a distant convergent plate margin. Also, domes and basins may be the result of changing temperatures in the underlying mantle.

Differential Erosion on the Stable Platform in Arid Climates

Differential erosion of nearly horizontal strata also produces many fascinating small landforms. These landforms are best displayed in arid regions, where details of the topography are not obscured by vegetation. **Buttes, pinnacles,** and **pillars** are some of the most spectacular of these small features (Figure 23.10). They are simply the result of differential erosion on receding cliffs composed of stratified sedimentary rocks. If a massive cliff has well-developed joints, vertical **columns** develop. Where stratification produces alternating layers of hard and soft rock, additional detail can be etched out by differential weathering and erosion.

Jointing commonly plays an important role in the evolution of these landforms, for it permits weathering to attack a rock body from many sides at once. The famous columns and pillars in Bryce Canyon National Park, Utah, for example, result from differential weathering along a set of intersecting vertical joints and horizontal bedding planes (Figure 23.12 and the photograph at beginning of the Chapter 10). The joints divide the rock into columns. Nonresistant shales separate the more resistant sandstone and limestone, and differential erosion forms deep recesses in the columns, producing the fascinating slopes and landforms. This configuration is in striking contrast to the thick massive homogeneous sandstone that forms nearby Zion National Park, Utah, where joints are the only significant zones of weakness. As a result, erosion along the joints separates the rock into large blocks with steep cliffs (see Figure 7.6).

Natural arches are also products of differential erosion in arid climates. The best examples are found in the massive sandstones of the Colorado Plateau, in the western United States. The diagrams in Figure 23.13 illustrate how natural arches may be formed. This arid region receives little precipitation, and much of the surface water seeps into the thick, porous sandstone. Groundwater is most abundant beneath dry stream channels, and its movement follows the general surface drainage lines. Groundwater, emerging as a seep in a cliff beneath a dry waterfall, dissolves the cement in that area. Loose sand grains are washed or blown away, so that an **alcove** soon develops at the base of the normally dry waterfall. If the sandstone is cut by joints, a large block can be separated from the cliff as the joints are enlarged by weathering processes. The alcove and joint surface continue to enlarge, and an isolated arch is eventually produced (Figure 23.13). Weathering then proceeds inward from all surfaces until the arch is destroyed, leaving only columns standing.

Why didn't a "Grand Canyon" develop in Kansas?

The Stable Platform of North America

The stable platform of North America consists of three distinctive parts: (1) the area underlain by Paleozoic strata in the east, (2) the Great Plains region underlain by Mesozoic and Cenozoic strata to the west, and (3) the Atlantic and Gulf coastal plains. The region north of the Ohio and Missouri rivers has been glaciated and is now largely covered with glacial moraine. However, to the south, the classic landforms of a stable platform are well developed—erosional landscapes on horizontal and gently inclined strata.

The major domal structures are the Cincinnati arch in Ohio, Kentucky, and adjacent areas; the Wisconsin dome; and the Ozark dome in Missouri. Large basins formed between the upwarps in Illinois, Michigan, and Ohio. The extension of the Cincinnati arch southward forms the Nashville dome in which weaker rocks in the center have been eroded away to form a topographic basin. Here limestones are

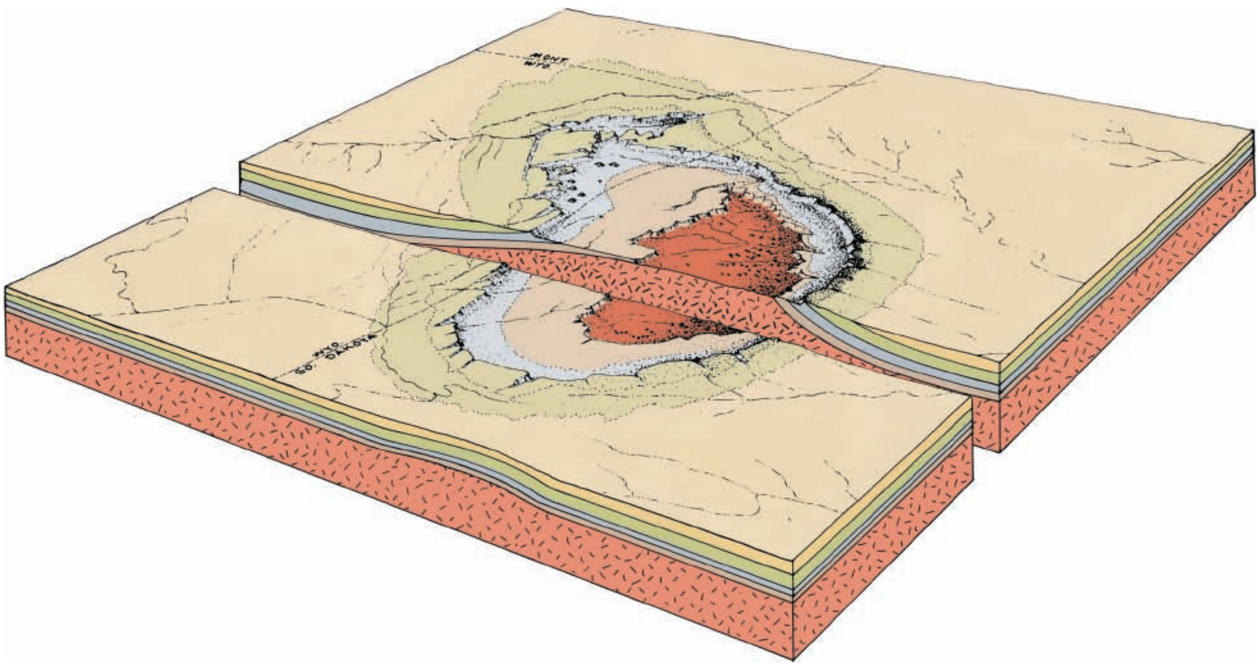
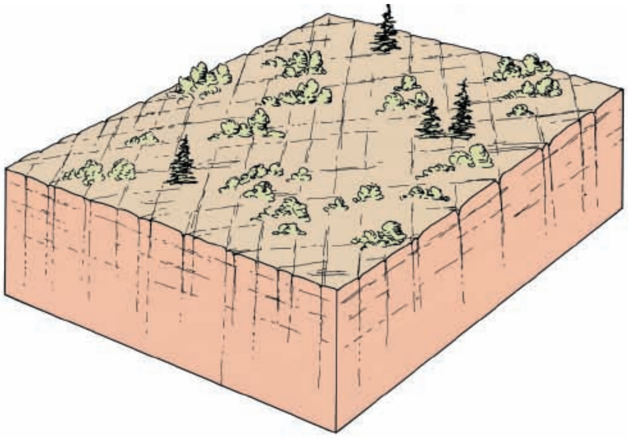
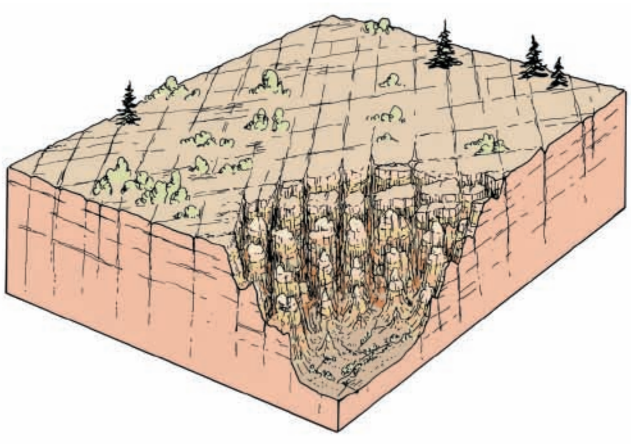


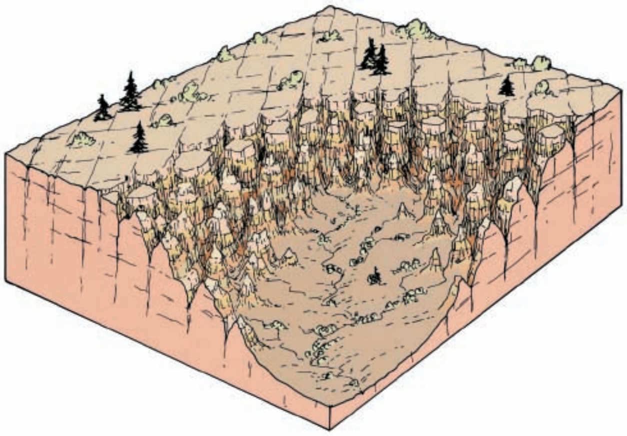
FIGURE 23.11 Hogbacks and intervening strike valleys form in domal structures in the stable platform. Differential erosion of a structural dome in the Black Hills of South Dakota is shown in this diagram.



(A) Initial stage. Intersecting joints separate the rocks into columns.



(B) Intermediate stage. Weathering and erosion along the joints accentuate the columns, which erode into various forms as a result of alternating hard and soft layers.



(C) Final stage. As weathering and erosion proceed, the cliff retreats. Old columns are completely destroyed, but new ones are continually created.

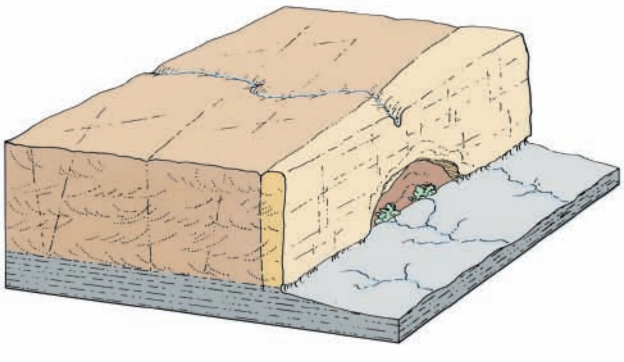
(D) Eroded columns provide the spectacular scenery in Bryce Canyon National Park, Utah. The columns were eroded into colorful Tertiary sedimentary rocks.

FIGURE 23.12 **The evolution of columns by differential erosion** along a receding cliff commonly is controlled by intersecting joint sets. Rapid erosion along joint systems separates the columns from the main cliff. Differential erosion, accentuating the difference between rock layers, produces the fluted columns.

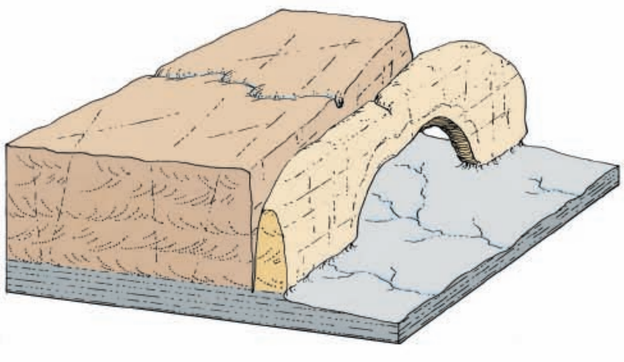
abundant and details of the topography developed on the dipping strata are greatly influenced by groundwater erosion with resulting typical karst landforms.

Throughout the Great Plains, the sedimentary strata dip gently westward. Erosion on the tilted strata has formed cuestas and intervening lowlands in Kansas, Oklahoma, and adjacent areas. A notable exception is the Black Hills dome in western South Dakota, which is a classic domal structure with surrounding elliptical hogbacks and strike valleys (Figure 23.11).

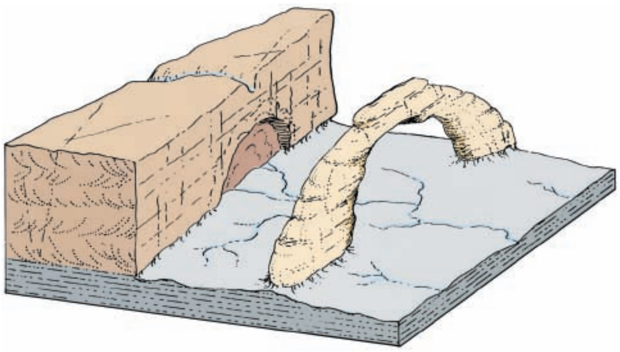
In the coastal plains of the Atlantic and Gulf Coast states, alternating layers of sandstone and shale deposited during the Mesozoic and Cenozoic Eras dip gently seaward. The topography of the coastal plains therefore consists of a series of low cuestas on the sandstone layers and broad, low strike valleys in the soft shales (Figure 23.14). The major streams developed as the seas receded, following the direction of the initial slope. These streams are called **consequent streams.** A younger set of streams eroded headward along the weak shale formations and excavated a belt of lowlands. These are called **subsequent streams.** The resulting drainage system in the coastal plains has a **trellis pattern.**



(A) Initial stage. In arid regions, much of the surface water seeps into the ground below a stream channel. This water may move laterally above an impermeable layer and eventually emerge as a spring at the base of a cliff. Cement holding sand grains together is soon dissolved in this area of greatest moisture; the sand grains fall away, so that a recess, or alcove, forms beneath the dry falls from the intermittent stream above.



(B) Intermediate stage. If a joint system in the sandstone is roughly parallel to the cliff face, the joints can be enlarged by weathering, which separates a slab from the main cliff.



(C) Final stage. An arch is produced as the alcove enlarges. Weathering then proceeds inward from all surfaces until the arch collapses.

(D) The initial stage in the development of a natural arch in Zion National Park, Utah. A well-developed alcove formed beneath a dry waterfall. Weathering along a large joint will soon separate the alcove from the cliff to make a natural arch.

FIGURE 23.13 **Natural arches** develop in massive sandstone formations by selective solution activity in nearly horizontal rocks of the semiarid or arid parts of a stable platform.

FOLDED MOUNTAIN BELTS

> Differential erosion of folded mountain belts produces a series of ridges and valleys conforming to the structural trends of the folds. The landscape generally reflects the specific structural style of the mountain belt.

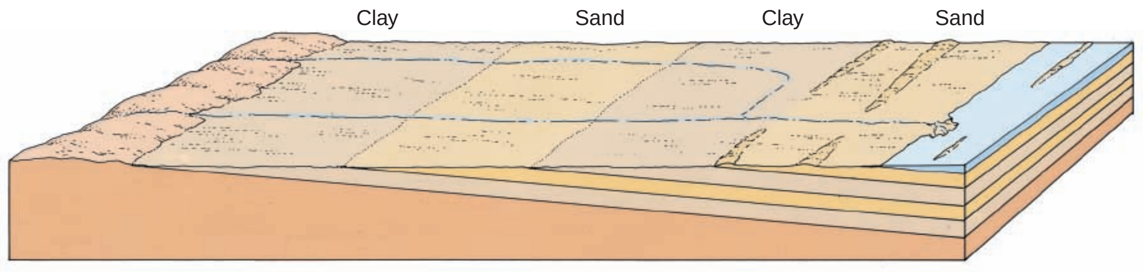
Folded mountains have complex structures that commonly include tight folds, thrust faults, accreted terranes, igneous intrusions, and andesitic volcanic rocks. Landforms are therefore quite variable and the features of mountainous topography will vary according to the age of the mountain and stage of development and the unique structure and rock assemblages that may exist. There are, however, some basic trends in the development of mountain landscapes. The fundamental factor for landscape development is for differential erosion to etch out the structural fabric of the mountain belt and form linear valleys along weak rocks and fault zones and linear ridges along the more resistant rock units. Since folds are the dominant structures in mountain belts, the nature and style of folds greatly influence the style of landforms to be developed.

Landforms that typically develop on folded strata are shown in Figure 23.15. In the initial stages of erosion, the anticlines may form ridges, and the synclines may form long valleys. Some major streams may be superposed across the anticlinal ridges. As erosion proceeds, the crests of the anticlines are cut by the narrow valleys that grow along the flanks of the ridge. As the crest of the ridge is breached, "anticlinal valleys" are enlarged and deepened so that the crest of the anticline becomes open along its length.

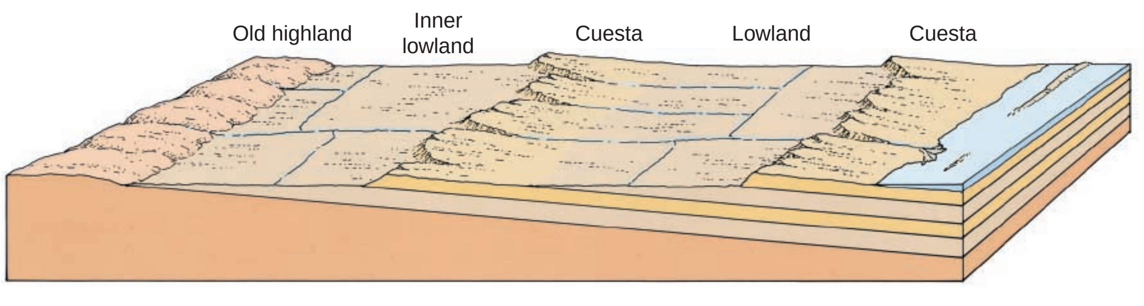
As erosion proceeds rapidly headward along the nonresistant formations, the crests of the anticlines are eroded away, and the surface topography bears little resemblance to the underlying folds. Differential erosion effectively removes the weak rock layers to form long strike valleys. Resistant rock bodies stand up as narrow hogback ridges. The ridges thus mark the limbs of the folds. The pattern of topography is typically one of alternating valleys and ridges that zigzag across the landscape, and the drainage system generally forms a trellis pattern.

It is important to note that folded and eroded formations of sedimentary rock imply the erosion and removal of huge volumes of rock from the landscape. Excellent examples are the hogbacks along the Front Range of Colorado (Figure 23.16). Hogbacks and strike valleys formed on Paleozoic and Mesozoic strata along the front of the Rocky Mountains throughout Colorado and into Wyoming. Sedimentary rocks once covered the older Precambrian granites and metamorphic rocks now exposed in the present mountain range. They have since been eroded, leaving the tilted and eroded edges of the strata as hogbacks and strike valleys.

In young folded mountain belts, especially those that are still active, andesitic volcanoes may dominate the landscape to produce features characteristic of a magmatic arc. Also, thrust faults may greatly complicate the structure so that the resulting landscape is more complex.

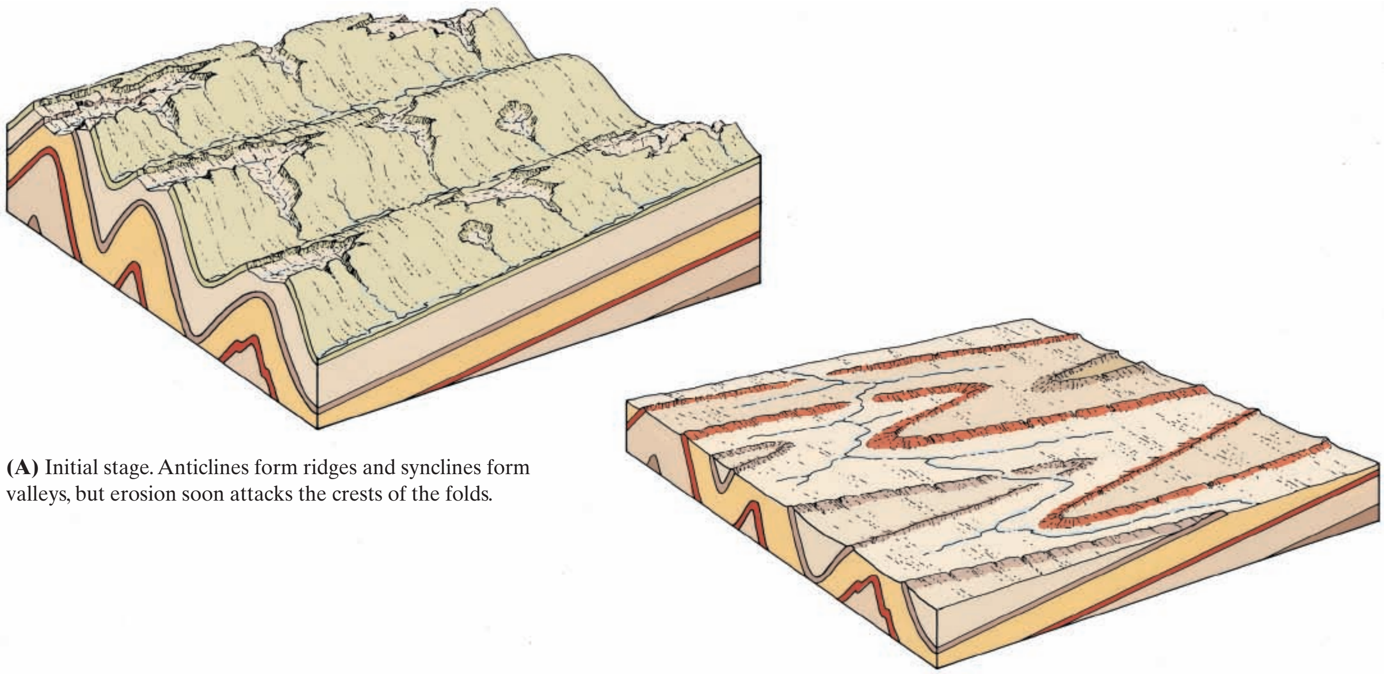


(A) As the coastal plains emerge above sea level, the drainage system is simply extended downslope directly toward the new shoreline. These are called consequent streams.



(B) Headward erosion of tributary streams along the nonresistant shale units produces linear lowlands (strike valleys). The more-resistant sandstone units remain as linear ridges called cuestas.

FIGURE 23.14 **The Atlantic and Gulf coastal plains** consist of Tertiary and Cretaceous rocks that are inclined toward the sea. The evolution of landforms developed on the inclined strata is shown in idealized block diagrams. *(After A. N. Strahler)*



(A) Initial stage. Anticlines form ridges and synclines form valleys, but erosion soon attacks the crests of the folds.

(B) Later stages. The tops of the folds are eroded away, so that hogback ridges are left along the flanks of the folds. These ridges commonly form a zigzag pattern.

FIGURE 23.15 **Differential erosion of folded rocks** typically forms alternating ridges and valleys. *(After A. N. Strahler)*

The Appalachian Ridge and Valley Province

The Ridge and Valley Province of the eastern United States is a classic example of a landscape formed on folded and thrust-faulted strata (Figure 23.17). It extends from Pennsylvania to central Alabama, a distance of more than 2000 km. In Alabama, the folded structures plunge beneath the younger sediments of the Coastal Plain. Similar topography is exposed again in the Ouachita Mountains in Arkansas and Oklahoma and in the Marathon Mountains in west Texas. A large segment of the folded Appalachian mountain belt is, therefore, still buried beneath younger sediments.

What landforms typically develop on folded mountain belts?

The deformation that produced the folds occurred during the late Paleozoic Era (more than 200 million years ago). The mountain belt was then deeply eroded, and most of the region was covered by Cretaceous and possibly Tertiary sediments. Regional uplift ensued, and renewed erosion began to remove the sedimentary cover. The major east-flowing streams were superposed on the northeast-trending structures, and differential erosion began to cut the extensive valley system between the resistant sandstone ridges (Figure 23.15). Extension of the drainage system by more rapid erosion of the nonresistant shale and limestone formations resulted in stream capture and the development of a trellis drainage pattern. (Note that in humid regions limestones are eroded rapidly, whereas in drier regions they are resistant.)

Folded mountain belts similar to the Appalachian are found in many areas of the world, such as in southwest China, the Zagros Mountains of Iran, the Urals of Russia, and parts of the Andes, as well as the foothills of the Himalayas.

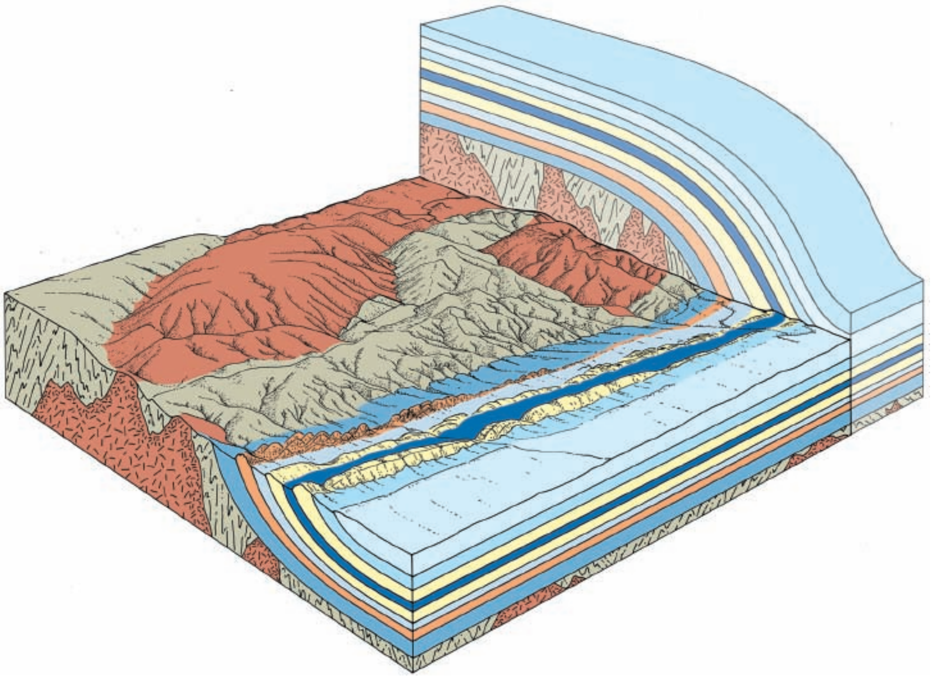


FIGURE 23.16 **Hogbacks along the Front Range of Colorado** are the remnants of a thick sequence of Paleozoic and Mesozoic strata that were deformed into a large dome. The sequence at the end of the diagram shows the amount of material removed by erosion.

CONTINENTAL RIFTS

Continental rifts produce horsts and grabens that are rapidly modified by erosion and sedimentation. Erosion dissects the uplifted blocks, and the sediment is deposited in the grabens as alluvial fans and lake deposits. With time, the rift may evolve into a continental margin.

A **continental rift** is a region where the crust has been arched upward, thinned, stretched, and fractured. The dominant structures in this tectonic setting are parallel systems of normal faults, with large vertical displacements. Typically, the faults produce large, elongate, down-dropped grabens and associated uplifted horsts. The major landform produced by normal faulting is a steep cliff, or **fault scarp,** which is soon dissected by erosion.

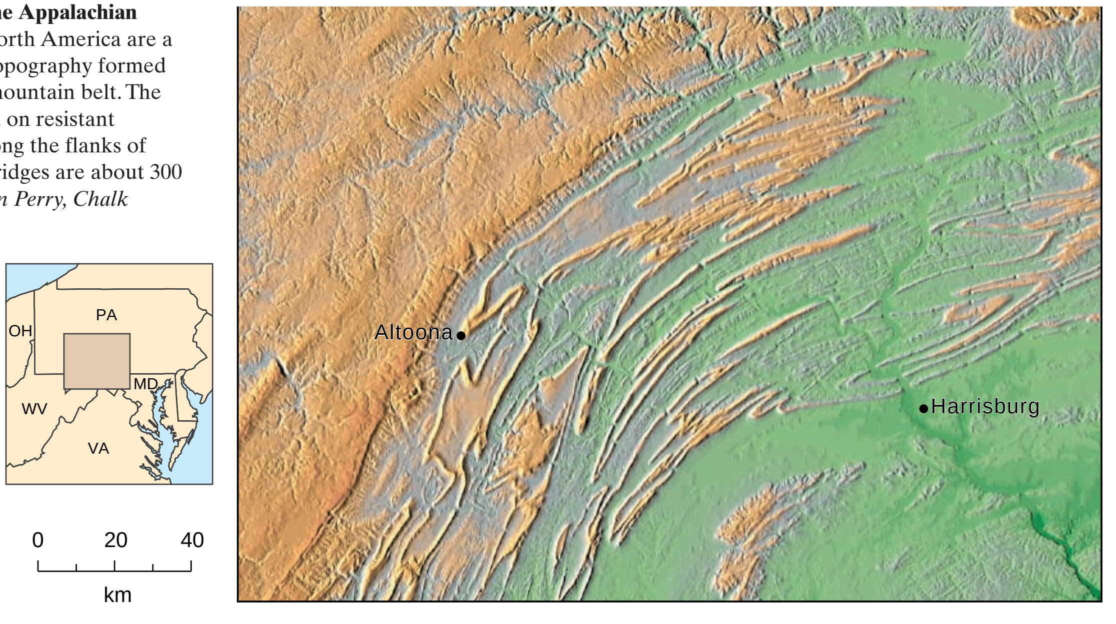


FIGURE 23.17 **The Appalachian Mountains** in eastern North America are a classic example of the topography formed by erosion of a folded mountain belt. The linear ridges are formed on resistant quartzite formations along the flanks of long, narrow folds. The ridges are about 300 m high. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

The evolution of erosional landforms developed on a normal fault block is shown in Figure 23.18. As soon as uplift occurs, stream erosion begins to dissect the cliff and produces a series of triangular faces known as **faceted spurs.** Erosion also forms gullies along the blunt face of the faceted spurs, so the cliff produced by faulting is considerably modified. Recurrent movement along the fault can produce a fresh scarp at the base of the older faceted spurs, but it is also rapidly modified by gullying to form a series of compound-faceted spurs. When movement on the fault ceases, the cliff continues to erode down and back from the fault line.

Why is the topography of the Appalachian Mountains so different from that of the Rocky Mountains?

The idealized stages in landscape development by block faulting in an arid region are illustrated in Figure 23.19. In the initial stage, maximum relief is produced by the uplift of fault blocks. Relief diminishes throughout subsequent stages, unless major uplift recurs and interrupts the evolutionary trend by producing greater relief during later stages. In arid regions, depressions between mountain ranges generally do not fill completely with water. Large lakes do not form because of the low rainfall and great evaporation. Instead, shallow, temporary lakes, known as **playa lakes,** form in the central parts of basins and fluctuate in size during wet and dry periods. They may be completely dry for many years and then expand to cover a large part of the valley floor during years of high rainfall. When rainfall is high enough to maintain a permanent body of water, the lake is commonly saline, owing to the lack of an outlet. Great Salt Lake, in Utah, is an example. Most basins in the Basin and Range Province have dry playas during most of the year; however, during the cooler, wetter climatic periods that accompanied the Pleistocene glaciers, lakes with surface areas of thousands of square kilometers developed in many of these valleys.

Weathering in the uplifted mountain mass produces more sediment than can be carried away by the intermittent streams, which may flow only during spring runoff. The overloaded streams commonly deposit much of their load where they emerge from the mountain front. This sediment accumulates in broad alluvial fans. Throughout their history, the mountain ranges are eroded and the debris is deposited in the adjacent basin. As erosion continues (Figure 23.19B), the mountain mass is dissected into an intricate network of canyons and is worn down. At the same time, the mountain shrinks farther as the front recedes through the process of slope retreat.

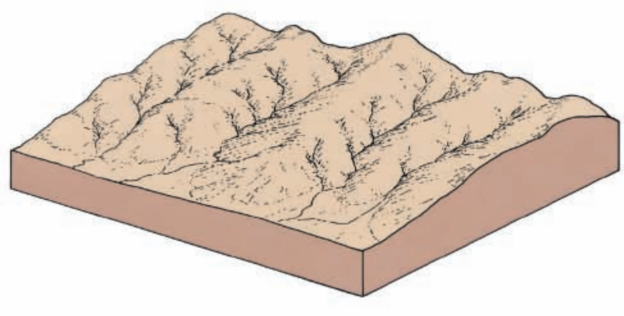
In the final stage (Figure 23.19C) of this model, the fans along the mountain front grow and merge to form a large alluvial slope, a **bajada.** As the mountain front retreats, an erosion surface, known as a **pediment,** develops on the underlying bedrock. It expands as the mountain shrinks. Pediments are generally covered by a thin, discontinuous veneer of alluvium. As shown in Figure 23.19C, pediments may become completely buried.

What landforms typically develop on continental rifts?

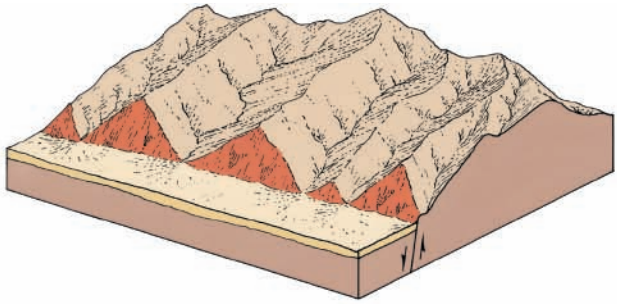
Basin and Range Province

This tectonic and erosional model effectively explains much of the landscape in the Basin and Range Province of the western United States (Figure 23.20). The Basin and Range is a large area where the crust has been uplifted and extended, forming a complex rift system that reaches from northern Mexico to southern Idaho and Oregon (Figure 19.29). The block faulting, resulting from extension, has produced alternating mountain ranges and intervening basins. There are more than 150 separate ranges in this province. Some are simple tilted fault blocks that are asymmetrical in cross section, the steeper side marking the side along which faulting occurred. Others are faulted on both sides. The internal structure of the fault blocks is complex, with folds, faults, and igneous intrusions recording an earlier history of crustal deformation.

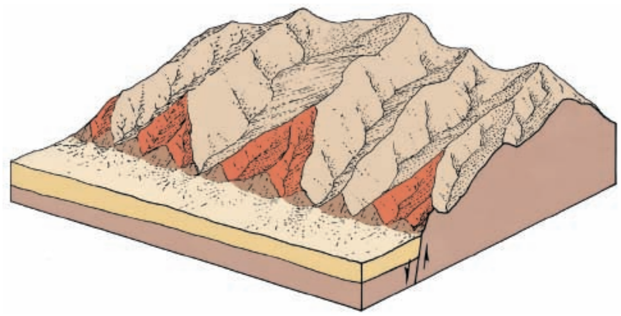
To the north, throughout much of western Utah and all of Nevada, the area is in the initial stage of development. The basins occupy about half the total area, and the pediments are small. The relief of the mountain ranges is high, with most alluvial fans just beginning to coalesce into broad alluvial



(A) The original dissected upland, before faulting, consists mostly of valley slopes.



(B) The first major period of faulting is accompanied by accelerated stream erosion. Valleys are cut through the scarp produced by faulting to form triangular faceted spurs.



(C) Recurrent movement along the fault can produce a series of fresh scarps, which are subsequently dissected by stream erosion. Older faceted spurs recede and are worn down.

(D) Faceted spurs on the Wasatch Mountains, central Utah. A normal fault lies at the base of the range. Stream erosion during uplift created valleys that bound triangular faceted spurs.

FIGURE 23.18 **Erosion of fault-block mountains** follows a series of stages in which faceted spurs are a prominent landform. This landscape is typical of the Basin and Range province of the western United States and illustrates the evolution of landforms in continental rifts.

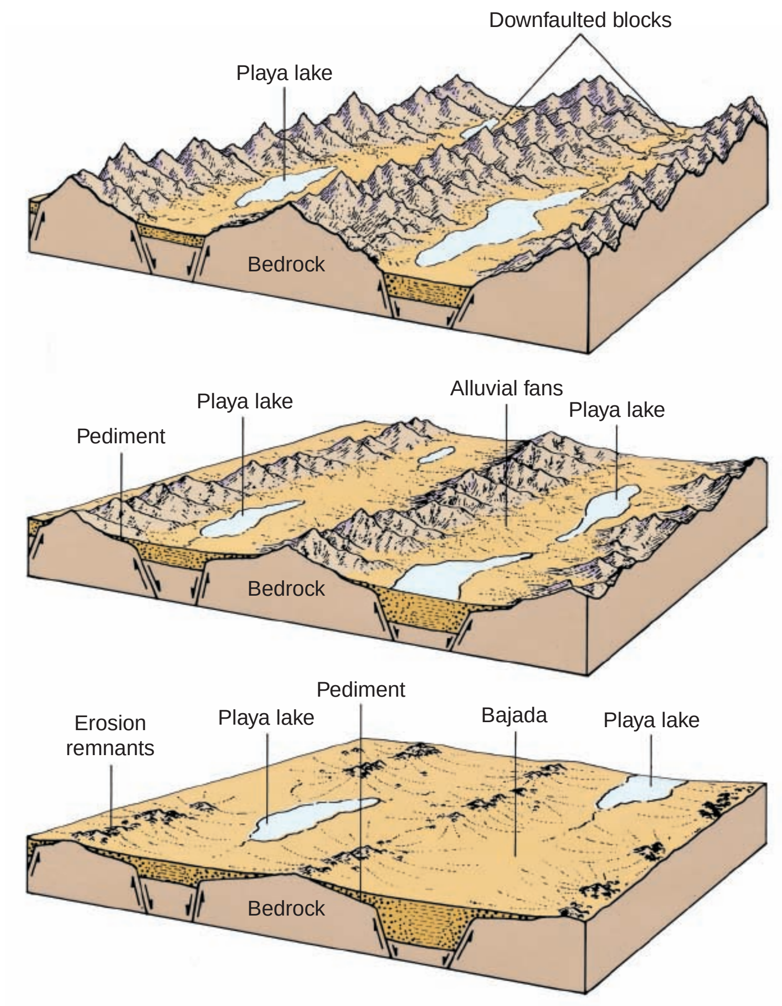
slopes. Recurrent movement along many fault systems is indicated by complex faceted spurs, similar to those illustrated in Figure 23.18D. Continued movement in recent times is clear from faulted alluvial fans and recurring earthquakes in the area.

In Arizona and Mexico, erosion in the Basin and Range has proceeded much further, and the area is in the late stage of development. The ranges are eroded down to small remnants of their original size. Extensive bajadas, spreading over approximately four-fifths of the area, cover wide pediments, through which isolated remnants of bedrock protrude.

FLOOD BASALTS: PLAINS AND PLATEAUS

The extrusion of large volumes of basalt may flood large areas of the landscape to produce a basaltic plain that commonly develops a series of distinctive landforms and ultimately evolves into a dissected basaltic plateau.

The tectonic setting for extrusion of continental flood basalts is commonly a rift system or a hot spot. The unique feature of flood basalts is that, as the name implies, huge volumes of fluid basaltic lava are extruded and flood the landscape, covering extensive areas of preexisting landforms. The floods of basalt thus provide a new surface that is modified by erosion through a series of stages resulting in a distinctive landscape quite unlike that of a shield, stable platform, or folded mountain belt.



(A) Initial stage. Faulting produces maximum relief. Initially, some areas in the mountains are undissected. Playa lakes may develop in the central parts of the basins.

(B) Intermediate stage. The mountain range is completely dissected, and the mountain front retreats as a pediment develops. Alluvial fans spread out into the valley.

(C) Late stage. The basins become filled with sediment. Erosion wears down the mountain ranges to small, isolated remnants. The pediments expand and are buried by the alluvial fans, which merge to form bajadas. Most of the surface is an alluvial slope.

FIGURE 23.19 A model of landscape development in the Basin and Range Province of the United States. Continental rift systems such as this evolve through a series of stages until the mountains are consumed.

Evolution of Basaltic Plains

The general trends in the evolution of **basaltic plains** might best be understood by considering what develops in areas of local volcanism because the local areas provide a small-scale model of the major trends in landform evolution of regional basaltic floods. The sequence of landforms resulting from erosion in areas where minor volcanic activity occurs is shown in Figure 23.21. Upon extrusion, lava follows established river channels and partly filled stream valleys. The lava flows disrupt drainage in two principal ways: (1) Lakes are impounded upstream, and (2) the river is displaced and forced to flow along the margins of the lava flow. Subsequent stream erosion is then concentrated along the lava margins.

As erosion is initiated in the displaced drainage system (Figure 23.21B), new valleys are cut along the flow margins and become gradually deeper and wider with time. Cinder cones, if formed during the volcanic activity, are soon obliterated because the unconsolidated ash is easily eroded. Only the conduit through which the lava was extruded remains as a resistant **volcanic neck.** With time, the area along the margins of the lava flow is eroded, so the old stream now flooded with lava is left standing higher than the surrounding area as an **inverted valley.** In the final stage of erosion (Figure 23.21C), the inverted valley is reduced in size and ultimately becomes dissected into isolated mesas and buttes.

In regions of extensive volcanism, such as those related to mantle plumes and flood basalts, large areas may be completely buried by lava flows. In the initial stage,

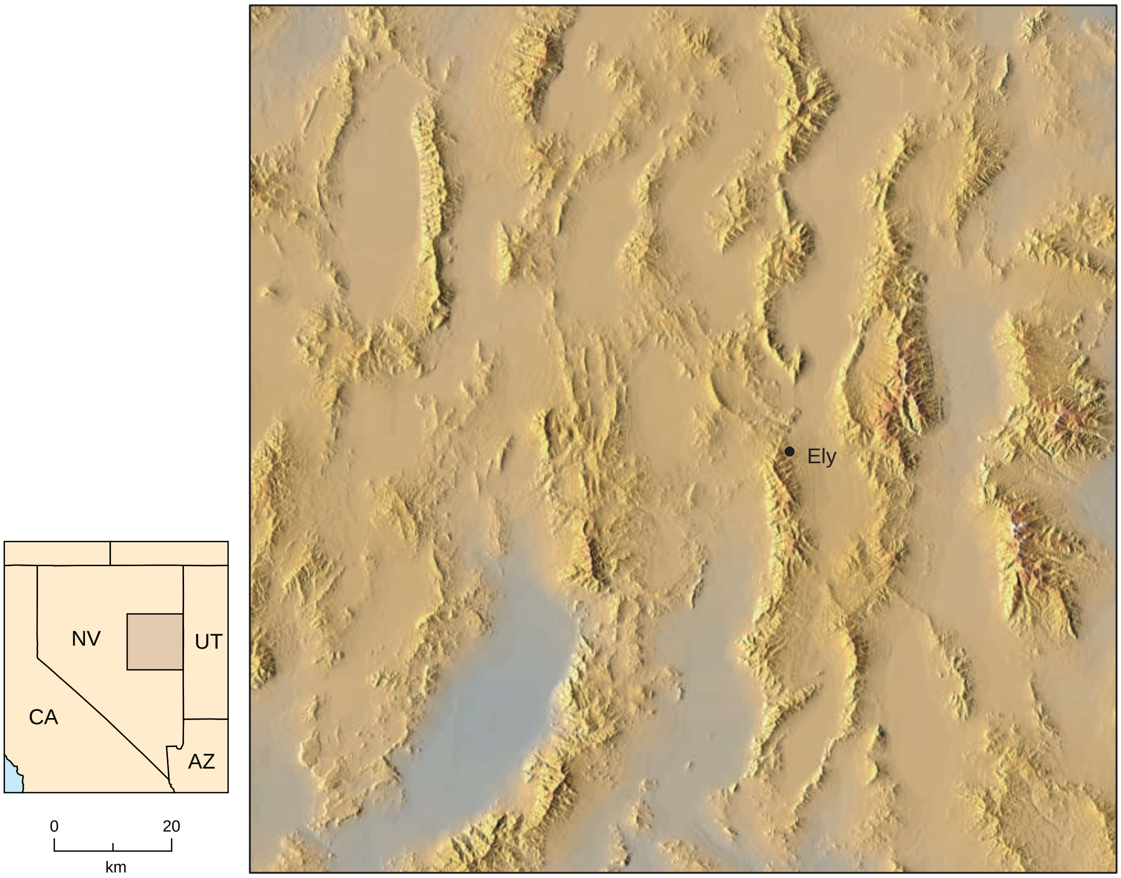


FIGURE 23.20 **Basin and Range Province in Nevada** shows the typical landforms developed in a broad rift system in an arid region. Erosion of the fault blocks produces alternating mountain ranges and intervening basins filled with sediment. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

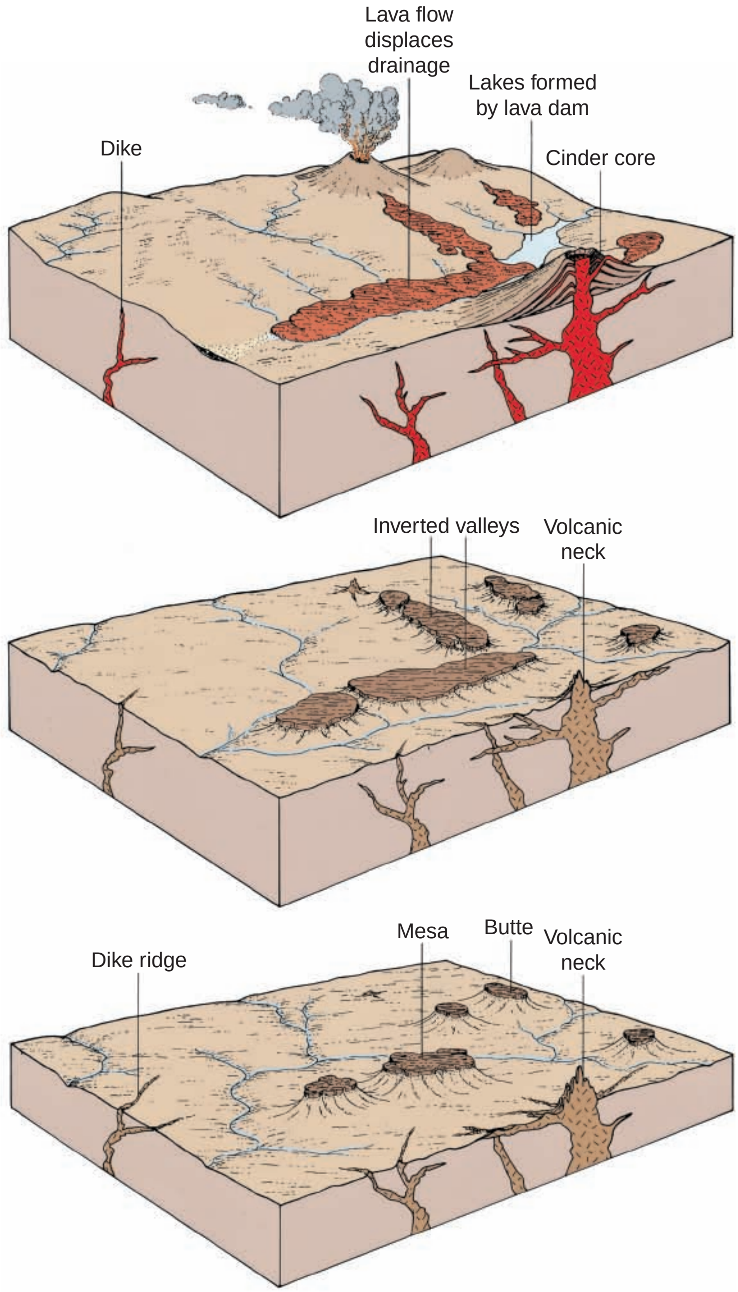
basaltic lava covers the lowlands, forming a lava plain. Drainage usually is displaced to the margins of the lava plain, but some rivers may migrate across the plain. When extrusion ceases, stream erosion begins to dissect the lava plain and eventually cuts it into isolated plateaus and mesas. These, in turn, are ultimately eroded away.

Foremost among the older basaltic plains that are now uplifted and eroded into dissected plateaus is the Ethiopian Plateau in northeast Africa. Here, floods of basalt associated with the East African Rift valleys are eroded into plateaus more than 4000 m above sea level. The Deccan basalts of India, the Parana basalts of South America, and the basaltic lava flows of northern Siberia have developed landscapes typical of plateau basalts.

Basaltic Plains of North America

What are inverted valleys? How do they originate?

An example of a landscape developed on basaltic plains is the Columbia Plateau and Snake River Plain of Washington, Oregon, and Idaho. This region of more than 400,000 km^2 represents one of the world's major accumulations of lava on a continent (Figure 23.22). Approximately 100,000 km^3 of basaltic lava was extruded in this area through fissure eruptions and small shield volcanoes. The lavas were very fluid and completely covered preexisting mountains and valleys with a local relief of more than 750 m. The age of the basalts ranges from about late Tertiary (17 million years) to Recent, with the youngest flows in Craters of the Moon National Monument being less than 2000 years old. As explained in Chapter 22, these lavas are probably related to the passage of North America over a mantle plume. Individual lava flows vary from 2 m to as much as 50 m in thickness. In places, the total sequence of basalt flows is more than 4 km thick.



(A) Initial stage. Lavas extruded from volcanic vents flow down existing rivers and streams and block the normal drainage system. Lakes commonly form upstream, and new stream channels develop along the margins of the lava flow. Volcanic cones are fresh and relatively untouched by erosion.

(B) Intermediate stage. The cinder cones are worn down until only volcanic necks are left standing. Erosion along the margins of the lava flow removes the surrounding rock, so the flow forms a sinuous ridge, or inverted valley.

(C) Late stage. Inverted valleys are eroded to mesas and buttes. Volcanic necks and dikes commonly form peaks and isolated ridges.

FIGURE 23.21 **A model of landscape development in an area of local basaltic volcanism** shows how inverted topography may develop.

The extrusion of the lavas produced a new surface that is currently being eroded and modified by the Columbia and Snake river systems. In southern Idaho, where the lavas are young, the region is in the initial stage of development, with large areas of basalt flows essentially untouched by stream erosion. In the eastern part of the region, the Snake River has been forced to flow along the southern margins of the plain because new young flows cover the central part of the area (Figure 23.22). In western Idaho, the Snake River has cut a deep canyon in the basalts. Hell's Canyon of the Snake, along the Idaho-Oregon border, is deeper than the Grand Canyon of the Colorado.

The Columbia Plateau in Oregon and Washington is made of much older basaltic lavas and is more deeply eroded. Erosion of the Columbia Plateau has been complicated by catastrophic flooding during the last ice age. But here again, the major drainage is displaced to the margins of the plains, where it is actively cutting deep canyons.

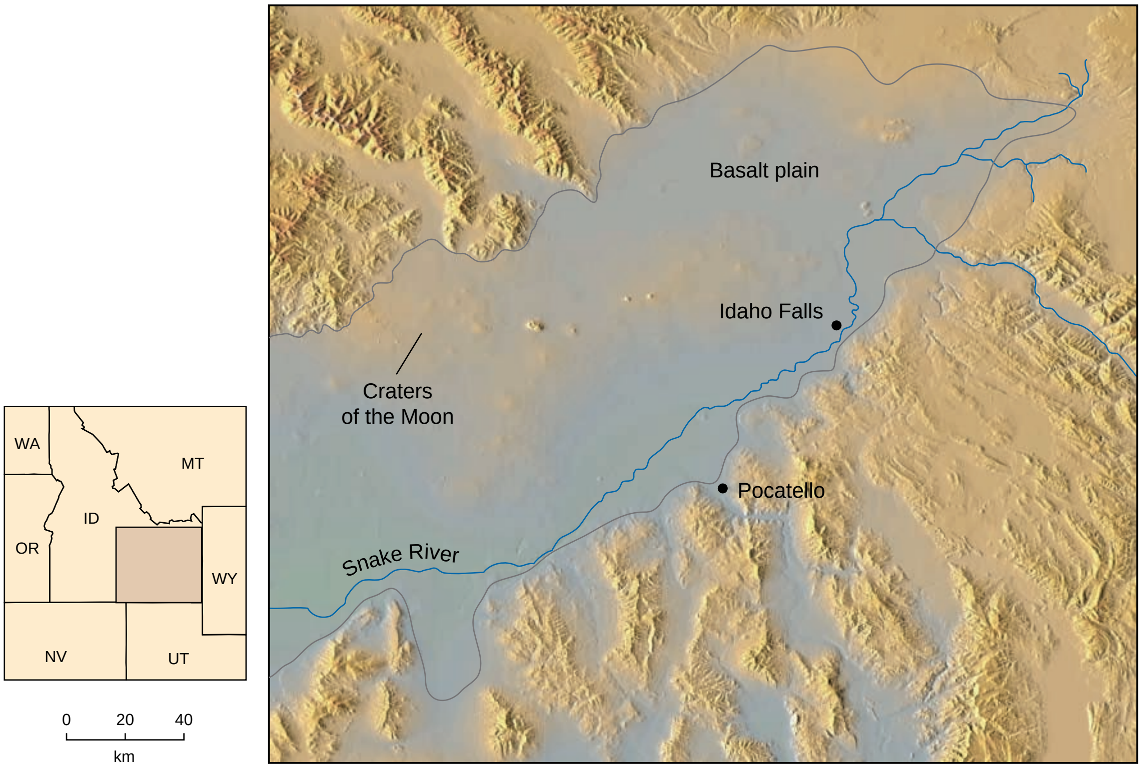


FIGURE 23.22 **The eastern Snake River Plain** in Idaho is underlain by extensive floods of basalt that form a broad, smooth plain. The young lava flows of the Snake River Plain are not eroded. Note how the Snake River has been displaced to the southern margin of the plain by repeated volcanism. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

MAGMATIC ARCS

> The landscapes of magmatic arcs formed above subduction zones are dominated by volcanic landforms that evolve by uplift and erosion until most of the volcanic features are erased. Ultimately, the volcanoes are eroded away to expose the deeper igneous intrusions.

Island arcs are the surface manifestation of magmatic activity produced at convergent plate boundaries. The most characteristic landform is a group of large composite andesitic volcanoes that rise thousands of meters above their surroundings.

FIGURE 23.23 **Two of the hundreds of volcanoes in the Kuril Island arc** of the western Pacific show the typical landforms developed on an active magmatic arc. Large calderas occur on the opposite ends of the island, each with a younger cone in the middle. Older volcanoes can be recognized by their circular forms. *(Digital image copyright 1996 Corbis; original image courtesy of NASA)*

The volcanoes extend in a linear zone parallel to the convergent plate margin. The general trend in landform evolution in a magmatic arc is for streams and glaciers to systematically erode the volcanoes even as eruptions continue. Thus, the high volcanic peaks and collapse calderas are soon eroded down to circular or elliptical remnants and rounded hills. Circular landforms dominate the landscape (Figure 23.23). Repeated extrusion occurs in magmatic arcs, however, so volcanic features representing a variety of ages occur within a given area. Drainage systems are constantly being displaced by new volcanoes, and large segments of a river system may be completely obliterated as extrusion continues. New drainage patterns develop in its place. A well-integrated drainage system is therefore difficult to establish in an active volcanic arc and many small lakes commonly develop. Glaciers also form on the high volcanic peaks, even in low latitudes such as the central Andes.

When igneous activity terminates, erosion and associated isostatic uplift occur so that, ultimately, the volcanic material is removed and granitic intrusions are exposed at the surface. Thus, the landscape evolves from a volcanic terrain to one formed on igneous intrusions.

The Cascade Volcanic Chain

The Cascade Mountains of northwestern United States is a magmatic arc built on continental crust (Figure 23.24). Here, famous composite volcanoes such as Mount Shasta, Crater Lake, Mount St. Helens, and Mount Rainier rise above the surrounding landscape, and hundreds of smaller volcanoes form a belt roughly 80 km wide and more than 500 km long. Between the volcanoes are beds of lava and tuff that mask all the other rocks and surface features. In many areas the average distance between these small volcanoes is little more than 5 km. Volcanic eruptions and contemporaneous erosion have been the dominant geologic processes for most of the last several million years.

California's Mount Shasta exceeds 4000 m in elevation and Mount Lassen, which last erupted in 1914 and 1915, rises to more than 3000 m. Much of the stream drainage has been disrupted by the flows and volcanoes. Lakes are numerous, but many are dry much of the time because of the porous nature of the lava and tephra. During the last ice age, glaciers formed on all of the volcanic peaks higher than about 3000 m, and many glaciers still exist today.

Cycles of eruption and erosion have persisted since 15 million years ago. In the middle Cascades, an imposing row of huge Quaternary (less than 1 million years old) volcanoes dominate the skyline. Volcanoes and volcanic material represent all ages from middle Tertiary to the present. For example, the flanks of Mount St. Helens are only a few years old. Crater Lake, in southern Oregon, was once a similar huge volcano, but 7000 years ago a cataclysmic eruption fractured the upper part of the cone as great quantities of ash erupted. The summit collapsed to form a caldera containing a lake about 600 m deep. The western Cascades are so completely eroded that no trace of their original volcanic landscape remains. North of Washington's Mount Rainier, the Cascades have been uplifted and deeply eroded to expose granitic batholiths that intrude older metamorphic and sedimentary rock.

We thus see in the Cascades examples of practically every phase of landscape developed in magmatic arcs, from active volcanoes to exposed granitic intrusions. This is America's segment of the great Ring of Fire that essentially surrounds the Pacific Ocean, and similar landforms can be found from the southern end of the Andes to the Aleutian Islands, Japan, the Philippines, and Indonesia.

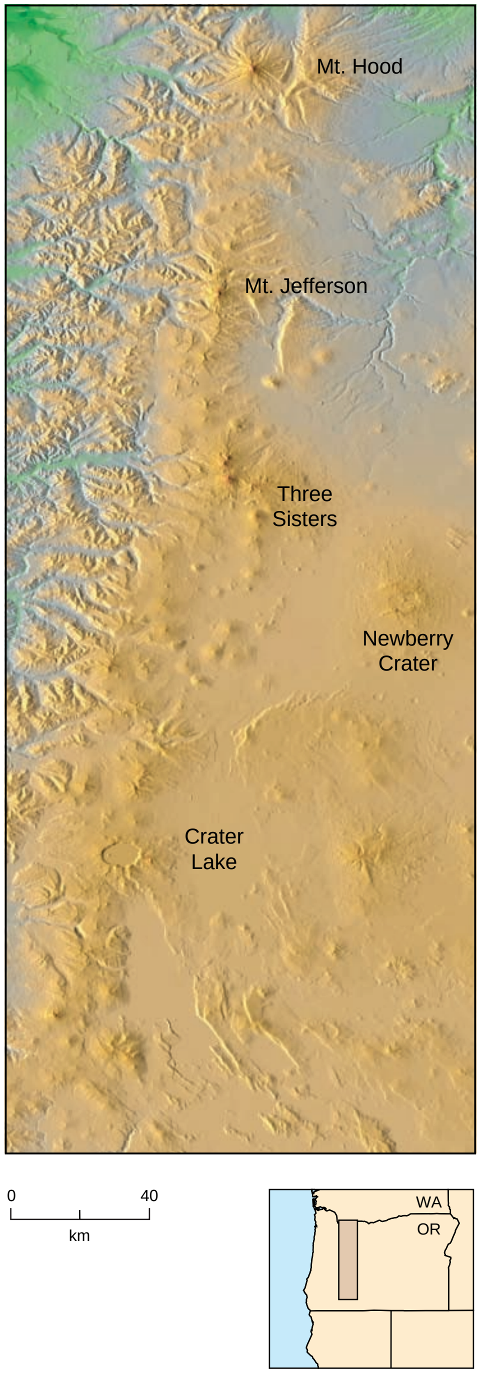
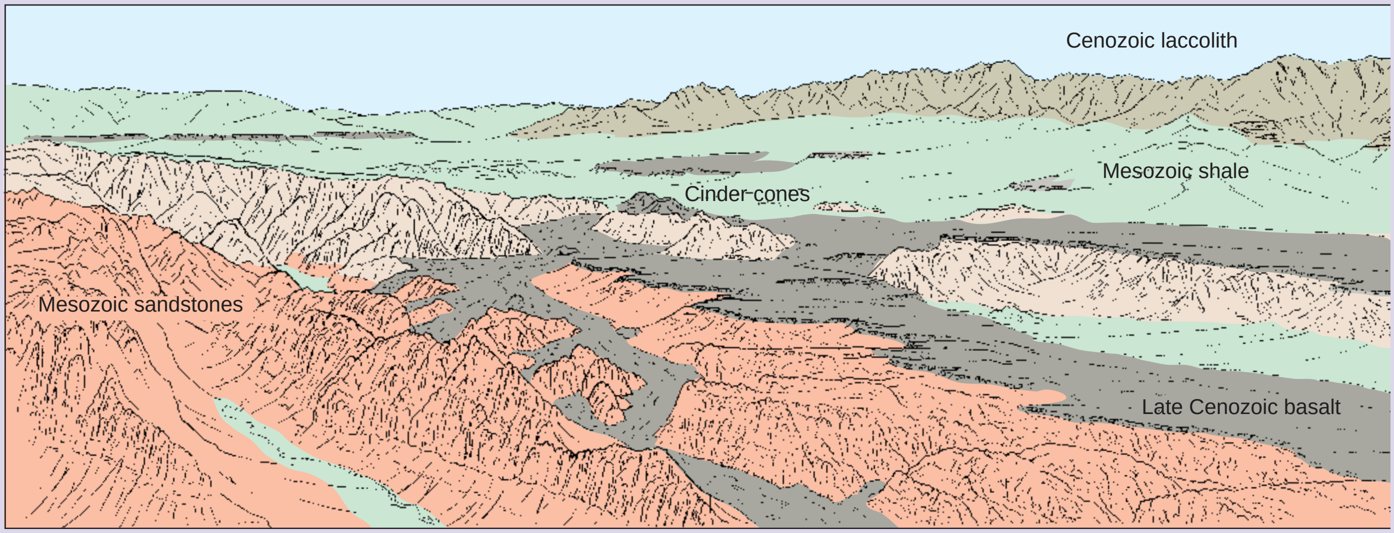


FIGURE 23.24 Erosion of a magmatic arc produces a landscape marked by circular forms that are the remnants of volcanoes and collapse calderas. Radial drainages commonly develop on the volcanoes. This shaded relief map shows the Cascade Mountains in Oregon. The young volcanoes are being eroded but their circular form is still preserved. An older volcanic terrain to the west is dissected into deep valleys and canyons. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

GeoLogic *Landscape of Snow Canyon, Utah*



This area is a land of colorful mesas, cliffs, and plateaus but there is much more to this area than spectacular scenery. The sketch will help you identify the major geologic features.

Observations

1. The red and white cliffs are made of Mesozoic sandstones that are resistant to erosion.
2. The tree-covered slope behind them is underlain by late Mesozoic shales that are less resistant to erosion.
3. The mountains in the background expose a middle Cenozoic granitic laccolith.
4. Late Cenozoic basalt flows bury part of the countryside. A road winds its way across one of them and another basalt flow forms a low inverted valley on top of the red sandstone in the central part of the scene. A third basalt flow forms a high inverted valley on top of the white cliffs and black cones of talus spill from it.

Interpretation

Initially, the layers of sedimentary rock were deposited by the wind, in rivers, or in shallow seas. At the time, this area was east of an active convergent plate margin. Eventually, subduction-related magmatism created granitic magma, which intruded into the sequence of sedimentary rock. But convergence ceased and was replaced by extension and rifting on a grand scale. As a result, the sequence of sedimentary rocks and the laccolith were raised several kilometers above sea level. Erosion by running water then stripped the sedimentary cover off the intrusion, and carved the rugged red and white cliffs and deep canyons. The nonresistant rock layers were easily stripped away to create the tree-covered slope. Continental rifting was accompanied by several episodes of basaltic volcanism. Lava flows cascaded down the white cliffs and flowed into the red canyons below. Continued uplift and erosion during the volcanism created the inverted valleys from the resistant lava flows.

KEY TERMS

alcove (p. 673)
bajada (p. 679)
basaltic plain (p. 681)
basin (p. 672)
butte (p. 672)
column (p. 672)
consequent stream (p. 674)
continental rift (p. 678)
cuesta (p. 672)
dendritic drainage (p. 671)
differential erosion (p. 662)
dome (p. 672)
faceted spur (p. 679)
fault scarp (p. 678)
folded mountain belt (p. 662)
hogback (p. 672)
inverted valley (p. 681)
mesa (p. 671)
natural arch (p. 673)
pediment (p. 679)
pillar (p. 672)
pinnacle (p. 672)
plateau (p. 671)
playa lake (p. 679)
shield (p. 662)
stable platform (p. 662)
strike valley (p. 671)
subsequent stream (p. 674)
trellis pattern (p. 674)
volcanic neck (p. 681)

REVIEW QUESTIONS

1. What are the major factors that influence the evolution of continental landscapes?
2. Contrast the landscapes formed on a shield found in a tropical climate with one found in a polar region.
3. How does differential erosion produce alternating cliffs and slopes?
4. Describe the model of evolution of a mountain belt into a new segment of the shield. At what stage are erosion rates highest?
5. Explain the origin of columns and pillars, such as those in Bryce Canyon National Park.
6. How are natural arches formed?
7. Describe and illustrate, with sketches, the landforms that typically develop on a stable platform.
8. Why is the Coastal Plain of the Atlantic so low and smooth?
9. What changes would be necessary for deep canyons to form in Kansas?
10. Describe and illustrate, by means of a cross section, the landforms that typically develop by erosion of folded sedimentary rocks found along a convergent plate margin.
11. What processes are responsible for the adjustment of a drainage pattern to flow along structural trends such as those found in folded mountain belts?
12. Describe and illustrate, by means of a cross section, the origin of landforms in a rift system.
13. How do the landforms of a magmatic arc differ from those of a folded mountain belt formed by continental collision? What landscape features might they have in common?
14. Why is the western slope of the Cascade Mountains (Figure 23.24) more intricately eroded than the eastern side?
15. How do rivers adjust in areas where eruptions of basaltic lavas are important?
16. On a map of North America, outline the extent of the shield, stable platform, folded mountain belts, and basaltic plains.
17. List several ways in which tectonics influence or control the nature of landscapes.

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Earth's Dynamic Systems Website

The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Slide show on differential erosion
- Computer-guided tour of the major geologic provinces of North America
- A direct link to the Companion Website