22.7 PHANEROZOIC TECTONICS OF THE UNITED STATES MIDCONTINENT

22.7.1 Introduction

If you've ever driven across the United States, or have looked at a relief map of the country, you can't help but notice that the nature of topography varies radically with location. Along the East Coast, the land rises to form the long ridges of the Appalachian Mountains, whereas in the west, numerous chains of rugged peaks together compose the broad North American Cordillera. In between these two mountain belts, a region known geographically as the **Midcontinent,** the land surface is relatively flat and low-lying (Figure 22.7.1). Roads wind among dramatic cliffs and deep valleys in the mountains, but shoot like arrows across the checkerboard of farmland and rangeland in the Midcontinent. These contrasts in topography reflect contrasts in the character and geologic history of the continent's crust.

Following the definitions of Table 22.7.1, we classify the Midcontinent region as a **continental-interior platform.** Here, a cover of Phanerozoic strata was deposited in wide but shallow seaways over a basement of Precambrian (crystalline) rock. A continental-interior platform is one of two kinds of crustal provinces that can occur in a craton. We define a **craton** as continental crust that has not developed penetrative fabrics and tight folds, and has not been subjected to regional metamorphism since the beginning of the late Neoproterozoic (i.e., since about 800 Ma). In addition to continental-interior platforms, a craton can include a **shield,** a region where Precambrian basement rocks crop out extensively at the ground surface, either because cover strata were never deposited or because they were eroded away after deposition. In North America, much of the interior of Canada is a shield—not surprisingly, the region is known as the Canadian Shield.

The mountain ranges of the United States consist of two kinds of crust. Specifically, the Appalachians and the North American Cordillera can be considered Phanerozoic orogens, for during the Phanerozoic these regions developed penetrative deformation and, in places, regional metamorphism. They were also the site of widespread igneous activity and significant uplift. As a consequence of Phanerozoic tectonism, these orogens became warm and relatively weak. What is often overlooked is that the North American Cordillera also includes a large area of crust that is identical in character to that of the continental-interior platform, even though it has been uplifted significantly and has been locally subjected to deformation and igneous activity during the Phanerozoic. This crust underlies the Rocky Mountains and Colorado Plateau of the United States. In this essay, you will see that the tectonic behavior of the Midcontinent resembles that of the Rocky Mountains and Colorado Plateau, except on a more subdued scale.[1]

Cratons differ from younger orogens not just in terms of topography, but also in terms of physical characteristics such as strength, seismicity, heat flow, and crustal thickness. Specifically, orogens have less strength,[2] more seismic activity, higher heat flow, and thicker crustal roots, than do cratons. The contrast in strength reflects the contrast in heat flow, for warmer rock tends to be more plastic, and therefore weaker,

[1]Note that the Canadian Rockies, in contrast, comprise a fold-thrust belt and, as such, are part of a younger orogen.

[2]The collision between India and Asia illustrates the strength contrast between a craton and a younger orogen. India consists of old, cold Precambrian crust, while the southern margin of Asia consists of warm, relatively weak crust. During their collision, India pushed deeply into Asia.

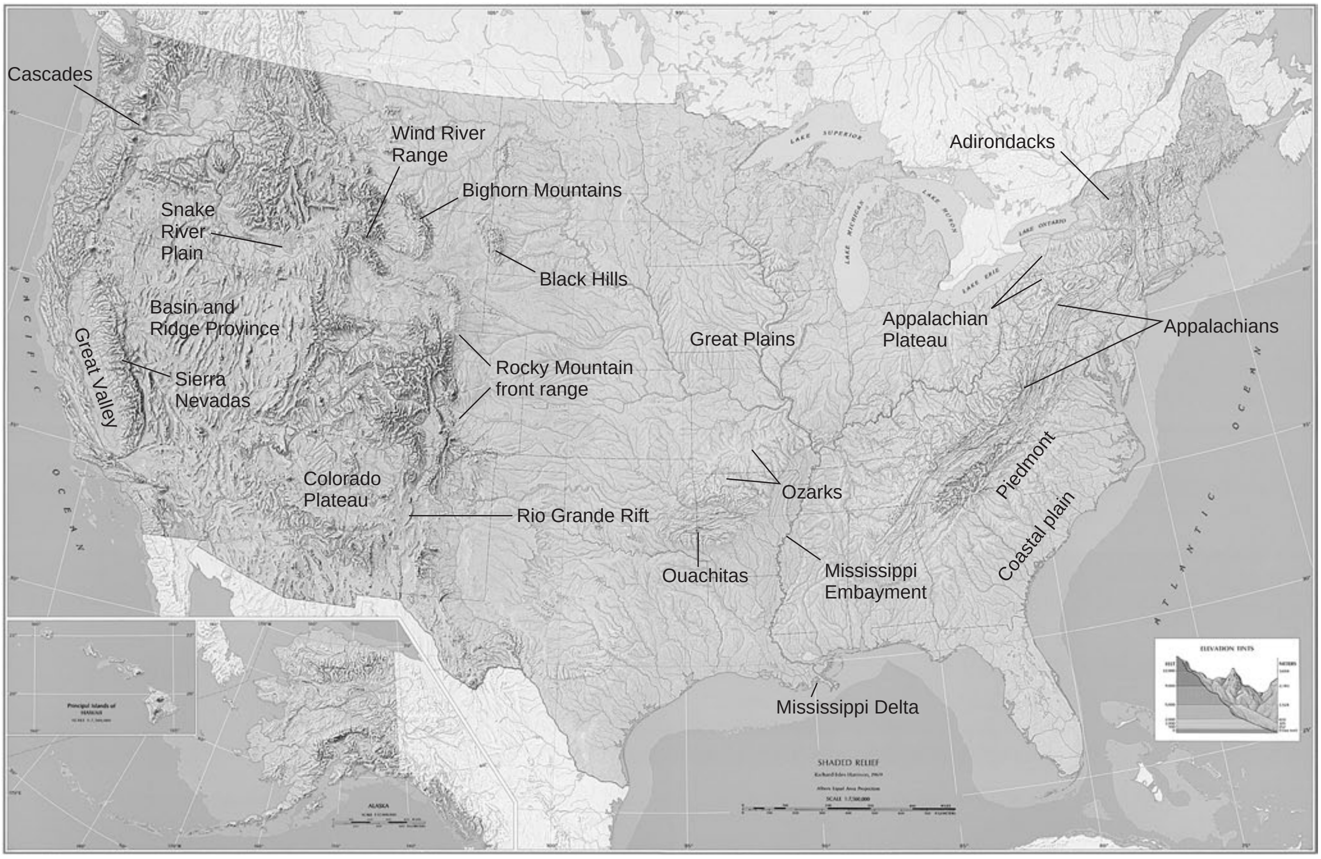

FIGURE 22.7.1 Topographic relief map of the United States, showing the contrast between Phanerozoic marginal orogens and the Great Plains.

than cooler rock of the same composition. Rock that makes up cratons initially formed either at volcanic arcs bordering convergent plate boundaries, or at hot-spot volcanoes above mantle plumes. Thus, the continental crust that eventually became the craton grew by successive collision of these buoyant blocks. This fact is well illustrated by studies in the Canadian Shield, where outcrops contain spectacular tectonite fabrics, folds, and faults that tell of a long and complex history of accretionary orogeny. If crust of the cratons began its life in orogenic belts, then how did it become strengthened and stabilized or, in other words, cratonized? Researchers suggest that cratonization comes in part from aging, because continental lithosphere loses heat and becomes stiffer as it ages. In fact, the lithospheric mantle beneath cratonic crust is thicker than that of other kinds of continental crust. Researchers also suggest that relatively buoyant asthenosphere has stayed attached to the base of the lithosphere and insulates the lithosphere from warmer parts of the asthenosphere. This special asthenosphere has been called the root of the craton.

In this essay, we discuss the Phanerozoic tectonics of the Midcontinent region of the United States. At first glance, the title may seem like an oxymoron, for the lack of topography and of penetrative structures gives the impression that this region has been tectonically stable during the Phanerozoic. However, while the Midcontinent has been *relatively* stable, it has not been *completely* stable. In fact, during the Phanerozoic, faults in the region have been reactivated, and broad regions of the surface have subsided to form sedimentary basins or have been uplifted to form domes or arches. Manifestations of Phanerozoic tectonism in the Midcontinent might not be as visually spectacular as that of North America's mountain belts, but tectonism has, nevertheless, occurred there.

22.7.2 Classes of Structures in the Midcontinent

To structural geologists raised on a diet of spectacular folds, faults, and deformation fabrics exposed in Phanerozoic orogens, the Midcontinent may seem, at first glance, to be structureless. But, in fact, the region contains four classes of tectonic structures: (1) epeirogenic structures, (2) Midcontinent fault-and-fold

TABLE 22.7.1 CATEGORIES OF CONTINENTAL CRUST

Active rift	A region where crust is currently undergoing horizontal stretching, so that crustal thicknesses are less than average crustal thicknesses. In active rifts, continental crust has a thickness of only 20–25 km, the crust has been diced up by normal faults, and volcanism occurs. Examples include the Basin and Range Province of the western USA, and the East African Rift.
Inactive rift	A belt of continental crust that underwent stretching, and became a narrow trough that filled with sediment, but never succeeded in breaking a continent in two. The Midcontinent rift of the central USA, and the Rhine Graben of Europe are examples.
Active orogen	A portion of the continental crust in which tectonism (faulting ± igneous activity ± uplift) currently takes place or has taken place in the recent past (Cenozoic). Such orogens tend to be linear belts, in that they are substantially longer than they are wide. Examples include the North American Cordillera and the European Alps.
Continental shelf	A belt fringing continents in which a portion of the continent has been submerged by the sea. Water depths over shelves are generally less than a few hundred meters. Continental shelves are underlain by passive-margin basins, which form subsequent to rifting, as a consequence of the subsidence of the stretched continental crust that bordered the rift. Sediment washed off the adjacent land buried the sinking crust. The stretching occurred during the rifting event and predated formation of a new mid-ocean ridge. Examples include the East Coast and Gulf coast of the USA.
Craton	A portion of a continent that has been relatively stable since the late Neoproterozoic (since at least about 800 Ma). This means that penetrative fabrics, regional metamorphism, and widespread igneous activity have not occurred in the craton during the Phanerozoic. The crust of a craton includes the eroded roots of Precambrian mountain belts.
Shield	A broad region, typically of low relief (though some shields have been uplifted and incised since the Mesozoic), where Precambrian crystalline rocks are exposed. In North America, a shield area (the Canadian Shield) is part of the craton. In South America, shield regions include cratons and Neoproterozoic orogens.
Continental platform	A broad region where Precambrian rocks (basement) have been covered by a veneer of unmetamorphosed Phanerozoic strata. Examples include the Midcontinent region of the USA, and large portions of northern Europe.
Inactive Phanerozoic orogen	Orogenic belts that were tectonically active in the Phanerozoic, but are not active today. Some inactive orogens, however, have been uplifted during the Cenozoic, so they are topographically high regions. Examples include the Appalachians of the USA and the Tasmanides of Australia.
Phanerozoic orogen	A general name for active Phanerozoic orogens and inactive Phanerozoic orogens, taken together.
Neoproterozoic orogen	Orogen active at the end of the Precambrian. Examples include the Pan-African/Brasiliano Orogens of Gondwana.

zones, (3) intragranular strain, and (4) regional joint systems. We'll describe these in succession.

EPEIROGENIC STRUCTURES When geologists first mapped the Midcontinent, they noted that Paleozoic strata of the region are nearly, but *not exactly* flat-lying. As a consequence, outcrop patterns of Paleozoic strata on a regional geologic map of the Midcontinent United States display distinctive bull's-eye patterns (Figure 22.7.2). In some examples, the youngest strata occupy the center of the bull's-eye, while in others, they occur in the outer ring. Bull's-eyes with the youngest strata in the center define intracratonic basins, in which strata are warped downward to form a bowl shape. Those with the youngest strata in the outer ring define intracratonic domes or, if elongate, intracratonic arches (by **"intracratonic"** we mean "within the craton"). As new data defining subsurface

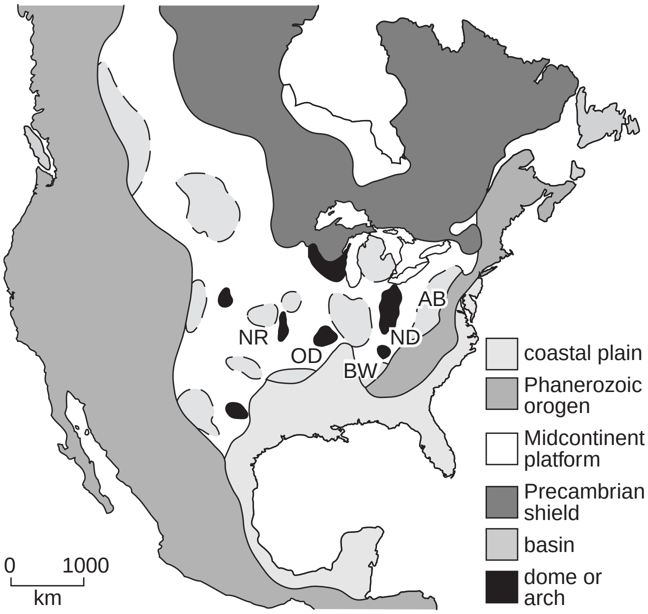

FIGURE 22.7.2 Regional tectonic map of North America showing the distribution of Phanerozoic orogenic belts, shield, continental-interior platform, and basins and domes.

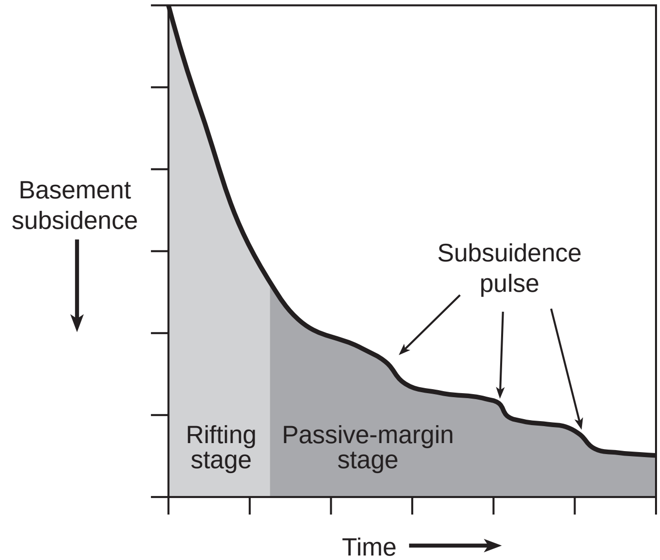

FIGURE 22.7.3 A graph illustrating how the rate of subsidence changes with time for an intracratonic basin. Rapid subsidence occurs at first, probably in association with rifting. Then, as the basin subsides due to cooling, the rate of subsidence gradually decreases. Pulses of rapid subsidence may occur during this time, perhaps due to the effects of orogeny along the continental margin. For example, an increase in stress may cause the lithosphere to weaken, so uncompensated loads beneath the basin may sink.

stratigraphy became available, primarily from correlation of well logs[3] and seismic-reflection profiles, researchers realized that stratigraphic formations thicken toward the center of a basin, and thin toward the center of a dome. Specifically, the Phanerozoic sedimentary cover of continental interior platforms thickens to about 5–7 km in basins, because that is where subsidence occurred most rapidly during deposition. In domes or arches, cover decreases in thickness to zero because these locations were emergent or were shallow shoals during deposition. A drop in sea level of the shallow oceans that covered the interior could expose the crest of a dome or arch, while the center of a basin could remain submerged. Thus, many more unconformities occur in the Phanerozoic section of domes and arches than in the interior of basins.

In effect, the lateral variations in sediment thickness that we observe in the Midcontinent indicate that there has been differential uplift and subsidence of regions of the Midcontinent during deposition. In other words, some regions went up while others went down as sediments were accumulating. Vertical movement affecting a broad region of crust is called **epeirogeny,** and the basins, domes, and arches that form as a result are **epeirogenic structures.** Significantly, the general position of basins and domes in the Midcontinent has remained fixed through the Phanerozoic. For example, the Illinois Basin and Michigan Basin have always been basins while the Ozark Dome and the Cincinnati Arch have been relatively high since their initial formation in the Late Proterozoic or Early Cambrian. Thus, these epeirogenic structures represent permanent features of continental-interior lithosphere.

Lack of stratigraphic evidence, either due to nondeposition or erosion, makes it impossible to constrain the rate of uplift of arches and domes precisely, but we can constrain rates of epeirogenic movement in basins by studying subsidence curves, which are graphs that define the rate at which the basement-cover contact at the floor of the basin moved down through time. Geologists generate subsidence curves by plotting sedimentary thickness as a function of time, after taking into account the affect of compaction (Figure 22.7.3). Subsidence curves for intracratonic basins demonstrate

[3]When drilling for oil, exploration companies use a rotating drill bit, which penetrates into the earth by grinding the rock into a mixture of powder and small chips called "cuttings." Circulating drilling "mud," pumped down into the hole, flushes the cuttings out of the hole. Since this process does not yield an intact drill core, the only way to determine the precise depth at which specific rock units lie in the subsurface is to lower instruments down the hole to record parameters such as electrical resistively and gamma-ray production, parameters that correlate with rock type. A record of resistivity versus depth, or gamma-radiation versus depth, is called a well log.

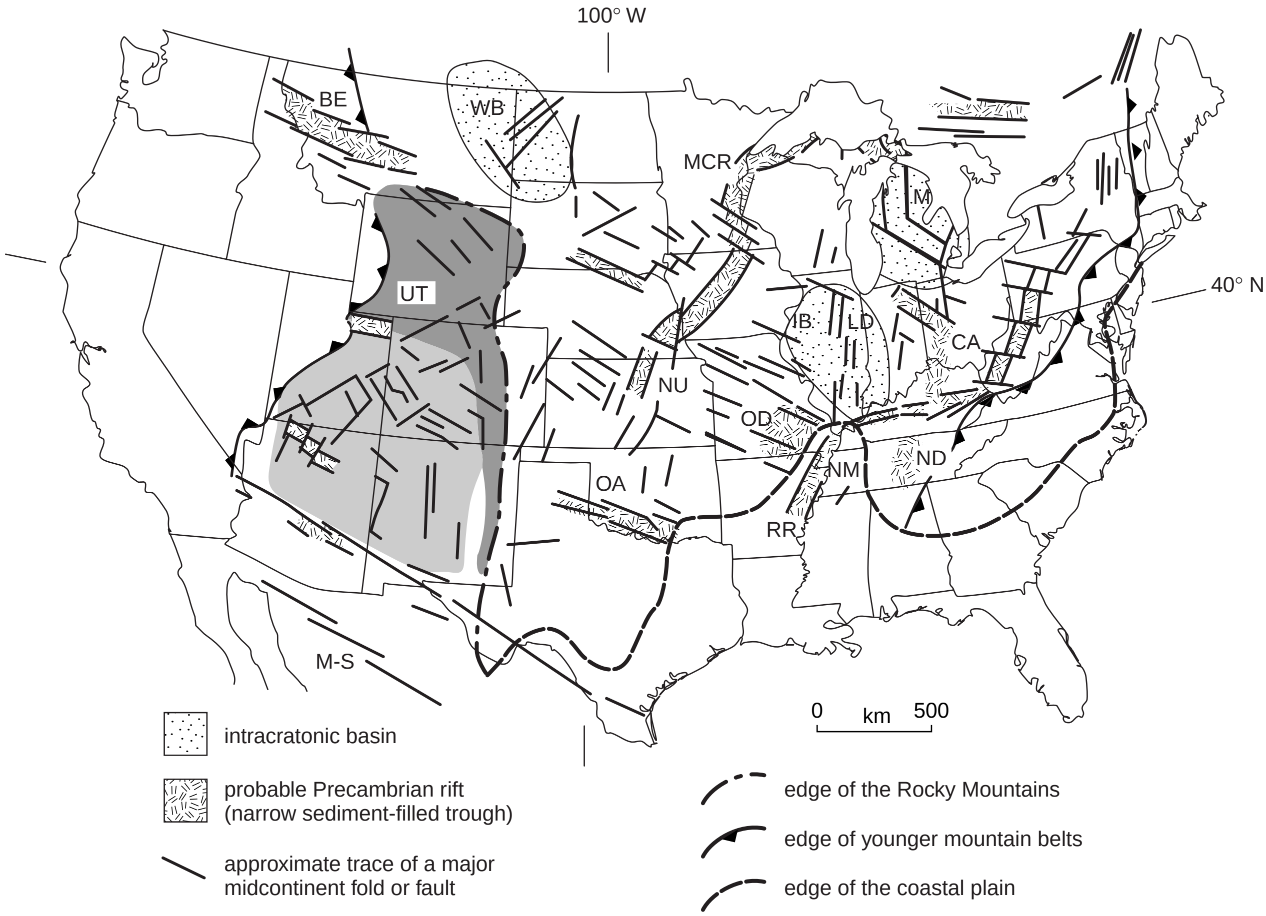

FIGURE 22.7.4 Map of the United States showing the distribution of Midcontinent fault-and-fold zones and of documented intracratonic rifts. BE = Beltian embayment, UT = Uinta trough, MCR = Midcontinent Rift, OA = Southern Oklahoma aulacogen, RR = Reelfoot Rift, LD = La Salle deformation belt, WB = Williston Basin, IB = Illinois Basin, MB = Michigan Basin, ND = Nashville dome, CA = Cincinnati arch, M-S = Mojave-Sonora megashear.

that basins have subsided overall through most of the Phanerozoic, probably due to slow cooling of lithosphere beneath the basins, but emphasize that the rate of subsidence for a basin varies with time. For example, pulses of rapid subsidence occurred in the Michigan and Illinois Basins during Ordovician, Late Devonian–Mississippian, and Pennsylvanian–Permian time. Notably, the timing of some, but not all, epeirogenic movements in the Midcontinent roughly corresponds with the timing of major orogenic events along the continental margin. For example, the time of Late Paleozoic subsidence in the Midcontinent U.S. basins roughly corresponds with the time of the Alleghanian Orogeny (the collision of Africa with the eastern margin of North America).

MIDCONTINENT FAULT-AND-FOLD ZONES Bedrock geology of much of the Midcontinent has been obscured by Pleistocene glacial deposits and/or thick soils. In the isolated exposures that do occur, geologists have found occurrences of folds and faults. The regional distribution of such structures has slowly emerged from studies of well logs (compiled on structure-contour and isopach maps), potential-field data (compiled on gravity- and magnetic-anomaly maps), and seismic-reflection profiles. Abrupt steps and ridges on structure-contour maps or isopach maps, linear anomalies on potential field maps, abrupt bends or breaks in reflectors on seismic-reflection profiles—along with outcrop data—reveal that the Phanerozoic strata of the Midcontinent United States has been disrupted locally by distinct belts of deformation that we refer to here as Midcontinent fault-and-fold zones (Figure 22.7.4).

Individual fault-and-fold zones range in size from only a few hundred meters wide and several kilometers long, to 100 km wide and 500 km long. The north-northwest trending La Salle fault-and-fold zone of

Illinois serves as an example of a larger zone—it effectively bisects the Illinois Basin (Figure 22.7.5). Larger zones include numerous non-coplanar faults that range in length from <5 km to as much as 50 km. At their tips, these faults overlap with one another in a relay fashion. Locally, a band of *en echelon* subsidiary fault segments borders the trace of principal faults. In the upper few kilometers of the crust, major faults of a Midcontinent fault-and-fold zone dip steeply and divide upwards into numerous splays. The resulting array of faults resembles that of a flower structure. At depth, major faults decrease in dip (i.e., some faults appear to be listric) and penetrate basement (Figure 22.7.6). Some, but not all, faults clearly border narrow rift basins that contain anomalously thick sequences of sediments and volcanics. The largest of these intracratonic rifts, the Midcontinent Rift, consists of two principal arms, one running from Lake Superior into Kansas and the other running diagonally across Michigan (Figure 22.7.4). Faults along these rifts initiated as normal faults, but later reactivated as thrust or strike-slip faults.

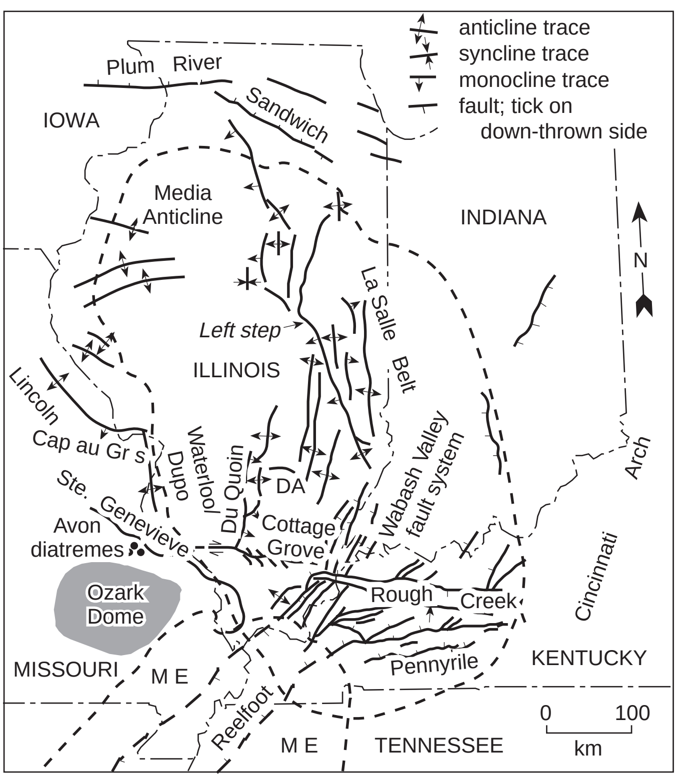

FIGURE 22.7.5 Structure map of the Illinois Basin region showing the map traces of Midcontinent fault-and-fold zones. Note that the Cottage Grove Fault is bordered by short *en echelon* faults, indicative of strike-slip displacement.

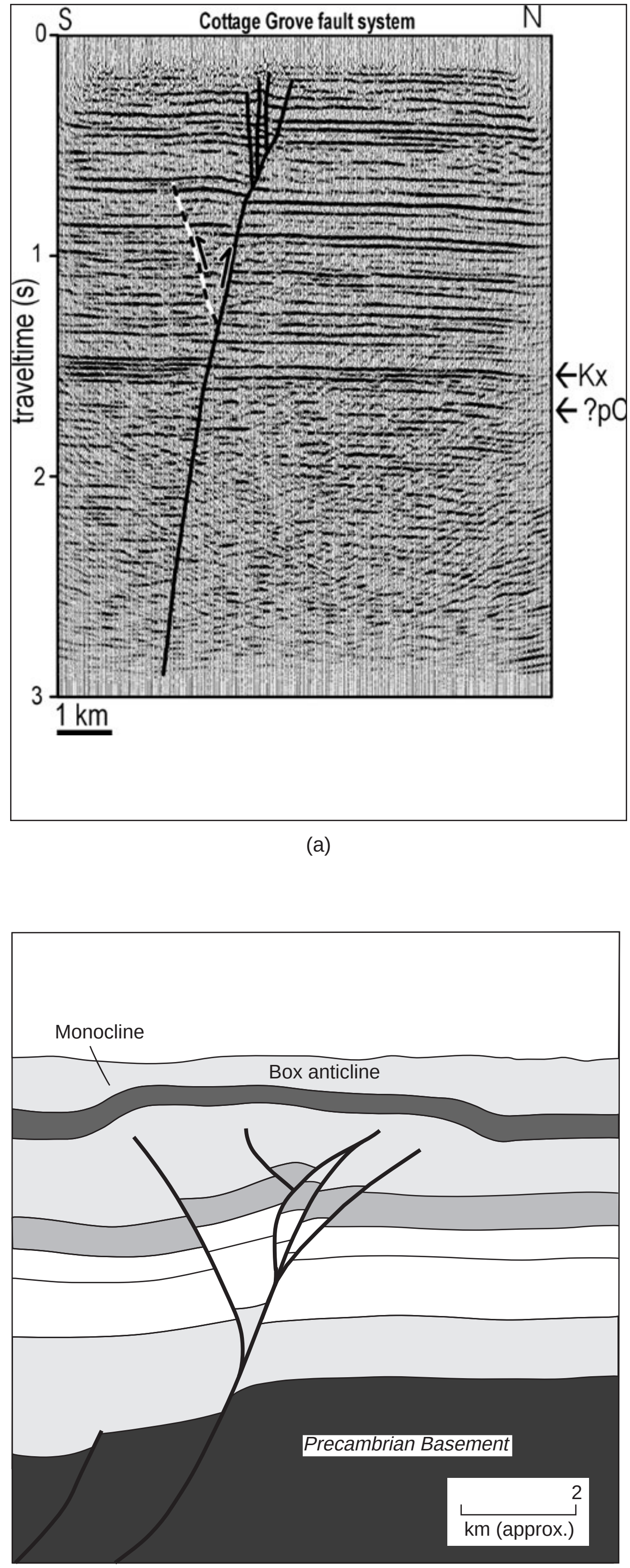

FIGURE 22.7.6 Cross-sectional structure of a Midcontinent fault zone. (a) Seismic-reflection profile of the Cottage Grove fault system; (b) Schematic cross section showing the principal features of a Midcontinent fault zone.

Cross sections indicate that major faults in the Midcontinent locally have vertical throws of as much as 2 km, but more typically throws are less—no more than tens to hundreds of meters. Strike-slip components of displacement across continental-interior faults are difficult to ascertain because of lack of exposed shear-sense indicators on fault surfaces and the lack of recognizable offset markers. But geologists have found strike-slip lineations on faults exposed in coal mines, and the *en echelon* map pattern of subsidiary faults adjacent to larger faults resembles the *en echelon* faulting adjacent to continental strike-slip faults. Such features suggest that a component of strike-slip motion has occurred on some Midcontinent faults. Where such motion has occurred, the faults can be considered to be oblique-slip faults. The occurrence of oblique slip, in turn, suggests that transpression or transtension has taken place in some Midcontinent fault-and-fold zones.

In general, folds of the continental interior are monoclinal in profile, meaning that they have one steeply dipping limb and one very shallowly dipping to subhorizontal limb. Locally, oppositely facing monoclinal folds form back-to-back, creating “box anticlines” (Figure 22.7.6b). Though geologists have not yet obtained many clear images of Midcontinent folds at depth, several studies document that folds lie above steeply dipping faults and that structural relief on folds increases with depth.

Detailed study of spatial variations in the thickness and facies of a stratigraphic unit relative to a fault-and-fold zone, documentation of the timing of unconformity formation, as well as documentation of local slump-related deformation, permits determination of when the fold-and-fault zone was tectonically active. Such timing constraints suggest that the structures, in general, became active during more than one event in the Phanerozoic. Activity appears to have been particularly intense during times of orogenic activity along the continental margin, but occurred at other times as well. The most significant reactivation occurred during the late Paleozoic, at the same time as the Alleghanian Orogeny. This event triggered reactivation of faults across the entire interior platform. Fault reactivation in the region that now lies within the Rocky Mountains yielded localized uplifts (now eroded) that have come to be known as the Ancestral Rockies. Some authors now use this term for Late Paleozoic uplifts associated with faulting across the width of North America (Figure 22.7.7).

Midcontinent fault-and-fold zones do not have random orientations, but rather display dominant trends over broad regions of the craton. As indicated by the map in Figure 22.7.4, most of the zones either trend north-south to northeast-southwest, or east-west to northwest-southeast, and thereby outline rectilinear blocks of crust. Along-strike linkage of fault-and-fold zones seems to define transcratonic belts of tectonic reactivation, which localize seismicity today.

Of note, Midcontinent folds closely resemble Laramide monoclines of the Colorado Plateau, and Laramide basement-cored uplifts of the U.S. Rocky Mountain region, though

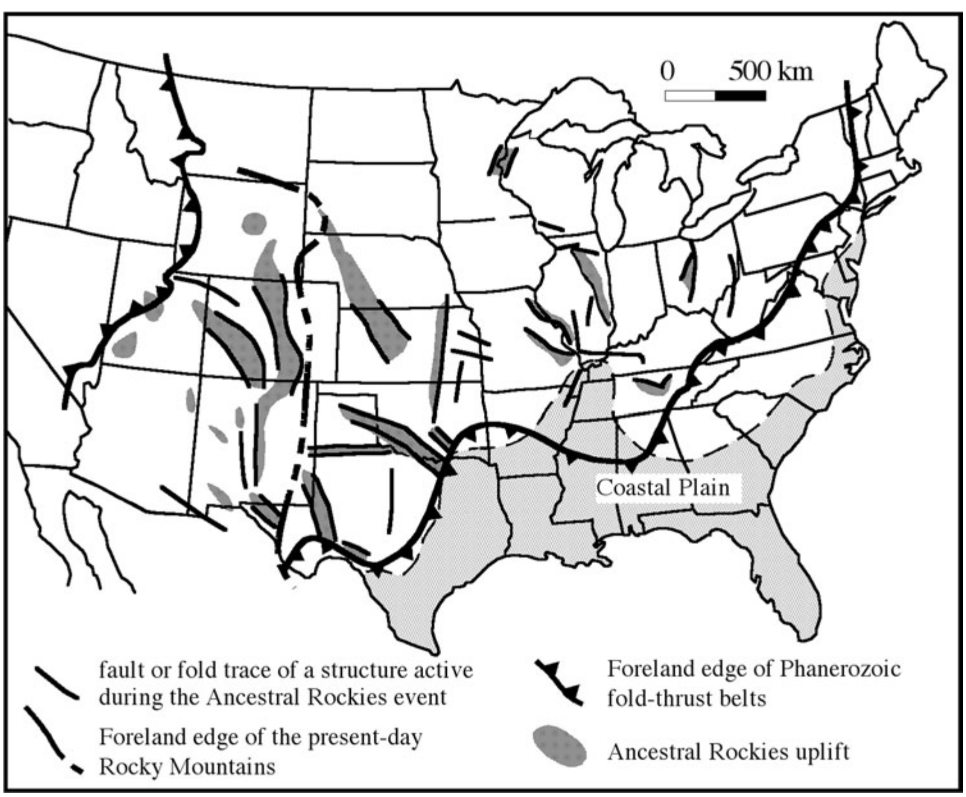

FIGURE 22.7.7 Late Paleozoic uplifts of the United States. The large ones west of the Rocky Mountain front have traditionally been referred to as the Ancestral Rockies.

at a smaller scale. This is not surprising because, as we noted earlier, the Colorado Plateau and Rocky Mountain region were once part of the craton's interior platform. These regions differ from the Midcontinent only in that they were uplifted and deformed during the Late Mesozoic–Early Cenozoic Laramide Orogeny. During this event, slip on some faults of the region exceeded 15 km, an order of magnitude more than occurred during Paleozoic reactivation of faults in the Midcontinent. Because of substantial Laramide and younger uplift, and because of the dry climate of the Plateau, fault-and-fold zones of the Plateau are brazenly displayed. But keep in mind that, if the Midcontinent region were stripped of its glacial sedimentary blanket and its prairie soils, it would look much like the Colorado Plateau.

INTRAGRANULAR STRAIN AND REGIONAL JOINTING When you traverse a large fold in the Appalachian fold-thrust belt, you will find that outcrops of argillaceous (clay-rich) sandstones and limestones contain well-developed spaced cleavage to slaty cleavage. But, if you walk across a large fold in the Midcontinent (or on the Colorado Plateau), you will find a distinct lack of cleavage. Layer-parallel shortening strains sufficient to form a regional cleavage apparently did not develop in the Midcontinent. Microstructural studies, however, indicate that subtle layer-parallel shortening did, in fact, develop in Midcontinent strata. This strain is manifested by the development of calcite twinning, a type of intragranular, crystal-plastic strain that can be seen only with a microscope and has developed in limestone.

Calcite twinning forms under the relatively low pressure and temperature conditions that are characteristic of the uppermost crust. Regional studies of calcite twinning in Midcontinent limestones indicate that the maximum shortening direction remains fairly constant over broad regions and trends roughly perpendicular to orogenic fronts, though more complex shortening patterns occur in the vicinity of Midcontinent fault-and-fold zones (Figure 22.7.8). Notably, strain and differential stress magnitudes in the eastern Midcontinent decrease progressively from the Appalachian-Ouachita orogenic front to the interior—strain magnitudes are 6% at the front but decrease to 0.5% in the interior,

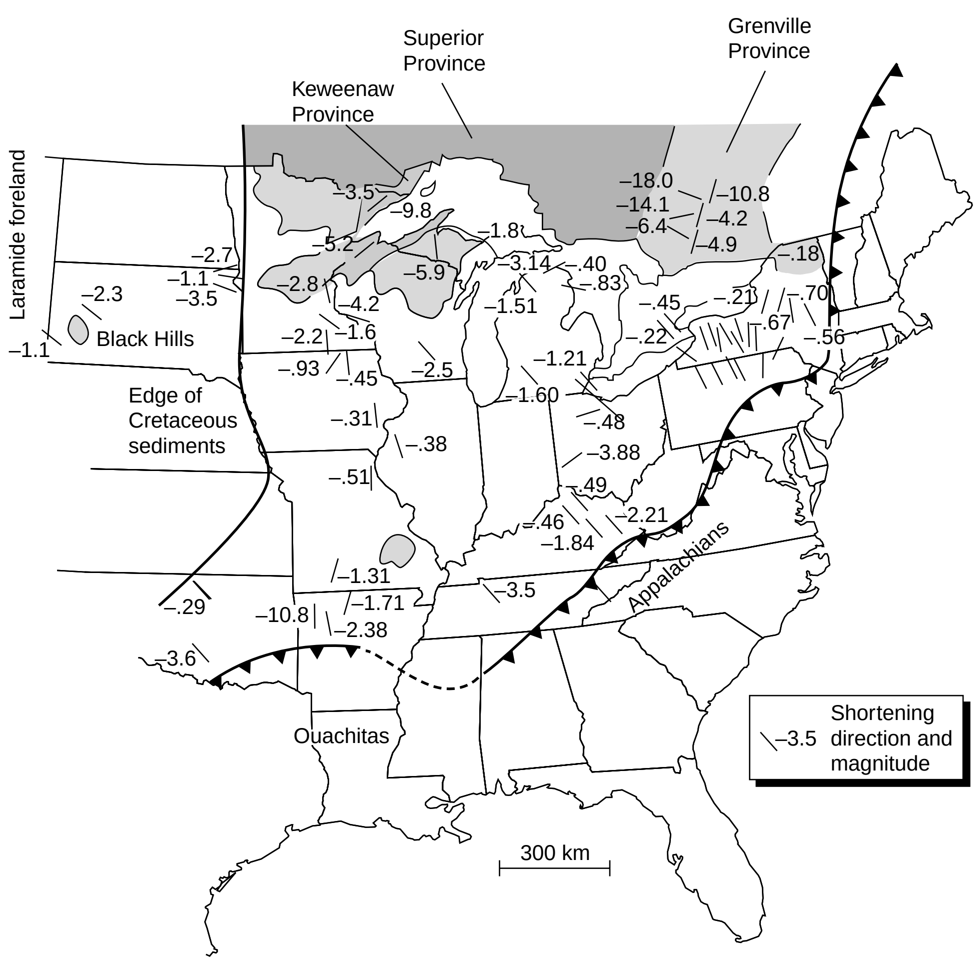

FIGURE 22.7.8 Calcite twinning strains in eastern North America. Regional tectonic provinces are labeled, except for the Paleozoic cover sequence inland from the Appalachian-Ouachita thrust front (bold, toothed line). Strains are presented by orientation (short lines) and magnitude in percent (negative is shortening); typically, maximum shortening is horizontal and perpendicular to the Appalachian-Ouachita thrust front. Twinning data from other tectonic provinces show patterns that are unrelated to Paleozoic deformation.

with associated differential stresses exponentially decreasing from ~100 MPa to less than 20 MPa. This pattern suggests that calcite twinning in strata of the eastern Midcontinent formed during the Alleghanian Orogeny, the Late Paleozoic collision of Africa with North America. In the western part of the Midcontinent, twinning strains also generally lie in the range of 0.5% and 3%, and the direction of maximum shortening trends roughly at right angles to the Rocky Mountain front. This geometry implies that layer-parallel shortening in strata of the western Midcontinent developed in association with compression accompanying the Sevier and Laramide Orogenies.

No one has yet compiled joint-trend data for the entire Midcontinent, but the literature does provide data from numerous local studies. Joint frequency diagrams suggest that there are two dominant joint sets (one trending generally northwest and one trending generally northeast) and two less prominent sets (one trending east-west and one trending north-south) in the Devonian strata of northern Michigan. Similar, but not exactly identical, trends have been documented in Ohio, Indiana, Illinois, and Wisconsin. Taken together, regional studies suggest that systematic vertical joint sets do occur in platform strata of the Midcontinent, and that in general there are east-west sets, northwest sets, north-south sets, and north-east sets, but that orientations change across regions and that different sets dominate in different locations. The origin of this jointing remains enigmatic.

22.7.3 Some Causes of Epeirogeny

Over the years, geologists and geophysicists have proposed many mechanisms to explain continental interior epeirogeny. The candidates that may explain epeirogeny will be briefly discussed and are illustrated in Figure 22.7.9.

- *Cooling of Unsuccessful Rifts.* Intracratonic basins may form because of thermal contraction due to cooling of unsuccessful rifts that opened during the Late Proterozoic. When active extension ceased, these rifts cooled and subsided, much like the rifts that underlie passive margins. Such epeirogeny continued through the Phanerozoic at ever-decreasing rates.
- *Variations in Asthenosphere Temperature.* Modern seismic tomography studies of the Earth's interior demonstrate that the Earth's mantle is thermally heterogeneous. As lithosphere drifts over this heterogeneous asthenosphere, it conceivably warms when crossing hot asthenosphere and cools when crossing cool asthenosphere. These temperature changes could cause isostatic uplift (when warmed) or subsidence (when cooled) of broad regions of the lithosphere.
- *Changes in State of Stress.* Changes in stress state in the lithosphere may cause epeirogenic movement in many ways. For example, as differential stress increases, plastic deformation occurs more rapidly, so that the viscosity of the lithosphere effectively decreases. Thus, an increase in differential stress weakens the lithosphere. If this were to happen, denser masses in the crust (e.g., a lens of mafic igneous rock below a rift), which were previously supported by the flexural strength of the lithosphere, would sink, whereas less dense masses (e.g., a granite pluton) would rise. Thus, differential epeirogenic movements may be localized by preexisting heterogeneities of the crust, which is set free to move in an attempt to attain isostatic equilibrium by the weakening of the lithosphere that accompanies an increase in differential stress. Some geologists have suggested that changes in horizontal stress magnitude may also cause epeirogeny by buckling the lithosphere, or by amplifying existing depressions (basins) or rises (arches).
- *Flexural Response to a Load.* Creation of a large load, such as a volcano or a stack of thrust sheets, results in flexural loading on the surface of the continent, and thus bending down of the continent's surface. Flexural loading due to emplacement of thrust sheets leads to the development of asymmetric sedimentary basins, called foreland basins, on the craton side of fold-thrust belts. In addition to causing a depression to form, the levering effect of the loaded lithosphere may cause an uplift, or outer swell, to form on the cratonic-interior of the depression. This effect may have caused Midcontinent uplifts, like the Cincinnati arch, to rise in response to loading the continental margin by thrust sheets of the Appalachian orogen.
- *Block Tilting.* As noted earlier, Midcontinent fault-and-fold zones divide the upper crust into fault-bounded blocks. Changes in the stress state in the continental interior may cause tilting of regional-scale, fault-bounded blocks of continental crust relative to one another. These could cause uplift or subsidence of the corners and edges of blocks.
- *Changes in Crustal-to-Lithosphere Mantle Thickness Ratio.* Continental elevation is controlled, regionally, by isostasy. Since crust and mantle do not have the same density, any phenomenon that causes a change in the proportion of crust to lithospheric mantle in a column from the surface of the Earth down to the level of isostatic compensation

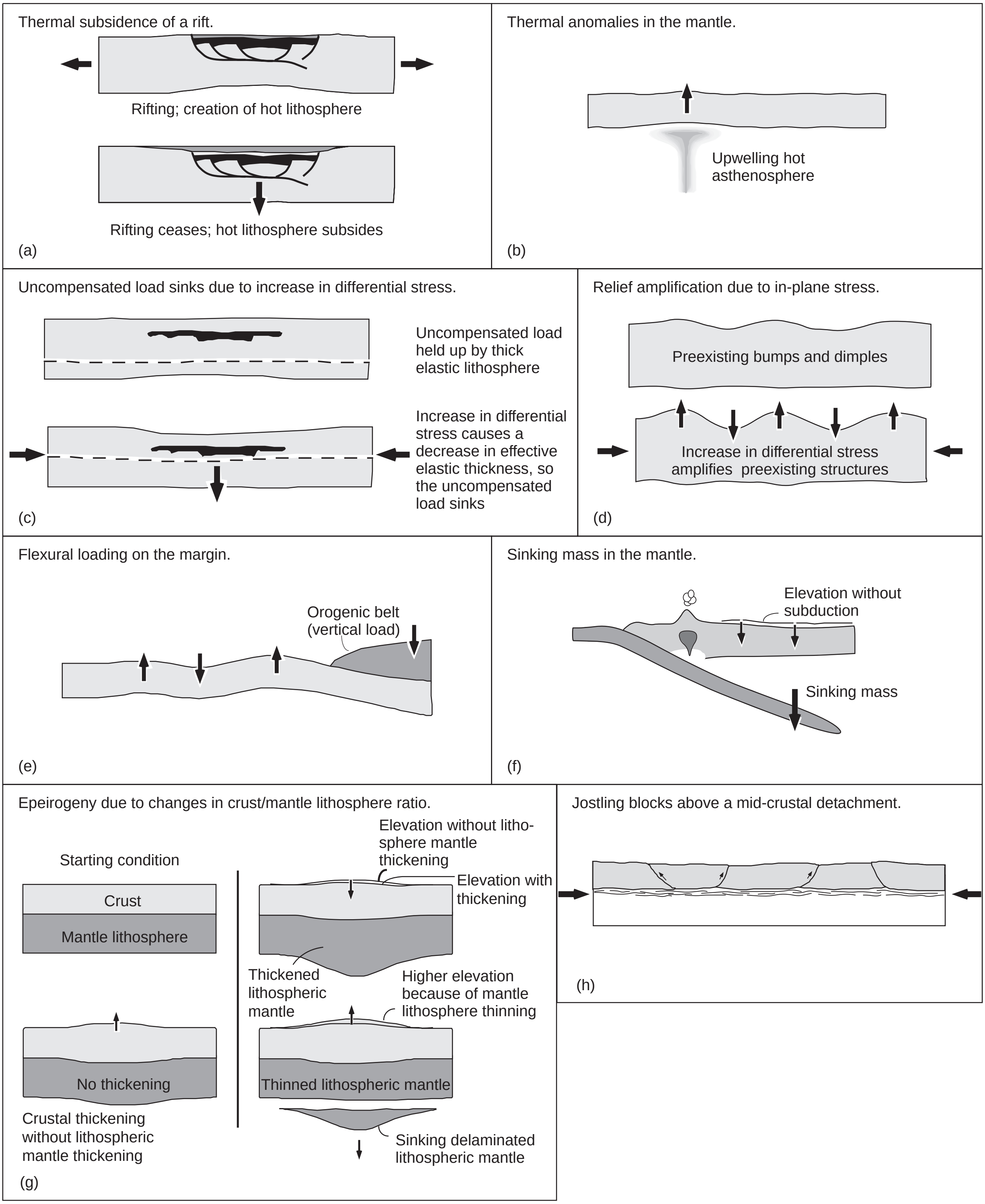

FIGURE 22.7.9 Models of epeirogeny. (a) Thermal cooling over an unsuccessful rift (before and after); (b) Uplift related to thermal anomalies in the mantle; (c) Vertical movement of an uncompensated load due to changes in the elastic thickness of the lithosphere; (d) Amplification of preexisting bumps and dimples due to in-plane stress; (e) Flexural loading of a lithospheric margin; (f) Epeirogeny related to subduction; (g) Epeirogeny due to changes in the ratio of crustal thickness to lithosphere mantle thickness; (h) Epeirogeny due to tilting of regional fault-bounded blocks.

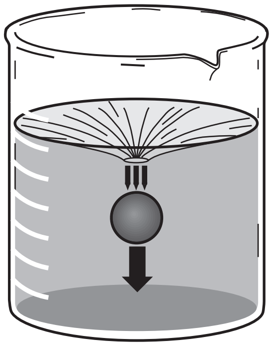

FIGURE 22.7.10 Schematic drawing showing the sinking ball model for epeirogeny caused by subduction (or dynamic topography). As the ball sinks through the honey (shaded area), the thin plastic film on the surface of the honey is pulled down.

has the potential to cause a change in the elevation of the continent's surface. For example, thickening of the crust, perhaps due to plastic strain in response to tectonic compression relative to the lithospheric mantle, would cause a rise in elevation; decreasing the thickness of the lithospheric mantle in response to delamination (separation of lithospheric mantle from the base of the plate) could also cause a rise in crustal elevation; adding basalt to the base of the crust (a process called underplating) would thereby thicken the crust and could cause uplift.

- *Subduction.* Subduction of oceanic lithosphere can cause epeirogenic movement because, as the subducted plate sinks, it pulls down the overlying continent. To picture this phenomenon, imagine a bucket filled with honey (representing the asthenosphere), in which an iron ball (representing oceanic lithosphere) has been suspended just below the surface (Figure 22.7.10). Now, place a film of plastic wrap (representing the continental lithosphere) over the top of the honey, and then release the ball. As the ball sinks (representing subduction of the oceanic lithosphere), the plastic wrap is pulled down. This downward motion is epeirogenic subsidence.

22.7.4 Speculations on Midcontinent Fault-and-Fold Zones

As noted above, stratigraphic evidence demonstrates that Midcontinent fault-and-fold zones were reactivated multiple times during the Phanerozoic. But how did the zones originate in the first place? Did the faults initiate during the Phanerozoic by brittle rupturing of intact crust in response to compression caused by orogeny along the continental margin? If so, then the faults started out as reverse or transpressional faults. Or did the structures form earlier in Earth history? We favor the second proposal, and suggest that Midcontinent fault-and-fold zones initiated as normal faults during episodes of Proterozoic extension. Thus, displacements in the zones during the Phanerozoic represent fault reactivation. We base this statement on the observation that Midcontinent fault-and-fold zones have the same trends as Proterozoic rift basins and dikes in the United States. They are not systematically oriented perpendicular to the shortening directions of marginal orogens.

If the above hypothesis is correct, then the fault-and-fold zones of the Midcontinent, as well as of the Rocky Mountains and Colorado Plateau, are relicts of unsuccessful Proterozoic rifting. Once formed, they remained as long-lived weaknesses in the crust, available for reactivation during the Phanerozoic, when the interior underwent slight regional strain. A reverse component of displacement occurred on the faults if reactivation was caused by regional shortening, whereas a normal sense of displacement occurred if reactivation was caused by regional extension. On faults that were not perpendicular to shortening or extension directions, transpression or transtension led to a component of strike-slip motion on faults. Regarldless of slip direction, displacement on the faults generated fault-propagation folds in overlying strata. Note that reverse or transpressional motion represents inversion of Proterozoic extensional faults, in that reactivation represents reversal of slip on the faults. In cases where the faults bounded preserved rift basins, the inversion led to thrusting of the rift's contents up and over the rift's margin. But rift basins do not occur in all fault-and-fold zones, either because Proterozoic displacements were too small to create a basin, or because the basin was eroded away during latest Proterozoic rifting, before Phanerozoic strata were deposited.

The hypothesis that Midcontinent fault-and-fold zones are reactivated Proterozoic normal faults is appealing because it explains how these structures could have formed with the orientations that they have, and how they formed without the development of regional cleavage. Zone orientation simply reflects the trends of preexisting Proterozoic normal faults, not the orientation of a regional stress field during the Phanerozoic. The lack of regional cleavage reflects the fact that development of these structures is not associated with significant shortening above detachments within the Phanerozoic section. This hypothesis also explains the timing of movement—faults were reactivated primarily during marginal orogenies or rifting events, when displacement of the continental margin caused a slight strain in the interior, and this strain was accommodated by movement on faults. Perhaps a way to envision Phanerozoic Midcontinent faulting and folding is to think of the upper crust in the craton as a mosaic of rigid fault-bounded blocks that jostle relative to one another in response to changes in the stress state of the continental interior (Figure 22.7.11). Depending on the geometry of the stress during a given time period, blocks may move slightly apart, move slightly together, or move laterally relative to one another. Movements tend to be transpressional or transtensional, for the belts are not oriented appropriately for thrust, reverse, or strike-slip faulting alone to occur.

The greatest amount of movement in Midcontinent fault-and-fold zones occurred in Late Paleozoic time, when Africa collided on the east, South America collided on the south, and a subduction zone had formed along the southwest. This pulse resulted in the formation of the Ancestral Rockies of the Rocky Mountains Province as well in the kilometer-scale displacements in fault-and-fold zones across the Midcontinent (Figure 22.7.7). The intracratonic strain that formed at this time is significantly less than that in Asia during the Cenozoic collision of India with Asia. The contrast in continental-interior response to collision probably reflects the respective strengths of these two continents. The interior of Asia consists of weak continental crust of the Altaids Orogen, while the interior of the United States is a strong craton.

While major movements appear to have accompanied major marginal orogenies, movement on these faults can occur during nonorogenic times as well. For example, historic intraplate earthquakes (earthquakes occurring in a plate interior, away from plate boundaries) at New Madrid, Missouri, result from movements at the intersection of two Midcontinent fault-and-fold zones. This movement may be a response to the ambient stress in the continental lithosphere, caused by ridge-push force and/or basal traction, or to stress resulting from epeirogenic movements.

22.7.5 Closing Remarks

The speculative tone used in this essay emphasizes that geologists need to obtain more data on structures in cratonic interiors before we can confidently explain them and assess their significance. However, it has become increasingly clear that cratonic interiors were not tectonically dead during the Phanerozoic. Rather, they were sensitive recorders of plate interactions, which may have caused jostling of upper-crustal blocks. Although we have focused on examples of structures in the Midcontinent of the United States,

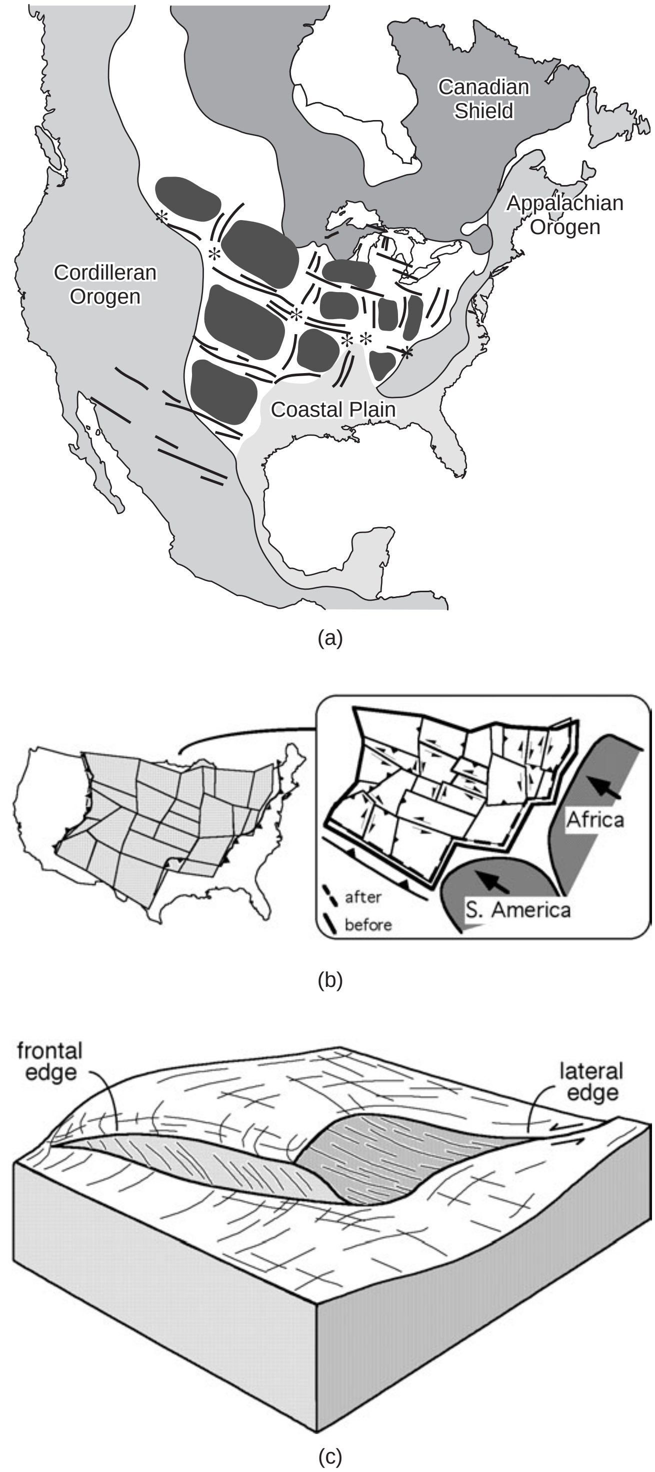

FIGURE 22.7.11 (a) Map showing block model of intracratonic tectonism in the United States. Stars indicate seismically active regions. The diagram in (b) illustrates how thrust and strike-slip motions can be reactivated in response to regional compression, while the diagram in (c) illustrates how uplift along a reverse fault leads to oblique slip along the side of the block.

keep in mind that these structures can be viewed as type examples for continental-interior platforms throughout the world. Finally, it is important to emphasize once more that the dramatic basement-cored uplifts that developed in the Rocky Mountains, as well as in the Sierra Pampeanas of Argentina, and the Tien Shan of southern Asia, are similar in style to those of the U.S. Midcontinent; all may have been formed by reactivation of preexisting faults.

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