DAVID BLOOM STANLEY, 1986

Jurassic time, when deposition ended with a final episode of faulting. After this time, the basins apparently moved so far westward along with the North American plate that they were no longer affected by the mid-Atlantic rifting. The fact that some of the basins are located several hundred kilometers from the present margin of North America (Figure 15-33) indicates how imprecise the fracturing of a large continent can be; in most such instances, many small breaks and ruptures occur rather than a clean separation from sea to sea.

Western North America

Throughout the Triassic Period, much of the American West was the site of nonmarine deposition. Shallow seas expanded and contracted along the margin of the craton but for the most part remained west of Colorado. During Middle and Late Triassic time, western North America was especially free of marine influence.

As in the Permian Period, the climate here remained largely arid. At times, however, there was sufficient moisture to permit the growth of large trees belonging to the Euramerian flora. The series of river and lake sediments in Utah and Arizona that are collectively known as the Chinle Formation, for example, erodes spectacularly in some places to reveal the well-known Petrified Forest of Arizona (Figure 15-38). In southwest Utah, the Chinle is overlain by the Wingate Sandstone, a desert dune deposit (Figure 15-39). This, in turn, is followed by a river deposit called the Kayenta Formation, on top of which rests the Navajo Sandstone. The Navajo, also a desert dune deposit, ranges upward in the stratigraphic sequence from approximately the position of the Triassic-Jurassic boundary. The Navajo is famous for its large-scale cross-bedding in the neighborhood of Zion National Park (Figure 15-40).

During Middle and Late Jurassic times, as sea level rose globally (Figure 15-30), waters from the Pacific Ocean spread farther inland in a series of four transgressions, each more extensive than the last. The first such transgression went no farther than British Columbia and northern Montana, but the last, which is known as the Sundance Sea, spread eastward to the Dakotas and southward almost to the Mexican border (Figure 15-41). Eventually, as mountain building progressed along the Pacific Coast in Late Jurassic time, the Sundance Sea retreated. We will now examine this tectonic episode and analyze how it caused marine sedimentation in the Sundance Sea to give way to nonmarine deposition.

FIGURE 15-38 Silicified logs that have weathered out of the Triassic Chinle Formation in the Petrified Forest of Arizona. (*National Park Service.*)

After the end of the Sonoma orogeny early in the Triassic Period, there was a brief interlude of tectonic quiescence along the west coast of North America. Then, in mid-Triassic time, the continental margin once again came to rest against a subduction zone, thus marking the beginning of an orogenic episode that extended from Alaska all the way to Chile. Mountain building along the Pacific coast of North America during the Mesozoic Era resembled the growth of the Andes to the south, which has continued to the present day (page 217).

Subduction of the oceanic plate beneath the margin of North America thickened the continental crust by leading to the accumulation of intrusive and extrusive igneous rocks. The oldest intrusives of the Sierra Nevada Mountains were emplaced during Jurassic time (Figure 15-42), although larger volumes were added later in the Mesozoic Era.

The Mesozoic history of the Pacific coast of North America is highly complex (Figure 15-43). At times, more than one subduction zone lay offshore, and exotic slivers of crust were added to the continental margin. Near the end of the Jurassic Period, the continent accreted westward when the Franciscan sequence of deep-water sediments and volcanics was forced against the craton along a subduction zone after having been metamorphosed at high pressures and at low temperatures. The Franciscan sediments

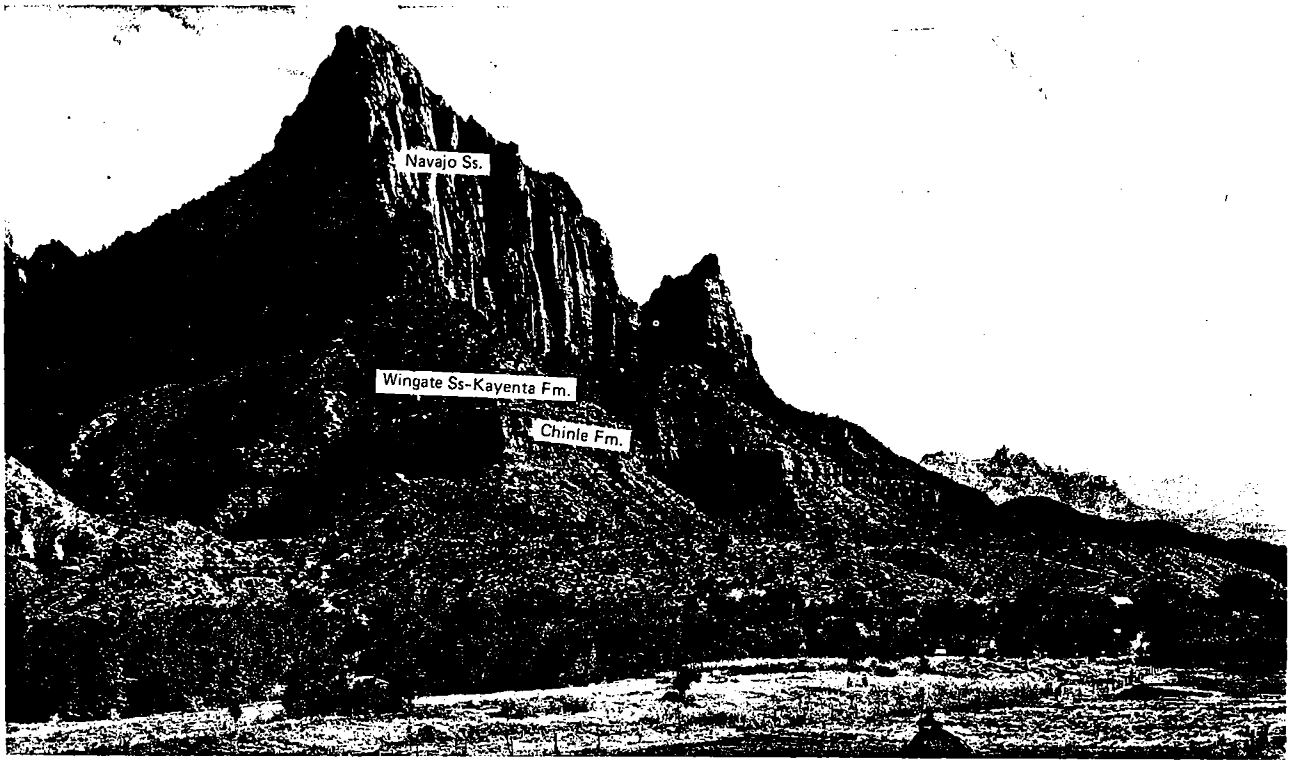

FIGURE 15-39 Nonmarine Triassic and Jurassic sediments exposed along the Virgin River in Zion National Park, Utah. The Triassic-Jurassic boundary probably lies near the base of the Navajo Sandstone. Figure 15-38 provides a more detailed view of the Chinle Formation, and Figure 15-40, of the Navajo Sandstone. (*National Park Service.*)

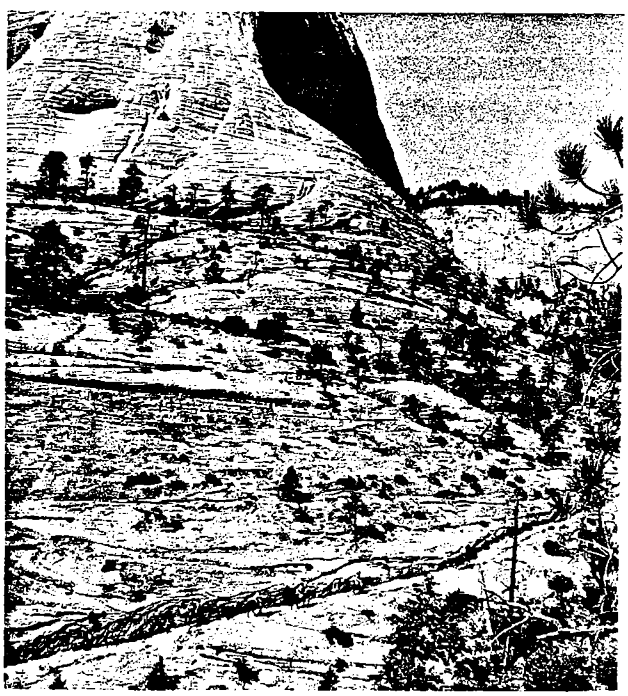

FIGURE 15-40 Enormous cross-beds within the Navajo Sandstone in Zion National Park, Utah. These Jurassic sediments almost certainly represent dune deposits. (*National Park Service.*)

include graywackes and mudstones together with smaller amounts of chert and limestone. As shown in Figure 7-51, these sediments became a mélange (page 200) that was piled up against the continent, with a segment of ocean floor (the Great Valley Ophiolite) squeezed in between. This Late Jurassic event approximately coincided with eastward folding and thrusting from the Sierra Nevada uplift. These tectonic events of Jurassic age are collectively known as the **Nevadan orogeny**, although related orogenic activity that is not generally assigned this name continued well into the Cretaceous Period.

The eastward thrusting and folding of Late Jurassic time greatly altered patterns of deposition as far east as Colorado and Wyoming. The Sundance Sea spread over a large area of the western United States, representing the most extensive marine incursion since late Paleozoic time (Figure 15-41). In latest Jurassic time, however, the folding and thrust faulting that extended over Nevada, Utah, and Idaho produced a large mountain chain. The elevation of the land and the shedding of clastics eastward from the mountains drove back the waters of the Sundance Sea, leaving only a small inland sea to the north (Figure 15-44).

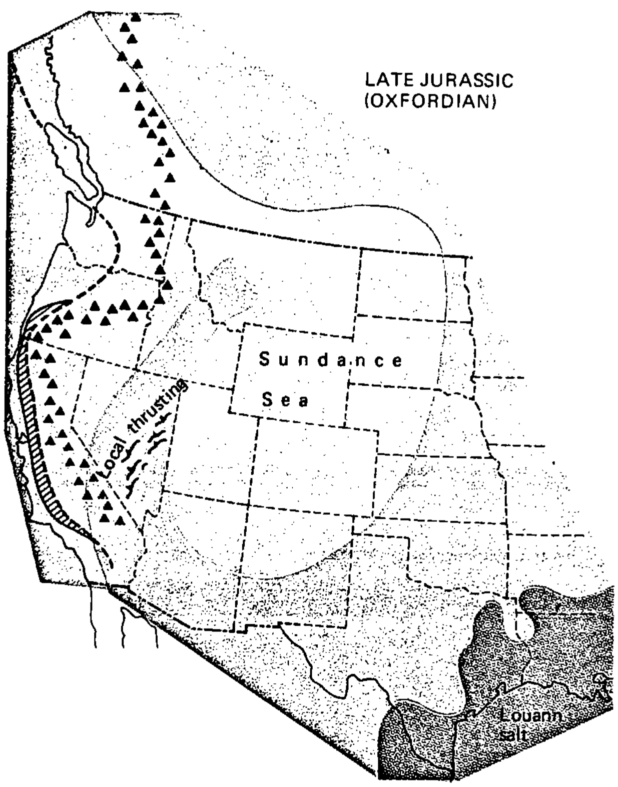

FIGURE 15-41 Geologic features of western North America during Late Jurassic (Oxfordian) time, when the Sundance Sea flooded a large interior region from southern Canada to northern Arizona and New Mexico. In mid-Triassic time, the western margin of the continent had ridden up against a subduction zone. As a result, during the Jurassic Period, a belt of igneous activity extended for hundreds of kilometers parallel to the Pacific Coast. At this time, thrust faulting was largely limited to the state of Nevada.

What remained in Colorado, Wyoming, and adjacent regions was a nonmarine foredeep in which molasse deposits accumulated. Apparently, on the gentle profile of the foredeep even the lowest depositional environments were above sea level, since there was no initial deposition of marine flysch. The molasse of the foredeep was deposited in rivers, lakes, and swamps, creating the famous Morrison Formation, which has yielded the world's most spectacular dinosaur faunas (Figure 15-45; see also Figures 15-24 and 15-25). The dinosaur skeletons in this formation are usually disarticulated, but often as many as 50 or 60 individuals are found together in one small area, indicating that these fossils may have accumulated during floods.

The Morrison Formation consists of sandstones and multicolored mudstones deposited over an area of about 1 million square kilometers. Caliche soil deposits indicate that the climate was seasonally dry during at least part of the Morrison depositional interval, while the scarcity of crocodiles, turtles, and fishes suggests that many of the lakes may have been saline at this time. The dinosaurs are found in deposits representing all of the Morrison environments—rivers, lakes, and swamps. This broad environmental distribution suggests that none of the species—not even the huge sauropods (Figure 15-24*A*)—was adapted specifically for a life of wading in large bodies of water. The Morrison Formation spans the last 10 million years or so of the Jurassic Period and is overlain by the nonmarine Cloverly Formation of Early Cretaceous age, which contains a completely different fauna of dinosaurs, apparently because of major extinctions at the end of the Jurassic Period.

Europe: The Triassic Period

In Europe, as in North America, the Triassic interval was a time in which nonmarine deposition prevailed. It was also a period in which the pattern of marine sedimentation underwent a major change. Early in the Triassic Period, as in Permian time, seas from the north periodically spread into northern Europe. Soon, however, the northern seas withdrew, and marine waters instead encroached on Europe from the south as a result of the major plate movements that were gradually carrying Africa away from Europe. As a consequence of this separation, the Tethys Seaway spread westward across what is now the Mediterranean region. As the sea expanded here, it was rising throughout the world (Figure 15-30), and thus it flooded southern Europe (Figure 15-46). To view these events in a broader geographic perspective, keep in mind that the Atlantic Ocean had not yet opened; Europe, Greenland, and North America remained connected (Figure 15-33). Given this perspective, we will view the effects of these events on deposition in northern and central Germany, Great Britain, and the Tethyan region of Europe.

Northern and central Germany Although Europe as a whole was not extensively flooded during the Triassic Period, the seas did encroach on northern Germany and adjoining areas, and the shift of influence from the northern seas to the Tethys Seaway can be seen there. Even in this broad depositional basin, however, most intervals of Triassic time were characterized either by nonmarine deposition or by the absence of deposition. The Triassic deposits of Europe indicate that hot, dry conditions persisted

FIGURE 16-36 The band of clay at the Cretaceous-Cenozoic boundary near Gubbio, Italy. The concentration of the rare element iridium is about 30 times higher in this clay than in sediments above and below. A rich assemblage of fossil coccoliths is present below the clay, but there is only a sparse assemblage above. (*Courtesy of W. Alvarez.*)

astating meteorite impact at the end of the Cretaceous Period has generated great interest in the scientific community. The dust cloud associated with the impact of a large extraterrestrial body might for a brief time, geologically speaking—a few years or perhaps a few thousand years—have screened out a large fraction of the sunlight that normally reaches the earth, killing off certain plants and perhaps cooling the planet as well. Still unexplained, however, would be the decline or disappearance before the very end of the Cretaceous of groups like rudists, inoceramids, ammonoids, and dinosaurs. It may be that a meteorite impact was the last in a series of events that led to excessive extinction near the end of Cretaceous time.

REGIONAL EXAMPLES

The great worldwide elevation of the seas that began near the end of Early Cretaceous time produced much of the Cretaceous record exposed on modern continents. This record tells many of the regional stories that follow. We will first examine the continuation of mountain building in western North America, a process that produced an enormous foredeep that became flooded by the seaway that extended from the Gulf Coast to the Arctic. We will see that the Gulf Coast itself was fringed by rudist reefs and that a rudist-rimmed carbonate bank also stretched along a large segment of the adjacent Atlantic coast until midway through the Cretaceous Period, when it gave way to the deposition of mud and sand that continues today. On the other side of the Atlantic, we will observe how siliciclastic deposition early in the Cretaceous Period was followed by the widespread accumulation of chalk in Europe. Finally, we will review the development of a vast interior sea in Australia.

Cordilleran mountain building continues

During Cretaceous time, an important change took place in the pattern of igneous activity in western North America. Subduction of the Franciscan complex along the western

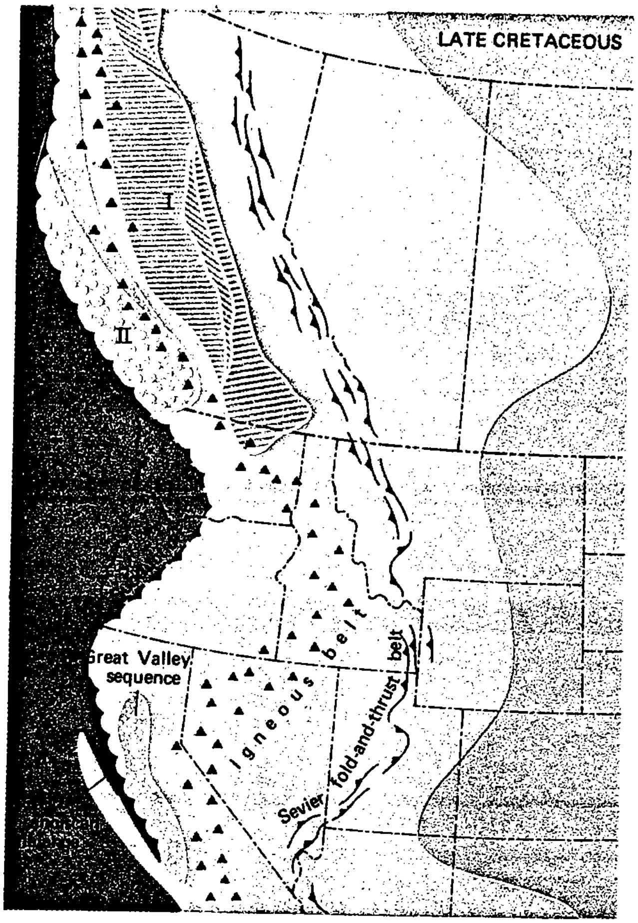

FIGURE 16-37 Late Cretaceous geologic features of western North America. Subduction produced the Franciscan mélange in California. North of California, igneous activity resulting from subduction was located far to the east of the continental margin; this activity, together with the folding and thrusting to the east, represented the latter part of the Sevier orogeny. In Canada, the margin of the continent consisted of two blocks of exotic terrane (I and II) that had been sutured to North America earlier in the Mesozoic Era; each of these blocks consisted of two or more slivers of crust that were welded together to form the block before it was attached to North America.

margin of the continent continued, as did the associated igneous activity. However, by Late Cretaceous time, although volcanic and plutonic activity persisted in the Sierra Nevada region, the northern igneous activity had come to be concentrated to the east, in Nevada and Idaho (Figure 16-37). This pattern contrasted with that of the Late Jurassic Epoch, when igneous activity in the north had been centered near the coast, in northern California and Oregon (Figure 15-41). The likely explanation for the eastward mi-

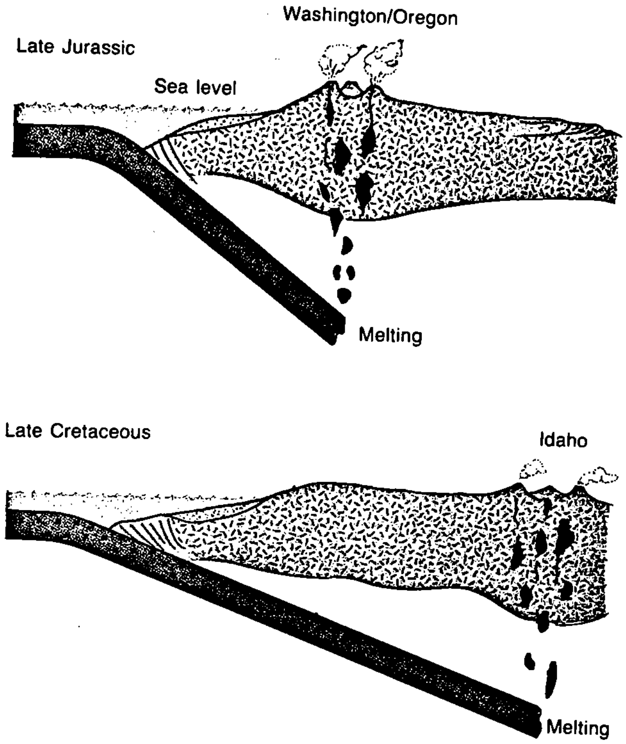

FIGURE 16-38 Diagram illustrating a likely explanation for the eastward migration of igneous activity in the Cordillera during Cretaceous time. As suggested here, the subducted plate began to pass downward at a reduced angle, so that it reached the depth of melting only after passing far to the east.

gration of igneous activity in the northern United States is that the angle of subduction there had changed. In mid-Cretaceous time, the subducted plate in this region probably began to pass downward beneath the continent at a low angle; the subducted crust therefore failed to sink deep enough to melt until it had extended far inland (Figure 16-38). The fold-and-thrust belt in front of the mountainous igneous regions also shifted inland in the northern United States. By Late Cretaceous time, folding and thrusting extended eastward as far as the Idaho-Wyoming border (Figure 16-37).

A major episode of igneous activity and eastward folding and thrusting coincided approximately with the Cretaceous Period; although this episode was not entirely separate from earlier and later tectonic activity, it has become known as the **Sevier orogeny**. East of the Sevier orogenic belt lay a vast foredeep; during almost all of Late Cretaceous time, this foredeep was occupied by a narrow seaway stretching from the Gulf of Mexico to the Arctic Ocean. The history of this seaway will be discussed in the section that follows.

The orogenic belt that occupied western North America during the latter half of Cretaceous time was unusually broad, apparently because of low-angle subduction—but in its development of a foredeep and certain other features, the orogenic belt was otherwise typical. Like the modern Andes (Figure 8-16), for example, it was symmetrical: The Franciscan deformation at the continental margin (Figure 16-37) was mirrored on a larger scale by the Sevier folding and faulting east of the belt of igneous activity.

The Mesozoic history of western Canada is far more complicated. For one thing, the crust that now forms most of British Columbia is made up of exotic terranes that actually became attached to North America during the Mesozoic Era. Subduction welded one large block of foreign terrane to the continental margin during the Jurassic Period and another during the Cretaceous Period (Figure 16-37). The evidence for these events comes from three sources: (1) paleomagnetic measurements show that the two blocks (I and II in Figure 16-37), were previously located far from North America; (2) paleontological evidence shows that block I and block II and adjacent North America belonged to different biogeographic provinces in Permian and early Mesozoic times; and (3) the three terranes are structurally incompatible. Furthermore, the same kinds of evidence reveal that blocks I and II are themselves composite terranes; before becoming attached to North America, each existed as a microcontinent that was formed by the coalescing of several smaller slivers of crust. Thus, the westward growth of Canada after the Paleozoic Era was achieved less by gradual accretion than by the stepwise suturing of elongate microcontinents to the continental margin.

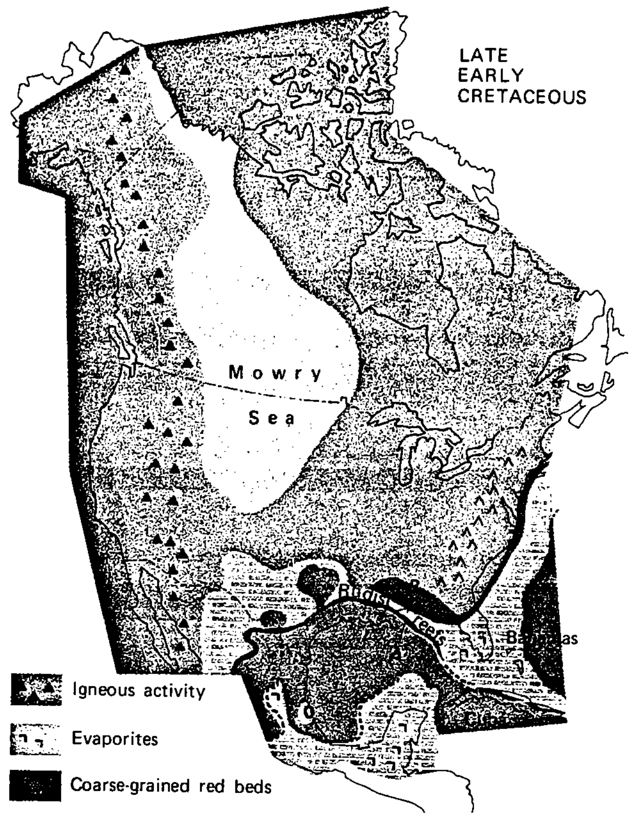

FIGURE 16-39 Geography of North America later in Early Cretaceous time. The Mowry Sea, which was the site of black mud deposition, spread southward from the Arctic Ocean. A carbonate bank bordered by rudist reefs encircled the Gulf of Mexico, and carbonate deposition extended far to the north along the East Coast. A cross section along the line *A–B* is shown in Figure 16-40.

The Gulf Coast and North American interior seaway

During the latter part of Early Cretaceous time, a spectacular array of marine environments developed in the Cordilleran foredeep. This foredeep extended from the Gulf Coast all the way to the Arctic Ocean, which was probably much warmer than today, judging by nearby Alaskan floras. We will now trace the events that led to the formation of this Cretaceous Interior Seaway.

Shortly before the end of the Early Cretaceous, during Albian time, Arctic waters spread southward, flooding a large area of western North America with the Mowry Sea (Figure 16-39). This body was named for the Mowry Formation that accumulated within it, and that consists mostly of oil shale containing large numbers of fish bones and scales. The Mowry Sea formed as a part of the great mid-Cretaceous marine transgression that resulted in the deposition of black shales on many continents (Figure 16-28).

To the south, the Gulf of Mexico was originally part of the tropical Tethyan realm (Figure 16-31). Reefs flourished around its margin, especially in Albian time, when the Gulf was almost entirely encircled by rudist-dominated barrier reefs (Figure 16-39). Behind the reefs, lime muds accumulated in protected lagoons. A broad carbonate bank encompassed the areas now occupied by peninsular Florida and the Bahamas and extended south to Cuba. Farther south, another broad carbonate bank extended northward from the Yucatán region, leaving only a narrow channel for communication between the Gulf and the Atlantic Ocean.

as we saw in the previous chapter, the Mid-Atlantic Rift proceeded northward along two forks, splitting Greenland from North America on the west and Eurasia on the east. Finally, in mid-Paleogene time, the pattern of plate movement simplified as the western arm of rifting ceased to be active, ending the relative movement of Greenland away from North America. Since that time, the rifting of the northern Atlantic has been limited to the area between Greenland and Scandinavia. It has been suggested that plate movements in this area, like those in the south polar region, contributed to the origin of the psychrosphere. The suggestion is that early in Paleogene time the Arctic Ocean was isolated from larger oceans to the south and thus retained its frigid waters. Then, late in Eocene time, rifting between Greenland and Scandinavia proceeded far enough to allow a channel to open up between the Arctic basin and the Atlantic, causing dense, frigid Arctic waters to spill into the larger ocean as part of the psychrosphere.

Meanwhile, throughout the Cenozoic Era, continental crust has continued to separate the Arctic and Pacific basins; Alaska and Siberia are connected by a stretch of continental crust despite the fact that this connecting segment now lies submerged beneath the Bering Sea. During much of the Cenozoic Era, this segment, which is known as the **Bering land bridge**, stood above sea level, serving as a land corridor between North America and Eurasia. Throughout Paleogene time, this corridor remained open, allowing mammals and land plants to migrate between Asia and North America. As we will see, however, during the Neogene Period, more frequent inundations of the sea prevented the exchange of species between the old and new worlds.

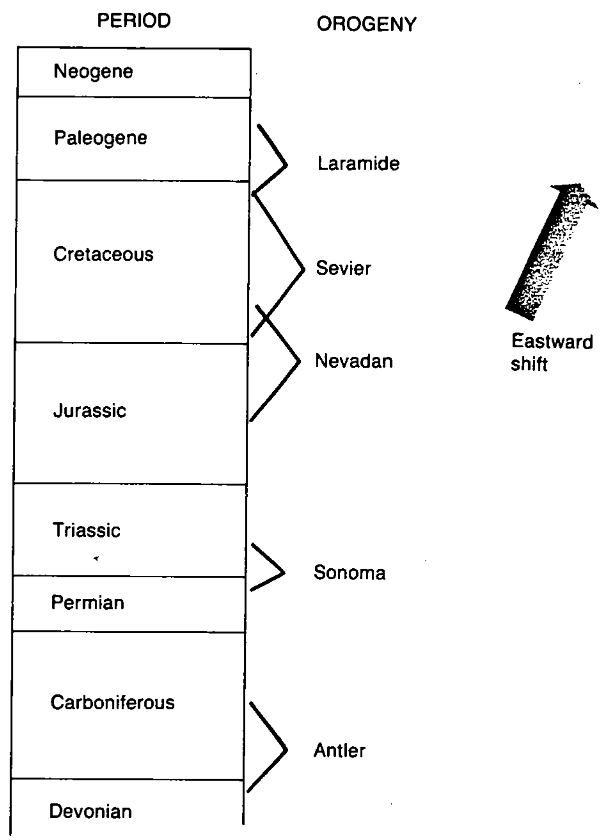

FIGURE 17-28 Summary of major orogenic events in the eastern Cordilleran region. Between Jurassic and Paleogene time, orogenic activity migrated eastward (see Figure 15-41).

Tectonics of western North America

Mountain-building activity in the Cordilleran region of North America continued into the Paleogene Period, but with a number of changes. Figure 17-28, which summarizes the orogenic history of the eastern Cordilleran region, shows that the Sevier episode occupied almost the entire Cretaceous Period. In latest Cretaceous time, however, a new style of tectonic activity was initiated, and it persisted through the Paleocene and well into Eocene time. The episode characterized by this new style is known as the Laramide orogeny.

The Laramide orogeny was not unusual in the north or in the south. In the north, extending from the United States into Canada, there remained an active belt of igneous activity and, inland from it, an active fold-and-thrust belt (Figure 17-29). Thrust sheets of enormous proportions are spectacularly exposed in the Canadian Rockies (Figure 17-30). A similar pattern of tectonism persisted both in the southern United States and in Mexico.

The unusual features of the Laramide orogeny were in the central part of the western United States, where a broad area of tectonic quiescence extended from central Utah through Nevada to California. East of this inactive region there was a strange pattern of tectonism in which large blocks of crystalline basement rock were uplifted in a belt extending from Montana to Mexico. The largest of these blocks were centered in Colorado, where the Ancestral Rocky Mountains had formed as basement uplifts more than 200 million years earlier, late in the Paleozoic Era (page 431).

What created the unusual tectonic pattern that characterized the central part of the Cordilleran region? Note that the Paleogene basement uplifts were for the most part positioned well to the east of Sevier orogenic activity (Figure 17-29), and recall, in addition, that an eastward migration of orogenic activity culminating in the Sevier orogeny took place during the Mesozoic Era. The widely favored explanation for the earlier eastward shift applies to the Laramide shift as well: A central segment of the subducted plate that passed beneath North America began to penetrate the mantle at a still lower angle, extending a great distance eastward before becoming deep enough to melt and to create igneous activity within the overlying crust (page 514).

Farther west, along the coast, the Great Valley of California continued to receive marine sediment, while north-

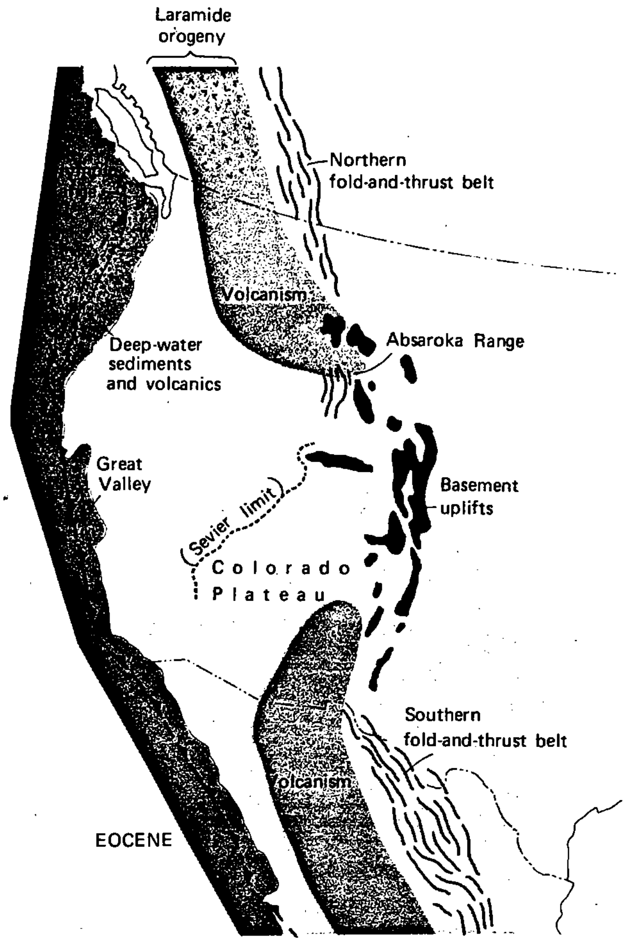

FIGURE 17-29 Geologic features of western North America during Eocene time. Subduction continued along the west coast. Marine sediments were deposited in the Great Valley region of California, and deep-water sediments and volcanics accumulated in a forearc basin to the north in Washington and Oregon. Farther inland in the north and south, the Laramide orogeny produced a band of volcanism and, inland from this, a belt of folding and thrusting. In Colorado and adjacent regions, however, the orogeny was expressed as a series of uplifts of crystalline basement that extended far to the east of the Cretaceous Sevier orogenic belt. These may have formed by a slight clockwise rotation of the Colorado Plateau relative to the continental interior.

FIGURE 17-30 The Lewis Thrust Fault in the Laramide fold-and-thrust belt of the northern Rockies. In this view, the fault is exposed in the side of Summit Mountain, Glacier National Park, Montana. The upper half of the mountain is formed of Precambrian rocks that were thrust over the lighter colored rocks below, which are of Cretaceous age. (*U.S. Geological Survey.*)

ern California and the Sierra Nevada region remained as highlands. A separate basin in Washington and Oregon received deep-water sediments and layers of pillow lava. Here the Olympic Range began to form along a sharp inward bend of the subduction zone (Figures 17-29 and 17-31).

Having reviewed the general pattern of Paleogene orogenic activity in the Cordilleran region, let us now focus on the eastern belt of uplifts, which stretches from Montana to New Mexico. Because this is the region in which the central and southern Rocky Mountains developed during Neogene time, Paleogene events that preceded the uplift of this segment warrant special attention. Deformation here began in latest Cretaceous time with the origin of north-south trending ranges and basins (Figure 17-32); in Utah and Wyoming, these structures lay along the eastern margin of the northern fold-and-thrust belt. The basement uplift farthest to the east formed the Black Hills of South Dakota (page 300). In Colorado, many ranges were formed by the elevation of large basement uplifts along thrust faults. It has been suggested that these uplifts were produced by a slight clockwise rotation of the Colorado Plateau, which behaved as a rigid crustal block, absorbing some of the convergence along the subduction zone to the west (Figure 17-29). It is not known why there was little volcanism in this central region.

Today, of course, many peaks and ridges of the central and southern Rocky Mountain uplifts stand at very high elevations; the Front Range uplift, for example, rises far above the high plains of eastern Colorado (Figure 14-48). It is inappropriate, however, to evaluate the effects of the Laramide orogeny simply by viewing the elevations of the Rocky Mountains today, since, as we will see, the high elevations of the modern Rockies reflect post-Laramide uplift. During the Laramide orogeny, erosion nearly kept pace with uplift in most areas of the United States, resulting in a regional topography that was less rugged than that which characterizes the area today. Basins in front of elevated areas were receiving large volumes of rapidly eroding material.

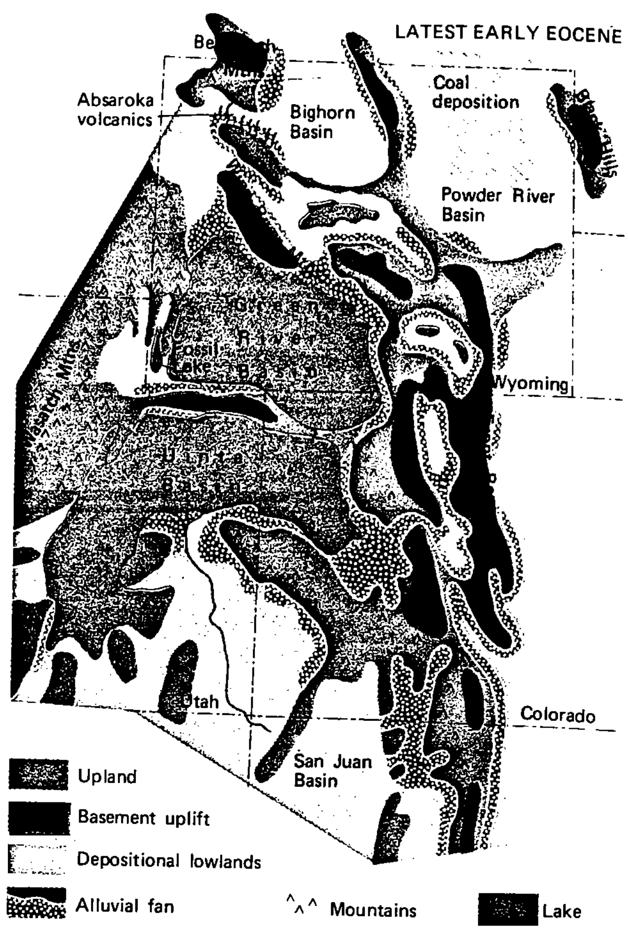

FIGURE 17-32 Geologic features associated with the Laramide basement uplifts of Colorado and adjacent regions at the end of Early Eocene time. The cores of major uplifts consist of Precambrian crystalline rock. The Green River Formation, which is well known for its oil shales and splendid fossils, was accumulating in the Green River and Uinta basins. To the north, volcanism formed the Absaroka Mountains, where Yellowstone Park is now located. The Black Hills of South Dakota represent the easternmost uplift.

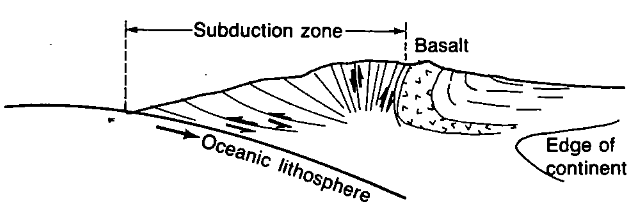

FIGURE 17-31 Formation of the Olympic Range in an embayment of the Pacific border of the state of Washington. Subduction piled sediments against basaltic rocks. (*After D. E. Kari and G. F. Sharman, Geol. Soc. Amer. Bull. 86:377–389, 1975.*)

By the end of Early Eocene time, the regional north-south pattern had weakened, and individual basins were experiencing independent histories. Most of these basins received alluvial and swamp deposits with abundant fossil mammal remains, and some were at times occupied by lakes. Near the beginning of Eocene time, sediments of the Wasatch Formation were laid down in and around rivers and swamps within the Bighorn, Green River, and Uinta basins. Then, later in Early Eocene time, lakes came to occupy most of the areas within the basins, and these lakes

FIGURE 17-33 The transition from the Wasatch Formation to the Green River Formation (*arrow* A) near the border between Wyoming and Utah. The Wasatch is famous for its fauna of terrestrial mammals, while the Green River is noted for fossils of many kinds. Arrow B points to the base of the Wilkins Peak Member of the Green River, depicted in Figure 3-13. (*U.S. Geological Survey.*)

survived, sometimes in restricted areal extent, throughout much of the Eocene Epoch (Figure 17-32). The famous Green River deposits accumulated in and around the margins of these lakes. The transition from Wasatch sediments to those of the Green River is well displayed today in many poorly vegetated areas of Wyoming and Utah (Figure 17-33). Plant remains in these sediments reveal that Eocene climates in this region were quite different from those of today, having been warm (perhaps subtropical) at times.

In Chapter 3 (page 71) we saw that the Wilkins Peak Member of the Green River Formation includes alluvial-fan, braided-stream, salt-flat, and lake deposits. These lake deposits, which are extremely well laminated, have commonly been termed "oil shales" because algal material within them has broken down to yield vast quantities of petroleum. Unfortunately, this petroleum is disseminated throughout the rock and has thus proved difficult to extract. Nonetheless, the Green River deposits form the largest body of ancient lake sediments known, and they may eventually serve as a valuable source of fuel. The fine undisturbed lamination of the Green River lake deposits accounts for the remarkable preservation of a host of animal and plant fossils, including delicate creatures such as frogs (Figure 17-15) and insects (Figure 17-16).

Another interesting group of rocks found in the region of Paleogene basins and uplifts are the volcanics that form the Absaroka Range in western Wyoming and Montana (Figure 17-34). A large portion of Yellowstone National Park lies within the Absarokas; here, the still-active geysers and hot springs serve as evidence that igneous activity has not ceased completely. Recall that Yellowstone seems to represent a hot spot in which igneous activity is localized (page 191). During Eocene time, this area stood at the eastern margin of the volcanic belt of the Pacific northwest (Figure 17-29). Volcanism at this time was episodic, and each episode yielded a variety of rocks, including volcanic

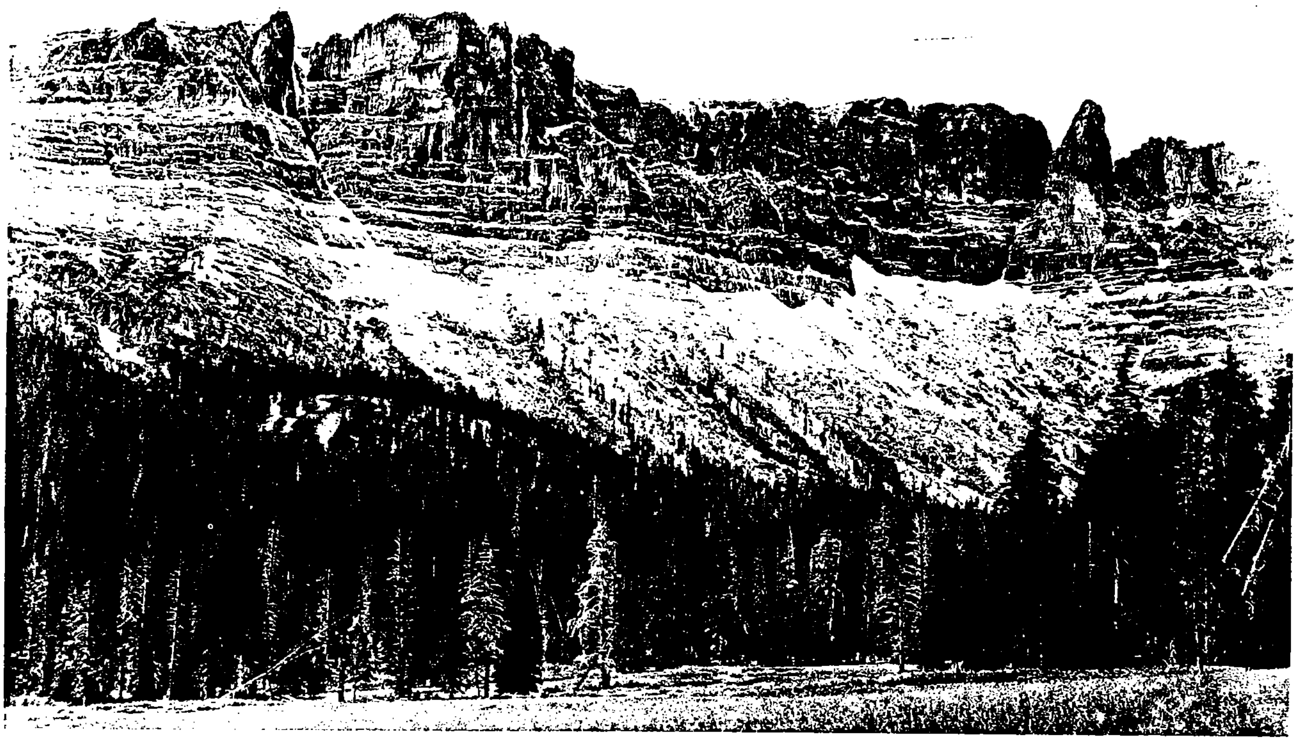

FIGURE 17-34 Table Mountain in the Absaroka Range of northwestern Wyoming. The Absarokas, which include most of Yellowstone National Park, consist of Eocene volcanic rocks of various kinds. The episodic nature of volcanic accumulation is evidenced by the layering visible on the side of Table Mountain. (*U.S. Geological Survey.*)

igneous units as well as sedimentary units composed of volcanic debris. All of these volcanic episodes, however, were catastrophic, destroying entire forests and, we must assume, the animal life within them. Fossilized leaves, needles, cones, and seeds reveal the presence of lowlands with subtropical vegetation, like that simultaneously occupying the Green River Basin, and of slightly cooler uplands. Today, the remnants of the Eocene forests can be seen at high elevations in Yellowstone National Park, where trees are preserved upright as stumps buried by lavas, mud flows, and flood-deposited volcanic debris (Figure 17-35). More than 20 successive forests, all of which were killed in this way, can be identified along the Lamar Valley in Wyoming (Figure 17-36).

As the Eocene Epoch drew to a close, the level of volcanism declined sharply in every part of the northwestern United States except Oregon and Washington. In a few areas to the east, including the Absarokas, volcanic activity persisted but was weak and sporadic. In addition, most of the depositional basins that lay between Montana and New Mexico were filled with sediment by the end of Eocene time. The Laramide orogeny was completed, and the uplands that it had produced were largely leveled; thus, as the Oligocene Epoch dawned, a monotonous erosion surface stretched across a broad expanse of western and central North America, interrupted by only a few isolated hills.

Where, then, did the modern Rocky Mountains come from? As we will see in the following chapter, the Rockies are the product of a renewed uplift that took place during Neogene time. In many areas in the Rockies today, a person can look into the distance and view a flat surface formed by the tops of mountains (Figure 17-37). This is what remains of the broad erosional surface that existed at the end of the Eocene Epoch, but the surface now stands high above the Great Plains as a result of Neogene uplift.

During the Oligocene Epoch, after most of the Laramide uplifts had been leveled, sediment moved eastward at a reduced rate, but a thin veneer of deposits spread as far east as South Dakota. The Badlands of South Dakota consist of rugged terrane carved from Oligocene deposits (Figure 17-38). These deposits, which were laid down largely in rivers and lakes, have yielded rich faunas of fossil mammals.

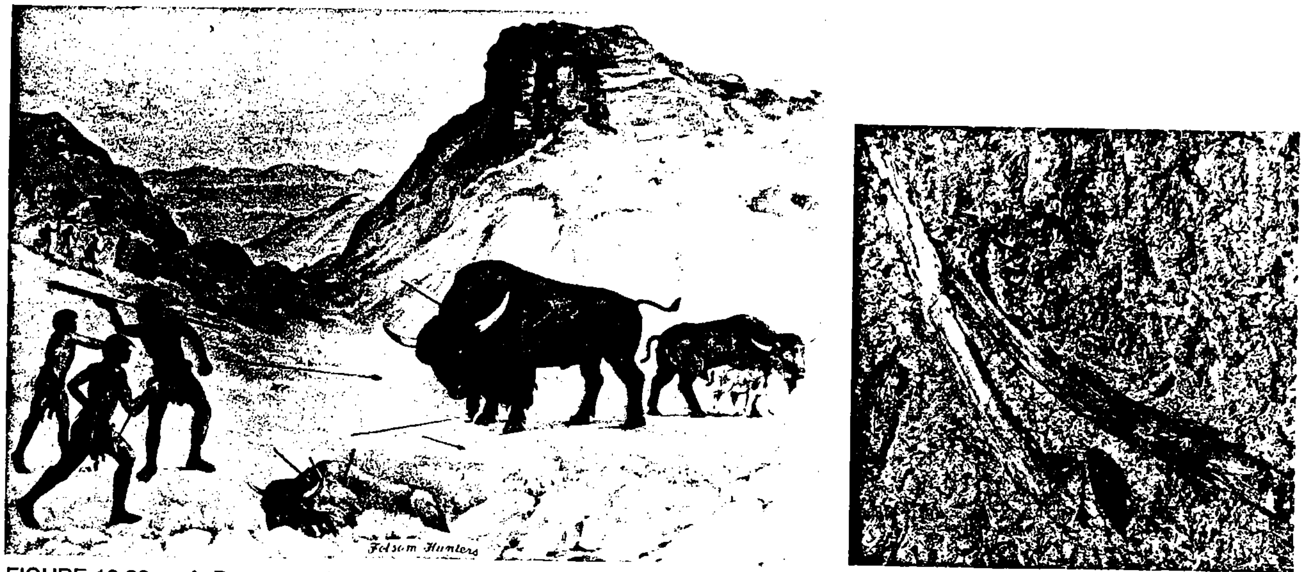

FIGURE 18-39 *A.* Reconstruction of "Folsom man" hunting giant bison. *B.* The original Folsom point, found between the fossil ribs of a giant bison. (*Denver Museum of Natural History.*)

mammals disappeared throughout the world. Some have argued that these extinctions occurred at the hands of humans armed with newly developed weapons for which large, conspicuous mammals were easy marks. Because they were represented by few individuals to begin with, such species were eventually hunted out of existence. This theory suggests that a wave of humans swarmed into North America about 11,000 years ago, by way of the Bering land bridge, and were such successful big-game hunters that their populations expanded and spread rapidly—perhaps by about 16 kilometers (~10 miles) per year—in their efforts to find new game. Radiocarbon analyses of wood associated with stone weapons reveals that humans at this time employed sophisticated projectile systems in the New World; they were known to have launched flint tips of many types at the ends of lances and may also have propelled darts with throwing sticks. The famous Clovis and Folsom projectile points represent this stage of weaponry development (Figure 18-39).

REGIONAL EVENTS

Because many shifts in climate and in biogeographic distribution have been reconstructed in detail for the Neogene Period, geologists have been able to relate many regional geologic events to these phenomena. This relationship represents a recurring theme in the review of Neogene regional events that follows.

We will begin our regional tour of the Neogene Period by reviewing the history of the western United States, which is highlighted not only by the elevation of imposing mountains that form part of our scenery today—the Cascade Range, the Sierra Nevada, and the Rocky Mountains—but also by climatic changes that resulted from the uplifting of these mountains. Next, we will examine events in and around the Atlantic Ocean; among our topics here will be the origin of the modern mountainous topography of the Appalachians, the uplift of the Isthmus of Panama, the origin of the Caribbean Sea, and the cooling of the Atlantic with the onset of the Ice Age. We will then review the Neogene history of the African continent and its famous rift valleys, which have contributed valuable fossil remains of human ancestors. Following this, we will learn how the northward movement of Africa against Eurasia closed the venerable Tethys Sea and, in the process, formed the Mediterranean. At one point, this remnant of the Tethys suddenly dried up, but it was soon refilled with sea water. Finally, we will observe how the northward movement of the Australian plate has brought biotas of the Southern Hemisphere into contact with animals and plants of Eurasian ancestry.

Development of the American West

The pre-Neogene history of mountain building in the Cordilleran region was described in earlier chapters and is summarized in Figure 17-28. By late Paleozoic time, uplifts resulting from the final mountain-building episode of the western interior, the Laramide orogeny, had been largely subdued by erosion, thereby setting the stage for the Neogene events that produced the Rocky Mountains. In the broad region west of the Rockies, the Neogene Period was a time of widespread tectonic and igneous activity, which built most of the mountains standing there today.

Provinces of the American West Lying between the great plains of the United States and the Pacific Ocean are several distinctive physiographic provinces that have taken shape largely in Neogene time, primarily as a result of uplift and igneous activity. Let us briefly review the present characteristics of these provinces before considering how they have come into being (Figure 18-40).

The lofty, rugged peaks of the **Rocky Mountains**, some of which stand more than 4.5 kilometers (~14,000 feet) above sea level, could only be of geologically recent origin. We have seen that the widespread subsummit surface of the Rockies was all that remained of the Laramide uplifts by the end of the Eocene Epoch about 40 million years ago (Figure 17-37). One question we must answer, then, is how the Rocky Mountain region became mountainous once again.

Centered adjacent to the Rockies in the "four corners" area where Colorado, Utah, New Mexico, and Arizona meet is the oval-shaped **Colorado Plateau**, much of which stands about 1.5 kilometers (~ 1 mile) above sea level. The Phanerozoic sedimentary units here are not intensively deformed. Some, however, are gently folded in a steplike pattern, and others, especially to the west, are offset by block faults (Figure 18-41). Cutting through the plateau is the spectacular Grand Canyon of the Colorado River (see Figure AII-17), but about 10 million years ago there was neither a Colorado Plateau nor a Grand Canyon. The origin of these features forms another part of our story.

West of the Rockies and the Colorado Plateau, within the belt of Mesozoic orogeny, lies the **Basin and Range Province** (Figure 18-42). This is an area of north-south trending block-fault valleys and intervening ridges (Figure 18-43)—features of Neogene origin. A large area of this

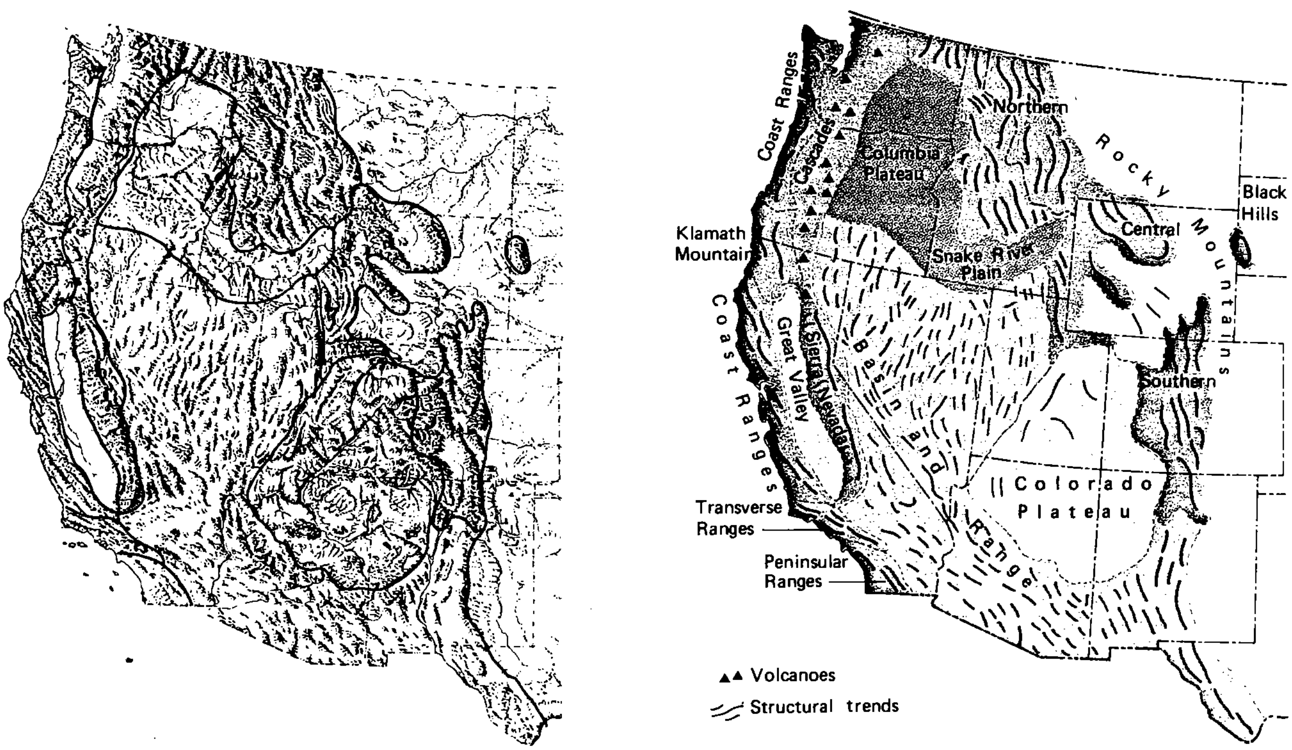

FIGURE 18-40 Major geologic provinces of western North America. The map on the left shows the relationships of the provinces to topographic features. (*Topographic map based on the United States Geological Survey, National Atlas of the United States of America.*)

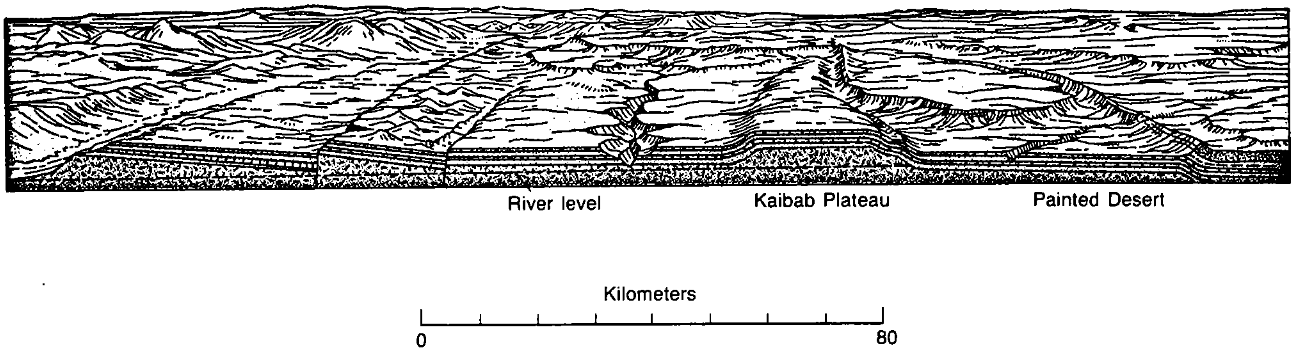

FIGURE 18-41 Block diagram of the western part of the Colorado Plateau north of the Grand Canyon. This high-standing region is characterized by block faulting (*left*) and by gentle, steplike folds (*right*). (*After P. B. King, The Evolution of North America, Princeton University Press, Princeton, New Jersey, 1977.*)

province forms the **Great Basin**, an arid region of interior drainage (page 69). Volcanism has been associated with some faulting episodes, and sediment eroded from the ranges blankets the valleys to depths ranging from a few hundred meters to about 3 kilometers (~2 miles). The thickness of the earth's crust in the Basin and Range Province ranges from about 20 to 30 kilometers compared to thicknesses of 35 to 50 kilometers in the Colorado Plateau. The thinning and block faulting in the Basin and Range Province point to extension of the crust by at least 65 percent and perhaps by as much as 100 percent.

Farther north, centered in Oregon, is a broad area covered by volcanic rocks of the **Columbia River and Snake River plateaus** (see Figure AI-8). Today the climate here

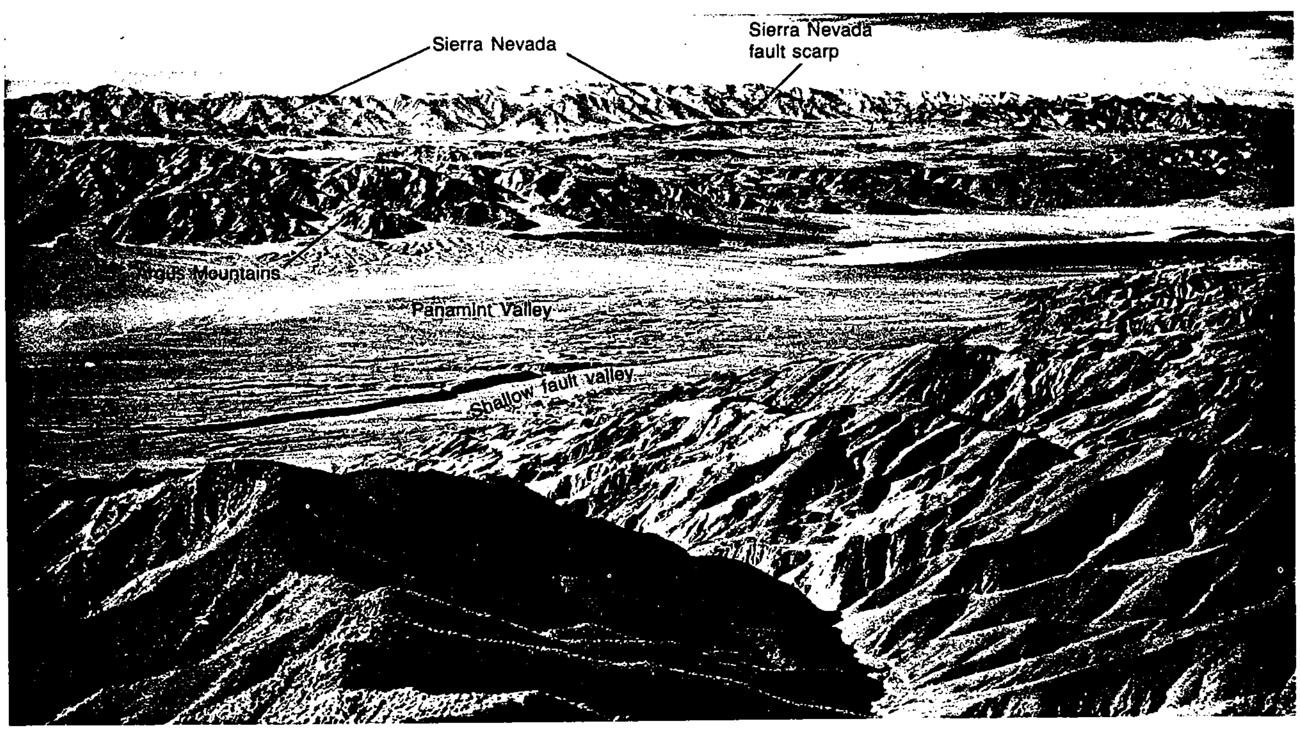

FIGURE 18-42 Fault-block mountains and basins of the Basin and Range Province. The view is from the Panamint Mountains. The eastern fault scarp of the Sierra Nevada can be seen in the distance. (*Courtesy of W. B. Hamilton, U.S. Geological Survey.*)

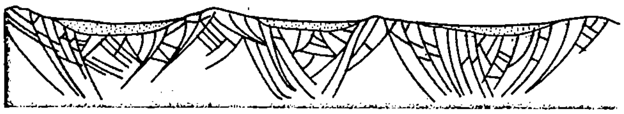

FIGURE 18-43 Diagrammatic cross section showing the possible pattern of the block faulting in the Basin and Range Province that might have been responsible for lateral extension of the crust.

is cool and semiarid; only about one-quarter of the plateau area is cloaked in forest and woodland, while sagebrush and drier conditions characterize about half of the terrane. In Oligocene time, however, lavas had not yet blanketed the region, and, as revealed by fossil plant remains, a large forest of redwood trees grew there.

Along the western margin of the Columbia Plateau stand the lofty peaks of the **Cascade Range** (Figure 18-44). These are cone-shaped volcanoes that represent the volcanic arc associated with subduction of the Pacific plate along the western margin of the continent. Volcanism began here in Oligocene time and continues to the present, as manifested by the recent eruptions of Mount St. Helens (Figure 1-1).

The Cascade volcanic belt passes southward into the **Sierra Nevada Range**, a mountain-sized fault-block of granitic rocks. The plutons forming the Sierra Nevada were emplaced in east-central California during Mesozoic time, before igneous activity at this latitude shifted inland. As we will see, however, the present topography of the Sierra Nevada is of Neogene origin. This mountain range is unusual in that throughout its length of some 600 kilometers (~350 miles), it is not breached by a single river. This is why it represented such a formidable obstacle to early pioneers attempting to reach the Pacific.

The Sierra Nevada Range stands between the Basin

FIGURE 18-44 Mount Hood, one of the high peaks of the Cascade Range in Oregon. (*Oregon State Highway Commission.*)

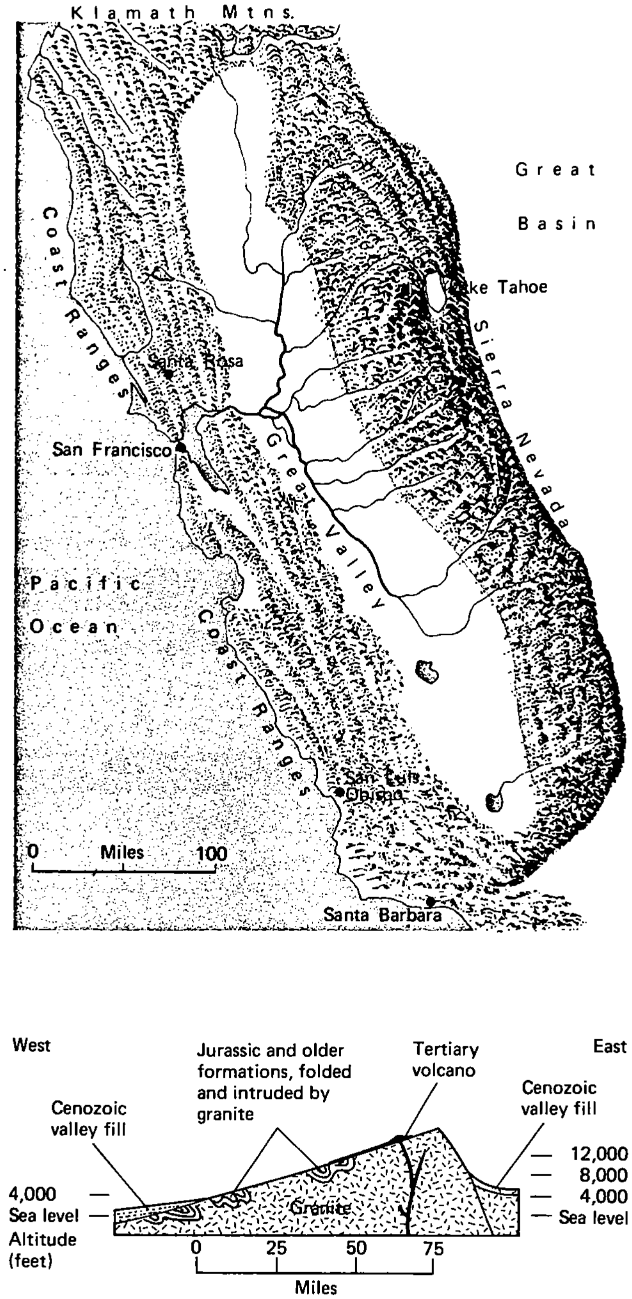

FIGURE 18-45 Map and diagrammatic cross section of the Sierra Nevada fault block of California and Nevada. Sediments of the Great Valley lap onto the gentle western slope of the Sierra Nevada. (*After C. B. Hunt, Natural Regions of the United States and Canada, W. H. Freeman and Company, New York, 1974.*)

and Range Province to the east and the **Great Valley** of California to the west (Figure 18-45). The Great Valley is an elongate basin containing large volumes of Mesozoic sediment (the Great Valley Sequence) eroded from the plutons of the Sierra Nevada region long before the modern Sierra Nevada formed by block faulting (Figure 15-43). Above these are Cenozoic deposits, some of which accumulated during marine invasions of the Great Valley and others during times of nonmarine sedimentation.

West of the Great Valley are the California **Coast Ranges**, which consist of slices of crust that include crystalline rocks representing Mesozoic orogenic activity, Franciscan rocks of deep-water origin (Figure 18-46), and Tertiary rocks. To the south, the **Transverse** and **Peninsular ranges** are formed of similarly faulted and deformed rocks, but these ranges lie inland of the main belt of Franciscan rocks in the region of intensive Mesozoic igneous activity. Striking features of all of these mountainous terranes are the great faults—including the Garlock Fault (Figures 18-47 and 18-48)—that divide the crust into sliver-shaped blocks. The longest and most famous of these faults is the San Andreas (facing page 1), which extends for about 1600 kilometers (1000 miles). Until the great San Francisco earthquake of 1906, it was not widely recognized that movement along the San Andreas persisted. The earthquake of 1906 was produced by a sudden movement of up to 5 meters (~16 feet) along the fault. Study of geologic features cut by the San Andreas Fault shows that its total movement during the past 15 million years has amounted to about 315 kilometers (190 miles). Continued movement at this rate for the next 30 million years or so would bring Los Angeles northward to the latitude of San Francisco—through which the fault passes. As we will see, the faulting and uplifting of the Coastal Ranges of California are probably causally related not only to the Neogene uplift of the Sierra Nevada but also to the origins of the Basin and Range topography to the east.

The **Olympic Mountains** of Washington have quite a different history. These relatively low mountains, which lie to the west of the Cascade Volcanics, consist of oceanic sediments and volcanics that were deformed primarily during Eocene time in association with subduction along the continental margin (Figure 17-31).

Development of the American West: The Miocene Epoch We will begin our story of the development of the modern Cordilleran provinces described above with a summary of major events of the Miocene Epoch. Then we will

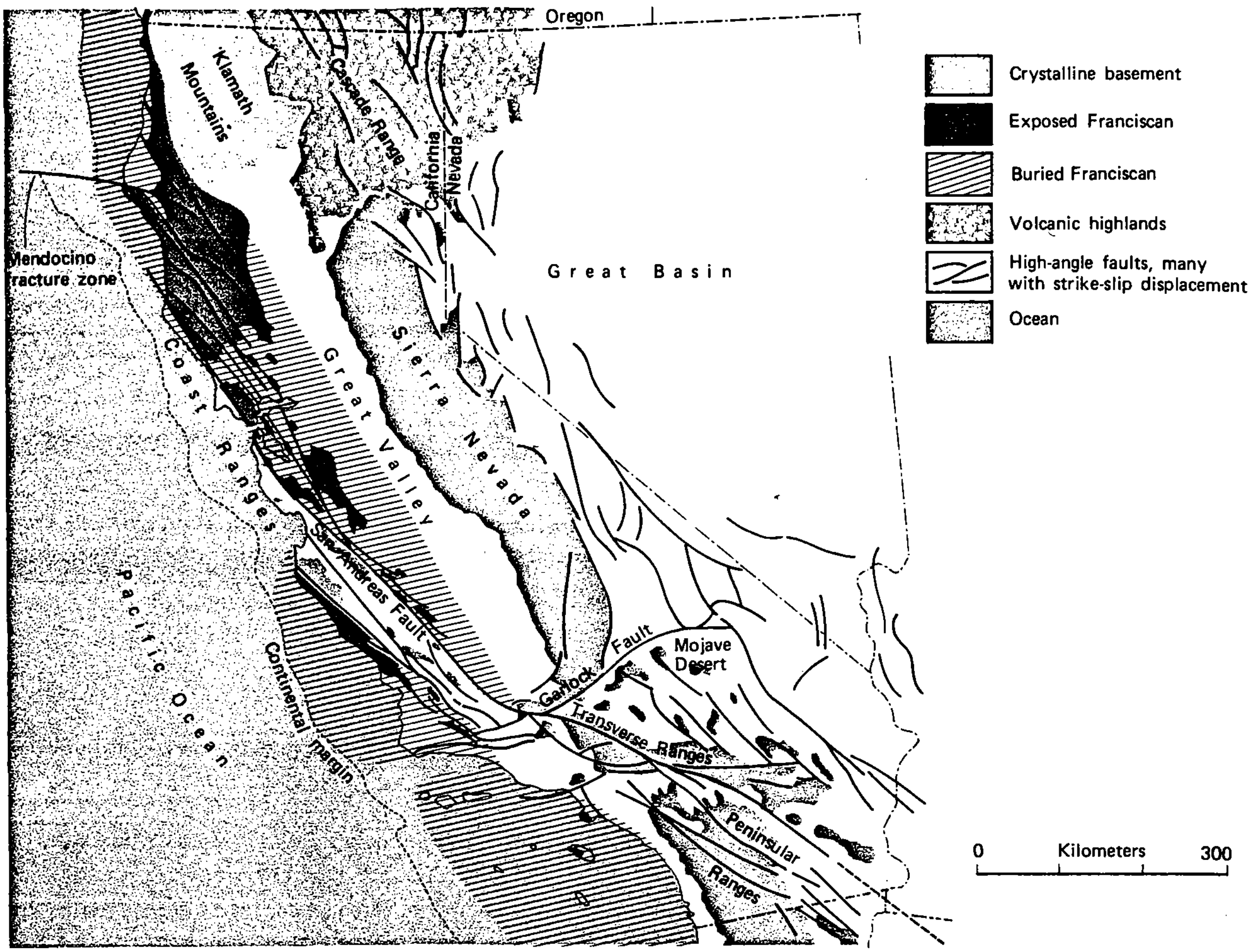

FIGURE 18-46 Major geologic features of California. The Franciscan terrane was attached to the coast late in the Jurassic Period (Figures 15-43 and 15-44). The many faults depicted here, including the famous San Andreas, are of Neogene Age. (*Modified from P. B. King, The Evolution of North America, Princeton University Press, Princeton, New Jersey, 1977.*)

examine the Pliocene events that followed, and we will conclude by analyzing the tectonic mechanisms that may account for events of both epochs.

Geologic features of the far west in Miocene time are shown in Figure 18-49. Subduction continued beneath the continental margin in the northwestern United States, and the resulting volcanic arc produced peaks in the Cascade Range, where volcanism continues today. To the south, in California, the mid-Miocene interval was a time of faulting and mountain building; elements of the modern Coast Ranges and other nearby mountains were raised, and the seas were driven westward. Meanwhile, as in Paleozoic time, the Great Valley remained a large embayment, and during Miocene time it received great thicknesses of siliciclastic sediments, most of which were shed from the region of the modern Sierra Nevada. Although the block faulting that eventually produced the Sierra Nevada did not begin until Pliocene time, volcanoes of the southern end of the Cascade Island Arc were shedding sediments westward, from the position where the Sierra Nevada later stood.

Before the Sierra Nevada rose appreciably, the Basin and Range Province began forming to the east. During Paleogene time, light-colored rhyolitic (felsic) ashfall deposits were occasionally spread across the province, but near the beginning of the Miocene Epoch basaltic volcanism predominated—and it was at this time or slightly earlier that the Basin and Range topography began to form. Since the beginning of block faulting, most lavas of the region have welled up along faults rather than reaching the surface through cylindrical vents. To the north of the Basin and Range Province, basalt also spread from fissures in

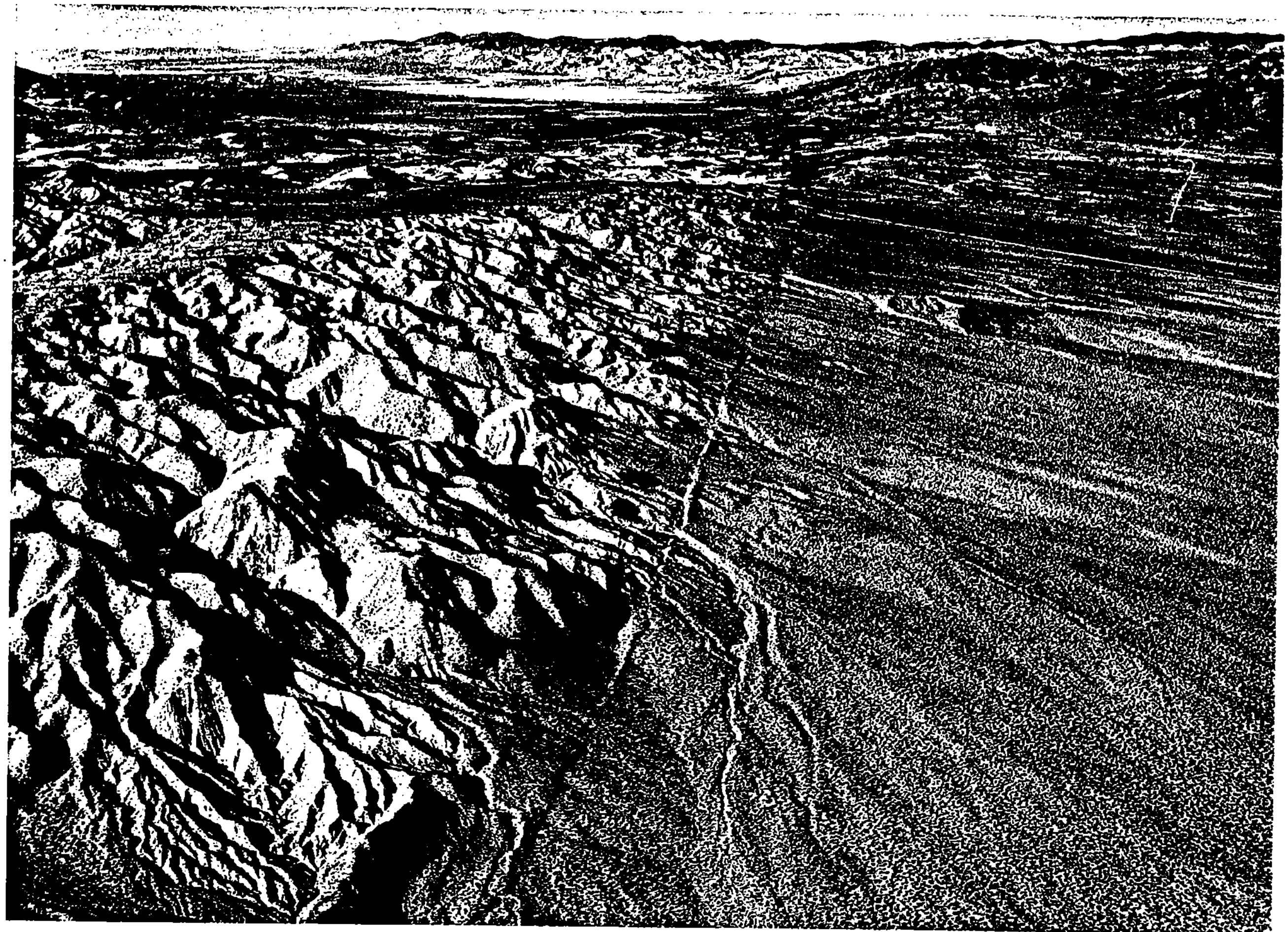

FIGURE 18-47 Aerial view of the Garlock Fault in the Mojave Desert of California, looking westward. The trace of this strike-slip fault is clearly visible. (*J. S. Shelton, Geology Illustrated, W. H. Freeman and Company, New York, 1966.*)

much greater volume. Most of the great Columbia Plateau formed in this way between about 16 and 13 million years ago; here, individual basalt flows range in thickness from 30 to 150 meters (~ 100 to 500 feet), and in places, the total accumulation reaches about 5 kilometers (~ 3 miles).

One of the most important Miocene events in the Cordilleran region was a broad regional uplift that affected the Basin and Range Province, the Colorado Plateau, and the Rocky Mountains. Today, even the basins of the Basin and Range Province nearly all stand at least 1.3 kilometers

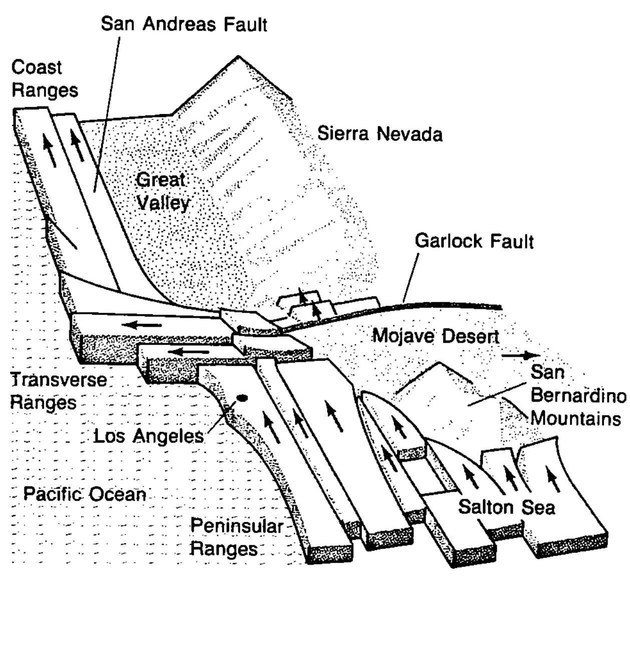

FIGURE 18-48 Movements of crustal blocks along faults in southern California. The San Andreas Fault bends at the southern end of the Great Valley and is met by the Garlock Fault. (*From D. L. Anderson, "The San Andreas Fault." Copyright © 1971 by Scientific American, Inc. All rights reserved.*)

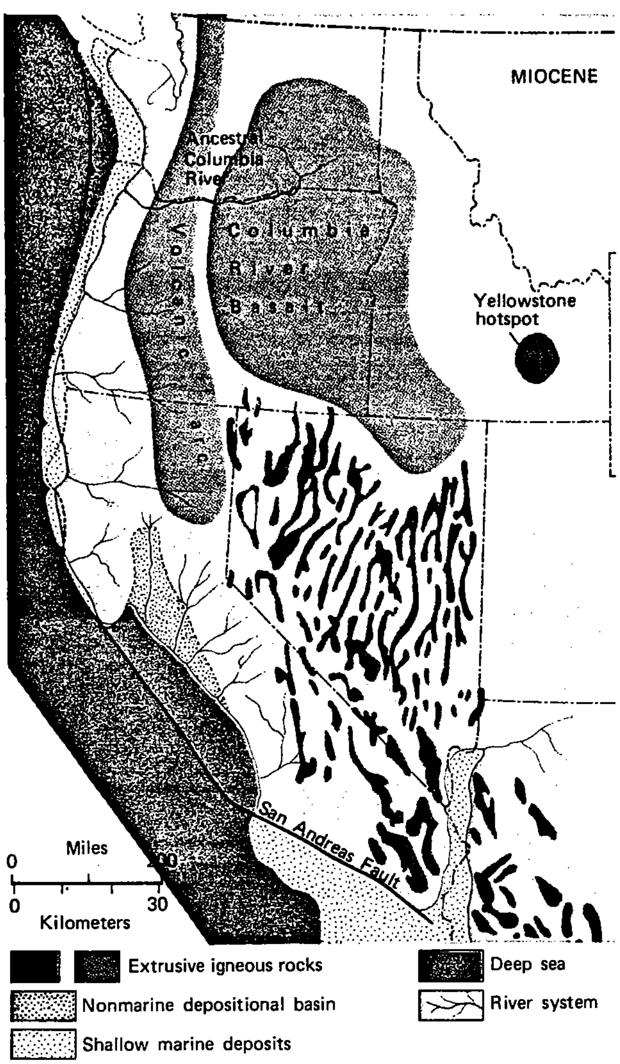

FIGURE 18-49 Geologic features of western North America in Miocene time. West of the San Andreas Fault, coastal southern California lay farther south than it does today. The area currently occupied by the Great Valley of California was for the most part a deep-water basin from which a nonmarine depositional basin extended to the north. Volcanoes of the early Cascade Range formed along a volcanic arc inland from the subduction zone along the continental margin. Igneous rocks were extruded along north-south trending faults in the Great Basin, and farther north the Columbia River Basalts spread over a large area. (*Modified from J. M. Armentrout and M. R. Cole, Soc. Econ. Paleont. and Mineral. Pacific Coast Paleogeog. Symp. 3:291–323, 1979.*)

($\sim\frac{3}{4}$ mile) above sea level. Thus, it is remarkable that mid-Cenozoic fossil floras of this region are characterized by species that could only have lived at low altitudes. Geologists have reconstructed even more precise histories of uplift for the Colorado Plateau and Rocky Mountains by studying the time at which rivers have cut through well-dated volcanic rocks. Many of the rivers of these regions existed before uplift began in the Miocene Epoch, and these cut rapidly downward as the land rose, producing deep gorges. A large part of the Grand Canyon, for example, was incised during the rapid elevation of the Colorado Plateau between about 10 and 8 million years ago.

Uplift in the Rockies began slightly earlier, in Early Miocene time, and terrane that now forms the Southern Rockies has since risen between 1.5 and 3.0 kilometers (~1 to 2 miles).

Development of the American West: Plio-Pleistocene time In both the Colorado Plateau and the Rockies, the Miocene pulse of uplifting was followed by a lull and then by an episode of renewed elevation; in fact, large-scale uplifting was the dominant process in the Cordilleran region during Pliocene and Pleistocene time. We will discuss some of the details of this uplifting after noting several other key Plio-Pleistocene events.

During the Pliocene and Pleistocene epochs, igneous activity continued in the volcanic provinces of Oregon, Washington, and Idaho (Figure 18-50). Many of the scenic volcanic peaks of the Cascades, including Mount St. Helens (Figure 1-1), have formed within the past 2 million years or so. Beginning in Late Miocene time and continuing sporadically to the present, the flowing of basalt from fissures has produced the Snake River Plain, which amounts to an eastward extension of the Columbia Plateau (Figure 18-50).

In California, faulting and deformation continued during the Pliocene and Pleistocene epochs. Since the beginning of the Pliocene Epoch about 5 million years ago, the sliver of coastal California that includes Los Angeles has moved northward on the order of 100 kilometers (~60 miles). The Great Valley has, of course, remained a lowland to the present day, but during Pliocene and Pleistocene time it became transformed from a marine basin into a terrestrial one (Figure 18-51). Early in the Pliocene Epoch, seas flooded the basin from both the north and the south. The sedimentary sequence of the basin reveals that several transgressions and regressions occurred during Pliocene time, but as the epoch progressed, uplift associated with

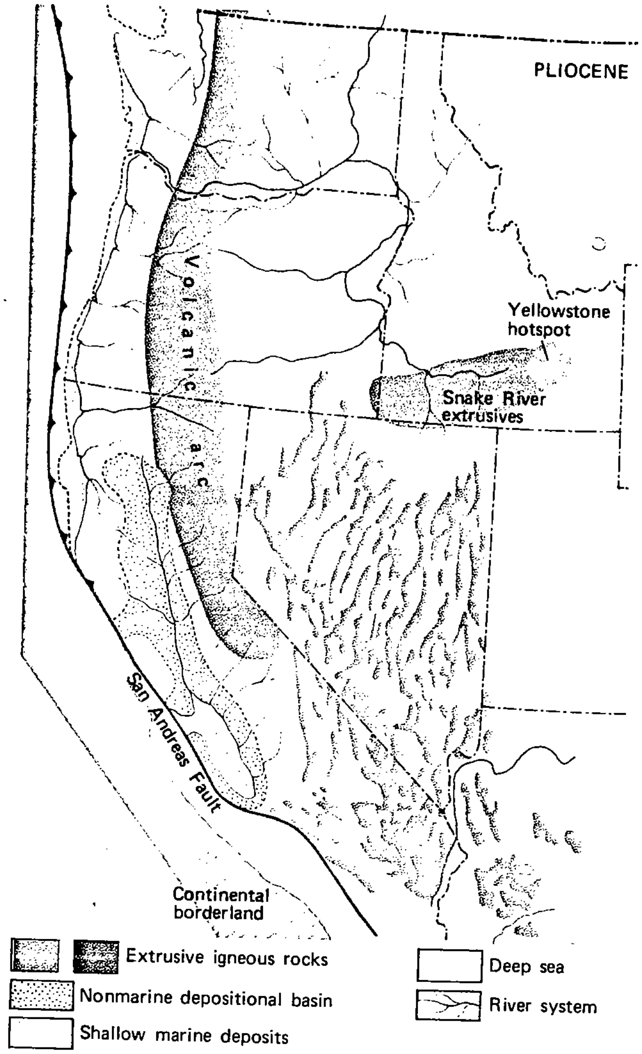

FIGURE 18-50 Geologic features of western North America in Pliocene time. The Great Valley of California was a shallow basin that received nonmarine sediments except where a shallow sea flooded its southern portion. The volcanic arc continued to form volcanoes of the Cascade Range, and igneous rocks continued to be extruded along faults in the Great Basin. The Snake River extrusives spread over a large area of southern Idaho west of Yellowstone. (*Modified from J. M. Armentrout and M. R. Cole, Soc. Econ. Paleont. and Mineral. Pacific Coast Paleogeog. Symp. 3:297–323, 1979.*)

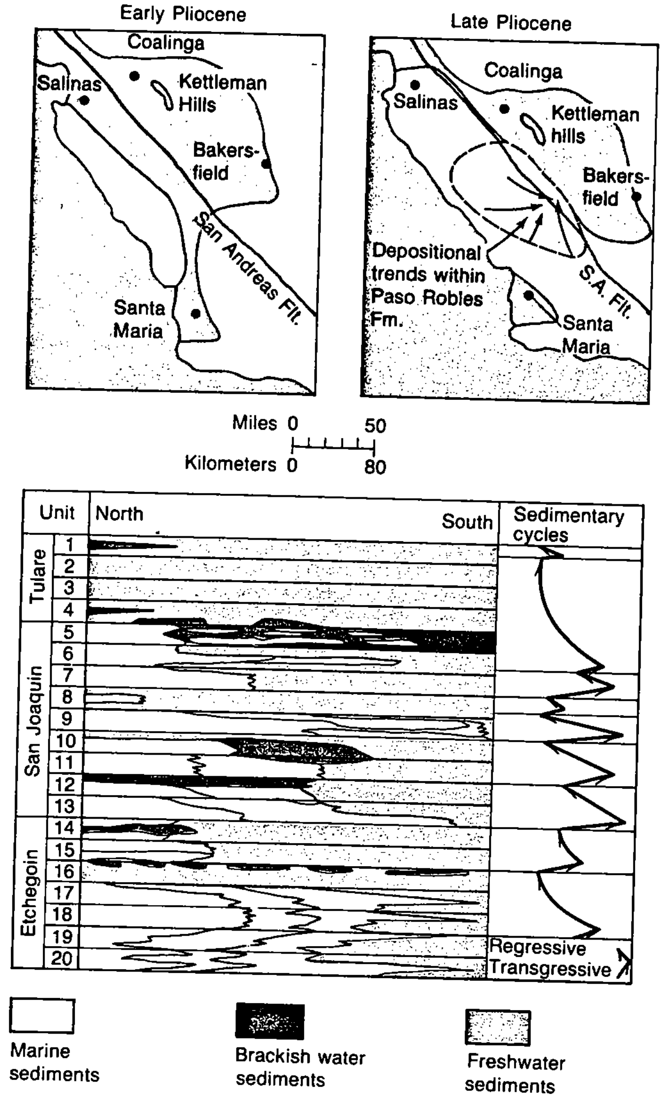

FIGURE 18-51 Decreasing marine influence in the Great Basin of California during the Pliocene Epoch as the sliver of crust west of the San Andreas Fault moved northwestward. The marine channel passing through Santa Maria was closed during the Pliocene Epoch; the Paso Robles Formation is of nonmarine origin. The lower diagram displays the history of deposition in the area now forming the Kettleman Hills; marine deposition dominated early in the Pliocene Epoch but gave way to freshwater deposition. (*After R. J. Stanton and J. R. Dodd, Jour. Paleont. 44:1092–1121, 1970.*)

movement along the San Andreas Fault eliminated the southern connection. Eventually, nonmarine deposition prevailed throughout the Great Valley, which is now one of the world's richest agricultural areas as well as the site of large reservoirs of petroleum.

Meanwhile, areas to the east of the Great Valley underwent major uplift. The Sierra Nevada had experienced considerable tilting during Miocene time, but fossil plants of Miocene age preserved on the crest of the Sierra Nevada were still types that could not have lived as much as a kilometer above sea level. Thus, it was not until Pliocene time that the Sierra Nevada (Figure 18-52) became elevated to its present height, which exceeds 4.3 kilometers

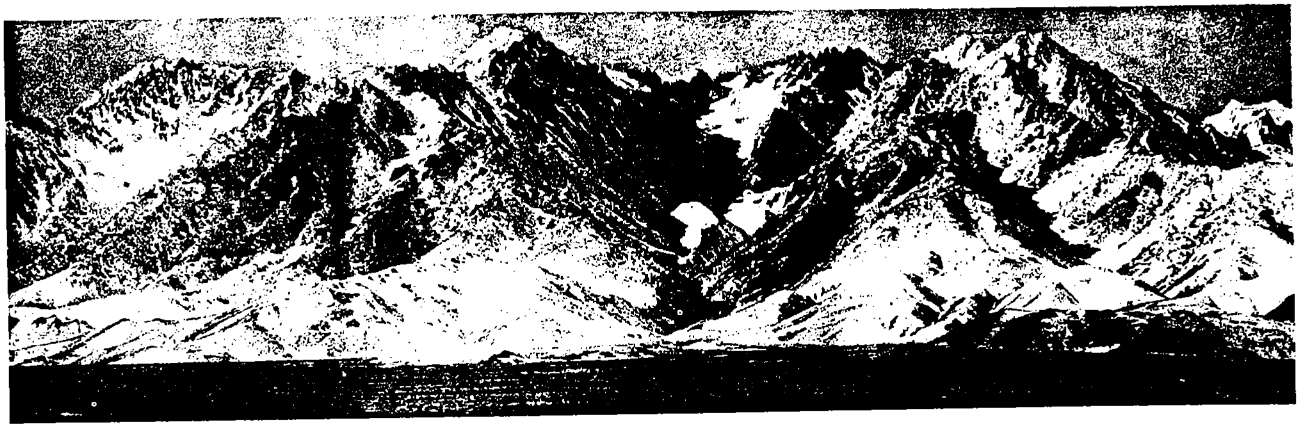

FIGURE 18-52 The eastern face of the Sierra Nevada. This is a fault scarp that is partly dissected by youthful valleys. The view is from the Owens Valley, Inyo County, California. (*Courtesy of W. C. Mendenhall, U.S. Geological Survey.*)

(~14,000 feet). The consequences of this uplift were enormous for the Basin and Range Province to the east, where uplift continued from Miocene time on a smaller scale. Sitting in the rain shadow of the Sierra Nevada (Figure 2-16), this area—which in Miocene time had been covered by evergreen forests—came to be carpeted by savannah vegetation. The trend toward increasing aridity, which was compounded by the global trend toward drier climates, continued into very late Neogene time, when the Great Basin became a desert.

The Colorado Plateau and Rocky Mountains, where uplift had slowed in Late Miocene time, experienced rapid elevation once again. Streams that had been established millions of years earlier cut rapidly downward as the uplift proceeded. The Rockies attained most of their modern elevation during Pliocene time, and the result was the origin of deep canyons that now carry streams through tall mountain ranges (Figure 18-53). One of the most scenic of these canyons is Royal Gorge near Canon City, Colorado (Figure 18-54). The Colorado Plateau also rose again during Pliocene and Pleistocene time, and the Colorado River responded by cutting swiftly downward. In fact, it appears that much of the Grand Canyon of the Colorado (see Figure AII-17) formed during just the past 2 or 3 million years!

The renewed elevation of the Rocky Mountains left the Great Plains to the east in a partial rain shadow. Sediments derived from the rejuvenated Rockies spread eastward, forming the Pliocene Ogallala Formation. Caliche nodules are abundant in many parts of the Ogallala, indicating the presence of seasonally arid climates (page 63). The Ogallala is a thin, largely sandy unit that lies buried under the Great Plains from Wyoming to Texas, and serves as a major source of ground water. Unfortunately, this is ancient water that is not being renewed as rapidly as it is drawn from the earth. As a result, severe water shortages may one day strike many areas of the central United States.

It is important to recognize that the rain-shadow effects of both the Sierra Nevada and the Rockies were superimposed on the larger global trend toward drier, cooler climates that has characterized the post-Eocene world. Then, with the onset of the Pleistocene Epoch, frigid conditions brought glaciation to mountainous regions of the western United States just as they foster glaciation in Alaskan mountains today (Figure 2-18). The Sierra Nevada, for example, was heavily glaciated, as were portions of the Rocky Mountains (Figure 18-16). Today, broad U-shaped valleys in both mountain systems testify to the scouring activity of Pleistocene glaciers (Figure 11-5).

Possible mechanisms of uplift and igneous activity in the American West What has led to the many tectonic and igneous events of Neogene time in the American West? It seems likely that the secondary uplift of the Colorado Plateau and the Rocky Mountains, which took place long after the Laramide orogeny, may to a large extent represent simple isostatic adjustment (Figure 1-19). When uplifts in these areas were largely leveled during Eocene time, they left behind felsic roots of low density. With the weight of the mountains removed, these roots were apparently out of isostatic equilibrium, and hence they began to rise up toward positions of equilibrium during the Neogene Period.

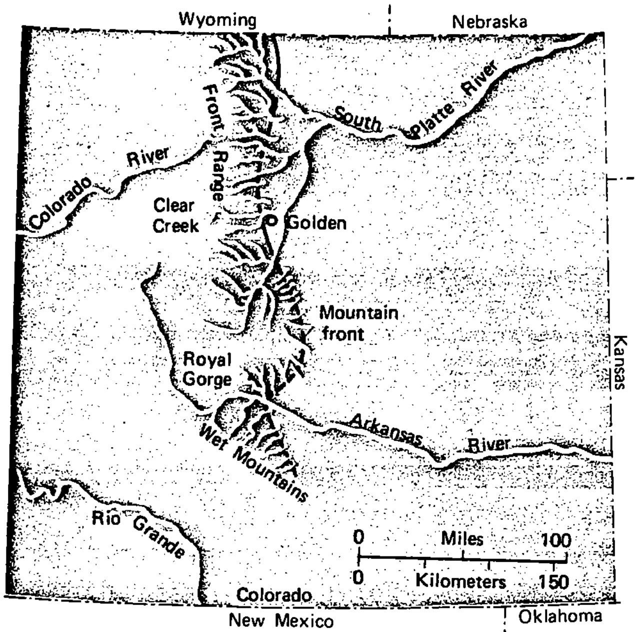

FIGURE 18-53 Large canyons cut during Pliocene time along the eastern flank of the Front Range and Wet Mountains of Colorado when these mountains underwent considerable elevation. (*After G. R. Scott, Geol. Soc. Amer. Mem. 144:227–248, 1975.*)

FIGURE 18-54 Royal Gorge, spanned by a bridge in the foreground. This is one of the deep Pliocene canyons of Colorado depicted in Figure 18-53. (*W. G. Pierce, U.S. Geological Survey.*)

The elevation of the Basin and Range, with its block faulting and relatively thin crust, requires a different explanation. Basin and Range events, the spreading of the Columbia River Basalt, and the extensive faulting and folding along the California coast all began in Miocene time and seem to be related in some way to plate-tectonic movements, including those that simultaneously occurred along the Pacific Coast. One idea is that the **East Pacific Rise**, a large oceanic rift that passes into the Gulf of California, breaks up as it passes inland through thick continental crust (Figure 18-55) and branches out to become the many normal faults of the Basin and Range Province that have caused thinning and elevation of the crust. The high heat flow that is associated with such a spreading zone is also alleged to have caused the Neogene elevation of the Basin and Range Province.

Objections have been raised against the rifting hypothesis for Basin and Range development based on the belief that spreading should have ceased when the East Pacific Rise came into contact with the subduction zone at the western boundary of the North American plate; instead, it is argued, movement must have been propagated along one or more transform faults such as the San Andreas, passing along the continental margin. This argument leads to an alternative hypothesis of Great Basin development (Figure 18-55*B*). The crux of this hypothesis is that crustal shearing adjacent to a strike-slip fault like the San Andreas will automatically cause extensional faulting similar to that of the Great Basin. This second hypothesis is deficient in one regard: It fails to account for the broad elevation of the Basin and Range Province during Neogene time.

Still another hypothesis is that heat from the subducted Pacific plate elevates the crust in the Basin and Range regions, placing it under tension that results in block faulting and in thinning of the crust. At present, we have no actual evidence that this mechanism has operated.

We are more certain, however, about the general pattern of tectonism along the Pacific coast. As Figure 18-55*B* illustrates, North America became attached to the Pacific plate near the beginning of the Miocene Epoch. Movements along the San Andreas and other faults that have formed

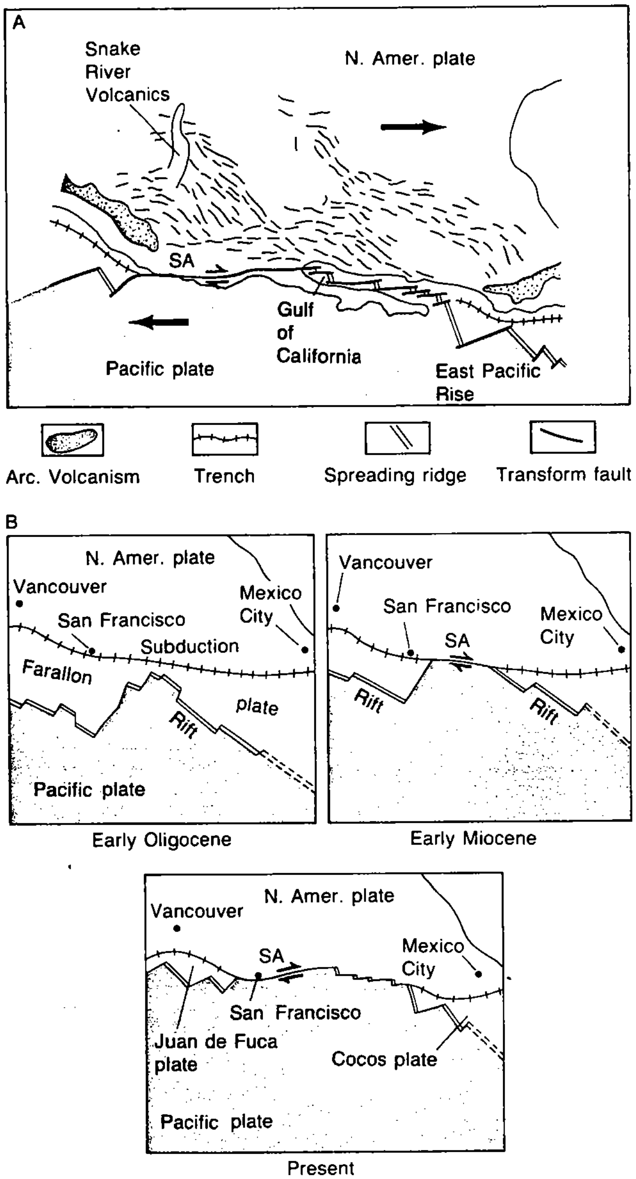

FIGURE 18-55 Plate-tectonic features that may account for the Basin and Range structure in western North America. *A.* The present situation, with the spreading ridge known as the East Pacific Rise passing into the Gulf of California. One idea is simply that the spreading ridge passes beneath western North America, thinning and widening the crust by extension along normal faults. An alternative idea is that the East Pacific Rise abuts against the North American continent and is offset westward along the San Andreas Fault (SA); according to this idea, shearing forces resulting from relative movement of terrane on either side of the San Andreas Fault (*heavy arrows*) pull the crust apart, producing the north-south trending faults of the Basin and Range Province. *B.* Illustration of the second alternative. The rift zone between the Pacific and Farallon plates encountered the thick crust of North America along the subduction zone that bordered the continent. Unable to pass inland, the rift was divided along a strike-slip fault (the San Andreas). (*Based on J. H. Stewart, Geol. Soc. Amer. Mem. 152:1–31, 1975. After Atwater.*)

since that time account for the complex slivering and deformation in the Coast Ranges and neighboring areas (Figure 18-46).

The Atlantic Ocean and its environs

Although the margins of the Atlantic Ocean were relatively quiescent during the Neogene Period, they did experience mild vertical tectonic movements—and these movements, together with more profound changes in sea level, had major effects on water depths and shoreline positions. We will review events in these regions first for Miocene and then for Plio-Pleistocene time.

Miocene events Global sea level has never stood as high during the Neogene Period as it did during much of Cretaceous or Paleogene time. For this reason, along the Atlantic Ocean, Neogene marine sediments stand above sea level in only a few low-lying areas. Among the most impressive of the Miocene deposits found here are those of the Chesapeake Group, which form cliffs along the Chesapeake Bay in Maryland (Figure 18-56). The Chesapeake Group accumulated during a worldwide high stand of sea level between about 16 and 14 million years ago, and they were deposited in the Salisbury Embayment, one of several downwarps of the American continental margin (Figure 18-57). Inhabiting the waters of the Salisbury Embayment was a rich fauna that included many large vertebrates, especially whales, dolphins, and sharks (Figure 18-1). Most of the fossils of baleen whales represent juvenile animals, which suggests that the embayment may have been a calving ground. Perhaps sharks were numerous because the young whales were especially vulnerable prey. Land-mammal bones are also found here and there in the Chesapeake Group, indicating that the waters of the embayment were shallow. Pollen from nearby land plants settled in the Salisbury Embayment, leaving a fossil record that shows a warm, temperate flora near the base of the Chesapeake Group slowly giving way upward in the sedimentary sequence to a slightly cooler but still temperate flora.

The Chesapeake Group and other buried deposits of earlier age to the south consist primarily of siliciclastic sediments shed from the Appalachians to the west. Erosional features associated with the Appalachians reveal that these ancient mountains have a complex history. Like the modern Rockies, the existing topographic mountains that we call the Appalachians are the product of secondary uplift. The Appalachian orogenic belt was largely leveled by erosion