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# POST-PRECAMBRIAN TECTONISM IN THE GRAND CANYON REGION

*Peter W. Huntoon*

## INTRODUCTION

This chapter will summarize in chronological order the post-Precambrian structural events that are recorded in the rocks of the Grand Canyon. Laramide compression and Late Cenozoic extension will receive particular attention because these events caused most of the deformation found here. A reading of this chapter will be greatly facilitated by having the geologic maps by Huntoon et al. (1981, 1982, 1996) and Billingsley and Huntoon (1983) at hand.

The typical section in this chapter will place structural events occurring in the Grand Canyon region into the larger contexts of cordilleran tectonics and plate tectonics. The evidence used to time the events, and the types and geometries of the structures associated with them, will be described at the local and regional levels. Causative stresses will be deduced. The influence of the events on paleogeography and on the movement of sediments into and out of the region will be outlined.

This is a skeletal history. Many pages and even chapters have been torn from the book by erosion during periods of uplift. One of the largest gaps is the 130 million years missing from the Paleozoic record inclusive of Ordovician through Middle Devonian time. Similarly, most of the Mesozoic record has eroded from the plateaus surrounding the canyon, and too much Cenozoic history has been carried away by the Colorado River thanks to Laramide and Tertiary. To draw some inferences, we will step away from the canyon to adjacent regions where fragments of the record still remain.

The terms "Colorado Plateau region" and "Grand Canyon region" are used for orientation purposes. However, be aware that the Colorado Plateau did not become fully defined until Miocene time. "Mogollon Highlands" refers to the Mesozoic and Cenozoic uplifts occurring south of the Colorado Plateau.

## THE COLORADO PLATEAU

The Grand Canyon is eroded into the southwestern corner of the Colorado Plateau, a geologic province that is underlain by a thick continental crust that became slightly separated on the east from the continental craton during the Cenozoic Era. As shown in Fig. 14.1, the plateau is ringed by zones of intense deformation, including the extended Rio Grande rift on the east, compressional Uinta uplift to the north, and drastically extended Basin–Range to the south and west. The Paleozoic rocks in the Grand Canyon are about a mile (1.6 km) thick. Nevertheless, they are but a thin, sensitive veneer resting on a 19- to 25-mile (30- to 40-km)-thick crust comprised of an ancient basement complex.

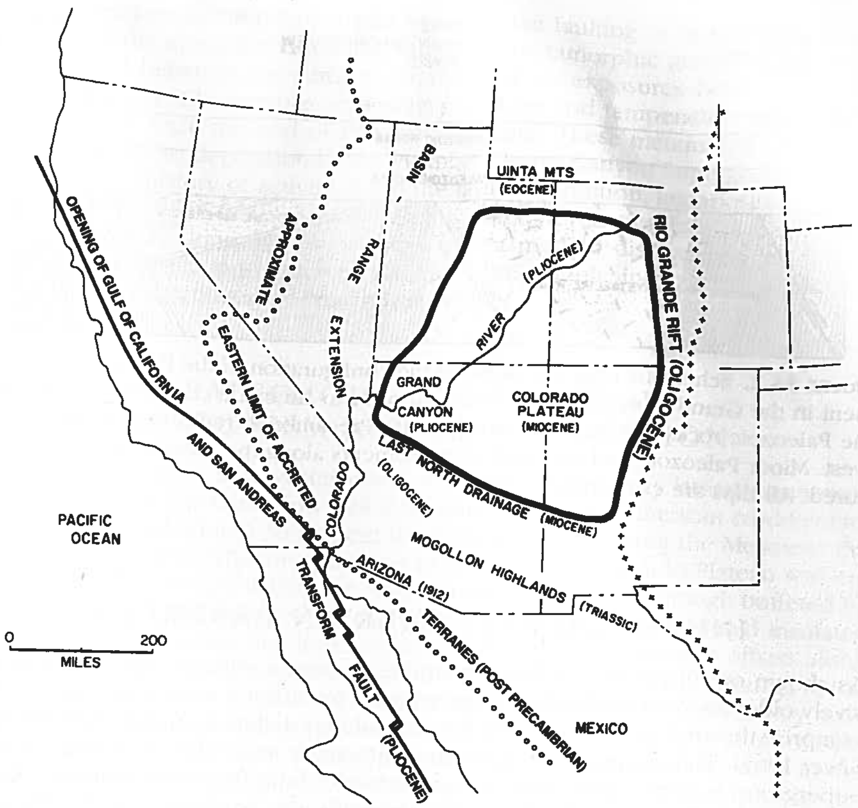

**FIGURE 14.1.** Selected tectonic elements in the western North American cordillera and the timing of their inception.

The record of Phanerozoic deformation reveals that the basement underlying the Colorado Plateau has enjoyed unusual stability since the close of Precambrian time. The Paleozoic rocks in the Grand Canyon region were deposited in the equatorial regions of the earth on the southwestern part of a growing continent. The plateau was an integral part of the larger land mass at that time. Subsequently, the continent was rafted through plate tectonic processes some 2000 miles (3200 km) northward across the face of the earth, and it rotated a few tens of degrees in a counterclockwise direction (Elston and Bressler 1977).

Between the beginning of Cambrian and the end of Cretaceous time, a period of roughly 480 million years, net subsidence of the Precambrian surface in the Grand Canyon region amounted to between 1.5 and 2 miles (2.4 to 3.2 km). In the last 70 million years, a period dominated by uplift, the Precambrian surface has risen in two pulses a total of approximately 2 miles (3.2 km). Clearly, the cratonic block upon which the Grand Canyon occurs has moved great lateral distances and has both lost and gained considerable elevation. However, it has not undergone serious internal fragmentation since the close of Precambrian time.

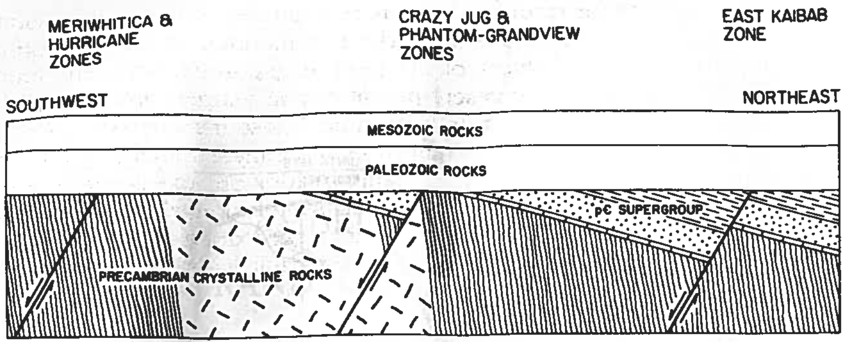

**FIGURE 14.2.** Schematic diagram showing the configuration of the Precambrian basement in the Grand Canyon region, Arizona, prior to Laramide contraction. Note that the Paleozoic rocks rest on successively older Precambrian rocks toward the southwest. Minor Paleozoic and Mesozoic(?) movements along the basement faults are ignored. All dips are exaggerated.

## INHERITED PRECAMBRIAN BASEMENT

As shown on Figure 14.2, a late Precambrian erosion surface exposed progressively older rocks in the Precambrian complex toward the west. The oldest rocks comprise the approximately 1.7-billion-year-old crystalline complex (Pasteels and Silver 1965). The younger Precambrian sedimentary and volcanic Grand Canyon Supergroup is preserved to the east on a series of fault-bounded, northeast-tilted basement blocks. These layered rocks generally dip between 6 and 8 degrees toward the east, and they are beveled above by the erosion surface into northeast-thickening wedges.

Supergroup wedges to the east contain increasingly more complete sections. Consequently, the youngest Precambrian sediments are found in the easternmost part of the Grand Canyon. Maximum thicknesses occur along the west side of the Butte fault. Huntoon et al. (1996) showed a thickness of approximately 9000 feet (2700 m) in the vicinity of Malgosa Canyon. Elston and Scott (1976) have reported thicknesses of between 12,000 and 14,000 feet (3600 and 4200 m), based on measured sections elsewhere.

The Precambrian faults defining the boundaries of the tilted basement blocks in the eastern Grand Canyon are north- and northwest-trending normal faults with extensive records of recurrent Precambrian displacement (Walcott 1889). The bounding faults include the Butte, Phantom-Cremation, Crystal, and Muav faults. Synchronous Precambrian deformation consisting of parallel, parasitic folds and grabens developed in bands as wide as 2.5 miles (4 km) along the eastern margins of the blocks. The resulting zones commonly are spaced about 10 miles (16 km) apart. Elston (1979) estimated the age of the latest Precambrian movements along these faults at 845 to 810 million years using K–Ar dates.

The north- and northwest-trending faults offset an older set of northeast-trending reverse faults. The Bright Angel fault is the most studied of these (Huntoon and Sears 1975). Shoemaker et al. (1975) conclude that there is a good possibility that considerable right-lateral, strike-slip displacement occurred along the northeast-trending faults prior to deposition of the Precambrian Grand Canyon Supergroup.

The best evidence for recurrent Precambrian faulting in the western Grand Canyon occurs along the Hurricane fault. The metamorphic grades of deformed rocks found between the surfaces of the fault in exposures between Granite Spring and 224-Mile canyons represent pressures and temperatures unavailable in the region since the end of Precambrian time. These metamorphic products developed before deposition of the younger Grand Canyon Supergroup, revealing a long prehistory of activity along the fault. In addition, juxtaposition of Precambrian crystalline terranes with differing fracture-foliation fabrics and lithologies is common along the fault. Rocks with a marked discordance in foliation trends are also juxtaposed across the Meriwhitica fault, indicating a substantial but unknown magnitude of Precambrian offset.

## PALEOZOIC AND MESOZOIC TECTONISM AND SEDIMENTATION

North America grew in a westerly and southerly direction by lateral continental accretion during Paleozoic and Mesozoic time. The North American cordillera increased by an additional 30 percent through accretion during the Mesozoic Era alone (Coney 1981). The area that was to become the Colorado Plateau was ensconced just to the east within the North American craton. Although buffeted by continental-scale tectonic events, the Grand Canyon region remained insulated by distance to the point that little happened in the form of discrete offsets along faults in the underlying basement or local volcanism. The forces operating in the Grand Canyon region were attenuated sufficiently that deformation mostly took the form of broad-scale but gentle warping of the crust and variable rates of subsidence or uplift. The lack of angular unconformities of regional extent in the Paleozoic section in the canyon reveals that, at least during Paleozoic time, the uplifts associated with the disconformities are best categorized as epeirogenic.

### Cambrian to Late Triassic Tectonics

The southwestern corner of the Colorado Plateau occupied a distant inboard position on the west-facing continental shelf through Devonian time. The edge of the continent is characterized as a passive margin undergoing a progression of marine transgressions and regressions (Woodward-Clyde Consultants 1982). The Cambrian sea transgressed eastward over the Precambrian foundation, burying a generally flat-lying surface broken locally by scattered, essentially isolated, small but rugged hills. The highest hills were 1200 feet (360 m), and they finally were covered by the Muav Limestone. Examples of buried Precambrian hills occur under Isis Temple, in Modred Abyss and Monadnock Amphitheater, and along the Colorado River immediately east of Deer Creek.

The longest hiatus in the Paleozoic stratigraphic record occurs between the undivided Cambrian carbonates and Late Devonian Temple Butte Formation, a gap of approximately 130 million years. Missing are rocks inclusive of Ordovician, Silurian, and Early and Middle Devonian age, yet the contact is a disconformity throughout the Grand Canyon. Similarly, the contact between the Temple Butte Formation and the Mississippian Redwall Limestone is a disconformity, even though this hiatus was caused by orogenic uplift associated with the Antler orogeny. The Grand Canyon region was being subjected to uplift and subsidence; however, the crust was not being deformed internally. The conclusion is that the region was distant from active orogenic zones.

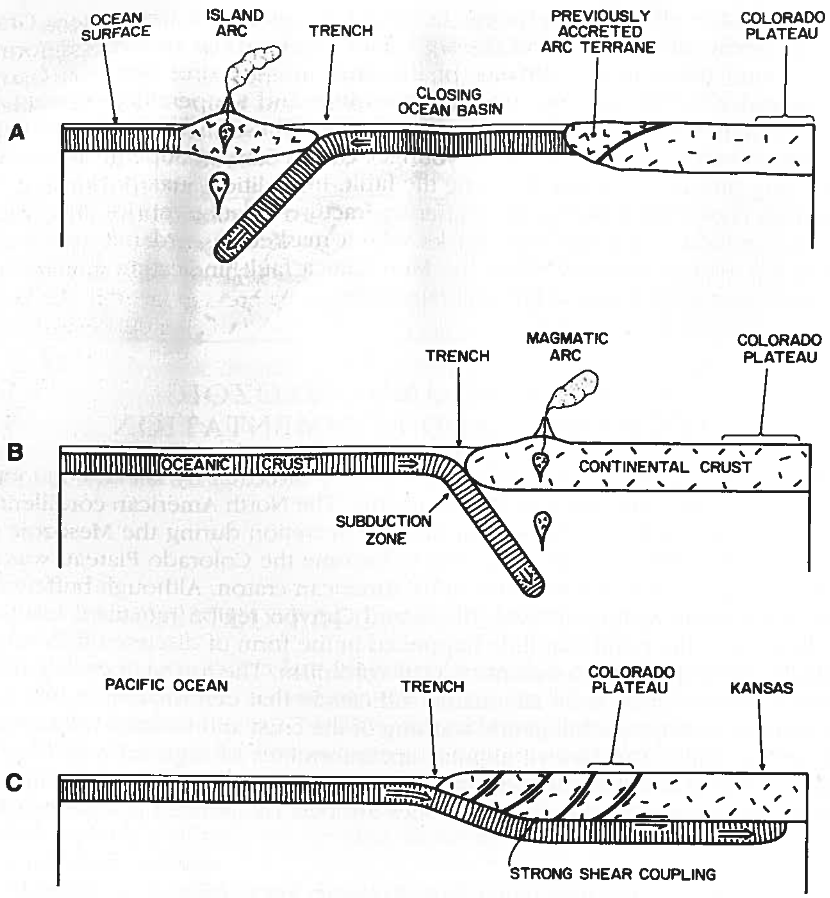

**Figure 14.3.** Convergent margin orogens along western North America. (a) Intraoceanic arc-trench orogen active periodically in post-Precambrian through Late Triassic time. Notice that the ocean basin closes, allowing island arc to accrete to continent, then another subduction zone and its island arc can form offshore and likewise eventually accrete to continent. (b) Slow landward subduction causing development of magmatic arc inboard on continent above steeply descending slab active from Late Triassic to Late Cretaceous time. (c) Rapid subduction resulting in shallow slab descent and slab underplating of continent to produce buoyant uplift and strong shear-coupling with eastward telescoping of continental crust during Laramide time. Vertical scales are greatly exaggerated.

Convergence of the oceanic and North American plates during the Antler orogeny in latest Devonian–Mississippian time resulted in the accretion of huge tracts of land to western North America and downwarping of the Cordilleran miogeocline along a north–south axis through eastern Nevada and southeastern California (Dickinson 1981). Accretion appears to have been accomplished as shown in Fig. 14.3a through plate convergence in an offshore arc-trench system. This mechanism involved the oceanward subduction of the oceanic lithosphere lying between an offshore trench and the continent. As the crust was consumed

in the trench, both the trench and island arc migrated toward the edge of the continent. Once the trench and continent met, the island arc became sutured to the continent, and a new arc-trench system developed offshore to repeat the process. The continent built progressively oceanward from central Nevada and eastern California in this fashion.

Orogenic belts associated with accretionary growth lay to the west of the Grand Canyon region and were subjected to large-scale eastward thrusting, uplift caused by crustal thickening, and deep-seated metamorphism. The north-trending depositional basin through east-central Nevada collected the detritus shed eastward off these uplifts. Marine limestones, such as the Devonian Temple Butte and the Mississippian Redwall limestones, were deposited in the Grand Canyon region on the eastern margin of the basin and thickened toward it.

One of the best-preserved erosional events in the Paleozoic section involves the Late Mississippian emergence of the Redwall Limestone. A series of west-ward-draining valleys are found in the western part of the canyon that were incised as much as 400 feet (120 m) into the limestone. The slightly uplifted Redwall surface was pervasively karstified so that the landscape took on the appearance of the modern Yucatan Peninsula. The Mississippian (Chesterian) Surprise Canyon Formation fills the valleys and caves; yet it and the Supai Group lie disconformably on virtually all the older rocks.

The only offsets along faults in the Grand Canyon that have been identified as dating from the Paleozoic Era are inferred from highly localized angular unconformities at the top of the Mississippian Redwall Limestone. These disturbances occurred in the interval between deposition of the Redwall Limestone and Surprise Canyon Formation. At least 150 feet of the Redwall section, including the entire Horseshoe Mesa Member, were truncated by erosion across the crest of a minor anticline at a site along the Tanner Trail (McKee and Gutschick 1969). This erosion surface is overlain unconformably by the Pennsylvanian Watahomigi Formation. The fold is attributed to displacement along the underlying Precambrian Butte fault. Huntoon and Sears (1975) observed a similar truncation of the upper 30 feet (9 m) of the Horseshoe Mesa Member in a band one-quarter-mile wide over the Bright Angel fault. The truncation and an anomalous 10-degree west dip of the Redwall Limestone were caused by reverse motion along the underlying Proterozoic fault, resulting from reactivation of that structure. These deformations are attributed to horizontal, generally east–west compression in the context of present compass directions that were caused by contraction associated with the Antler orogeny.

The Pennsylvanian and earliest Permian Ouchita orogeny developed when a terrane that now comprises the Yucatan Peninsula and South America was sutured to the North American continent along a collisional belt extending through northern Mexico, central Texas, and southeastern Oklahoma (Dickinson 1981). The resulting grand-scale internal stresses within the North American plate were sufficient to cause the intracratonic block uplifts and associated basins of the ancestral Rocky Mountains. The Uncompahgre uplift and Paradox basin developed northeast of the Grand Canyon region in response to this collision, and the Defiance uplift to the east gained additional elevation. Clastic sediments, such as those in the Supai Group, were shed from these highlands and transported south and west into the Grand Canyon region, which remained low. Some graded into carbonate facies toward the west across the Grand Canyon region.

There was possible Pennsylvanian rifting in the Antler belt in the western Basin-Range region, followed by local Early Permian emergence. The Grand Canyon region first collected the Coconino Sandstone, a coastal dune deposit facing the ocean to the west. The Coconino Sandstone, which is the shoreward facies of the Seligman Member of the Toroweap Formation, was buried by the southeastward transgressing marine members of the Toroweap Formation, and later the Kaibab Formation, as the land subsided. The marine shelf environment persisted, except for a brief period of uplift to the west and south at the end of Permian time, until after deposition of the marine Moenkopi Formation in Early and Middle Triassic time. The Late Permian–Early Triassic Sonoma accretionary event was occurring far to the west.

The huge interval of Paleozoic time spanning 325 million years was characterized by net subsidence and net accumulation of sediments that now thicken westward from 3500 to 5000 feet (1100 to 1500 m) through the Grand Canyon. The top of the accumulating sedimentary pile had fluctuated within several hundred feet of sea level, with most of the time spent below the water.

### Late Triassic to Late Cretaceous Uplift

A worldwide reorganization of plate motions between Late Triassic and Late Jurassic time resulted in the opening of the Gulf of Mexico and the Atlantic Ocean through sea floor spreading. Concurrently, the Pacific Ocean crust began to subduct under North America in contrast to earlier oceanward subduction (Fig. 14.3B). The result was the inboard development of a Mesozoic magmatic arc south and west of the Grand Canyon region that was characterized by batholithic intrusions, arc volcanism, and thermotectonic uplift. These events first caused general emergence of the Colorado Plateau region and strong uplift of the contiguous Mogollon Highlands to the southwest, and much later they caused uplift and eastward thrusting in the Sevier Highlands to the northwest during Cretaceous time (Woodward-Clyde Consultants 1982).

Most of Mesozoic time in the Grand Canyon region was characterized by low but emergent conditions in which continental sedimentation within intracratonic basins prevailed. The broad, gently sloping Mogollon Highlands began to rise during deposition of the marine Moenkopi Formation, and ultimately it caused regression of the Moenkopi sea toward the northwest. The uplift established a sediment dispersal pattern characterized by north and northeast flowing streams heading in the highlands that persisted until Cenozoic time in the Grand Canyon region. Thus the highlands became a major source for detritus in the Moenkopi Formation and succeeding Mesozoic units in the region. Large inland seas lay mostly to the northwest. The first of the Late Triassic units was the voluminous Chinle Formation, which, in the southwestern Colorado Plateau region, was comprised of fluvial detritus originating from the highlands south of the plateau region and air fall ash that probably came from the northwest. Debris eroded from the highlands included arc volcanics, sedimentary cover, and unroofed Precambrian basement. Erosion in the highlands appears to have exposed Paleozoic and Precambrian terranes as early as Late Triassic time based on clasts found in the Chinle Formation (Stewart et al. 1972). Continued continental sedimentation or erosion prevailed in the Grand Canyon region almost to the end of Mesozoic time, with the exception of the southward encroachment of the marine Middle Jurassic Carmel Formation. Although the Mesozoic section is almost completely eroded, upwards of 4000 feet (1200 m) of predominantly fluvial and eolian Mesozoic sediments were deposited in the region based on thicknesses and paleotrends in outcrops to the east and north.

The last marine transgression during the Mesozoic Era took place in Late Cretaceous time. The sea came from the northeast, and it resulted in the deposition of the Dakota Formation and Mancos Shale. Substantial volumes of older rocks had been eroded from the Grand Canyon region by this time, especially from the elevated area to the southwest. The surface buried by the marine deposits was very smooth and sloped gradually toward the northeast. Harshbarger et al. (1957) reported that the Dakota Formation lies unconformably on progressively older rocks toward the south in eastern Arizona. The unit rests directly on the Paleozoic section at McNary. However, it is doubtful if the sea extended to the southwest across the entire Grand Canyon region.

Neither discrete offsets along reactivated Grand Canyon basement faults nor development of local structural basins and uplifts during pre-Laramide Mesozoic time have been documented within the confines of the Grand Canyon. The primary reason is the paucity of Mesozoic strata in the area. Minor reactivation of basement faults undoubtedly occurred, particularly in response to east–southeast-directed compression associated with the Sevier orogeny along the northwestern margin of the Colorado Plateau during Cretaceous time. However, it cannot be proven here.

## LARAMIDE OROGENY

Laramide orogenesis in western North America, herein used to embrace latest Cretaceous (Maastrichtian) through Eocene events, involved widespread uplift and a significant eastward expansion of the belt of cordilleran deformation beyond the previous limits of accretion, orogenesis, and arc magmatism. Laramide deformation more than doubled the surface area encompassed within the pre-Laramide cordillera and defined the cordillera as we know it in the United States (Fig. 14.1). Crustal contraction and eastward transport in a zone extending from the trenches along the west coast to the eastern limits of the Rocky Mountains characterized Laramide deformation. Types of deformation included east-verging thrust faulting and reverse displacements along reactivated Precambrian basement faults. The faulting was accompanied by the development of monoclines and anticlines in the covering sedimentary rocks. Arc magmatism swept eastward across the cordillera, then waned in intensity (Snyder et al. 1976).

The plate tectonic explanation currently favored for Laramide orogenesis was a flattening of the angle of subduction of the Pacific oceanic plate under North America caused by rapid rates of subduction (Fig. 14.3c). Dickinson (1981, p. 125) summarized the attributes of this concept as follows. (1) The belt of magmatism moved inland as the locus of melting near the top of the subducted slab shifted away from the subduction zone. (2) Magma generation waned as slab descent became subhorizontal because the slab no longer penetrated as deeply into the asthenosphere. (3) Shallower descent of the slab increased the degree of shear and the area of interaction between the descending slab and the overriding cratonic crust. As rapid subduction took place, the subducted hot, buoyant, oceanic plate appears to have underplated North America as far east as the Great Plains, thereby contributing to the uplift of the west. The area that was to become the Colorado Plateau was caught in the eastward compressing Laramide cordillera.

The Laramide orogeny profoundly impacted the Grand Canyon region. It caused: (1) widespread uplift, (2) east–northeast crustal shortening, (3) compartmentalization of the Colorado Plateau region into subsidiary uplifts and basins, and (4) widespread erosion. The result, shown on Figure 14.4, was the development of generally north-striking, east-dipping monoclines as the underlying basement failed in response to east–northeast contraction. Laramide monoclinal

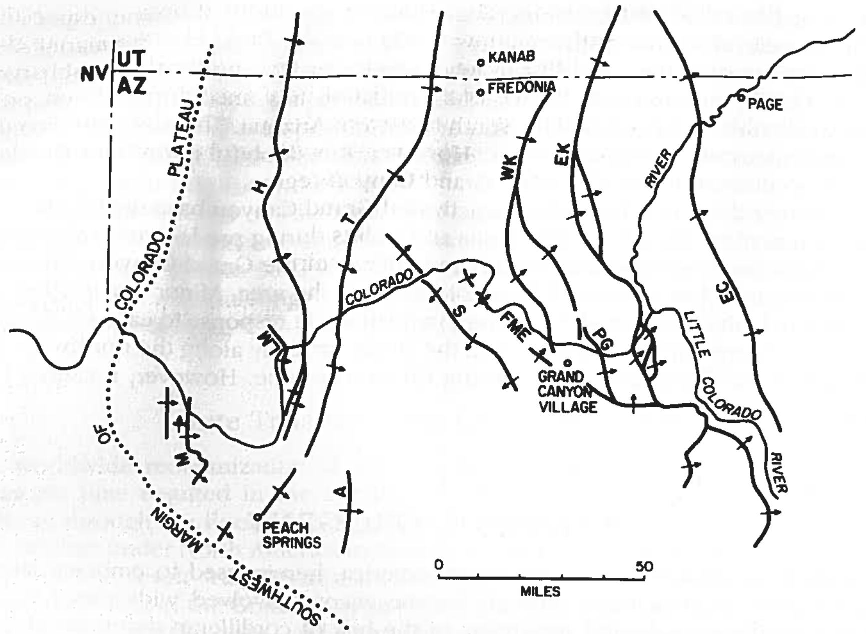

**Figure 14.4.** Locations of the Laramide monoclines in the Grand Canyon region, Arizona. From west to east: M, Meriwhitica; LM, Lone Mountain; H, Hurricane; T, Toroweap; A, Aubrey; S, Supai; FME, Fossil-Monument-Eremita; WK, West Kaibab; PG, Phantom-Grandview; EK, East Kaibab; EC, Echo Cliffs.

folding in the Grand Canyon region was accompanied by mild regional warping of the intervening structural blocks, a process that produced uplifts such as the Kaibab Plateau and downwarps such as Cataract basin.

Laramide erosion uncovered progressively older rocks to the south and west, including the Precambrian basement along the southwestern edge of the Colorado Plateau region. The enormous volume of detritus eroded from the Grand Canyon region and areas to the south was transported northeastward into the intracontinental basins of Utah and beyond. Areas in the Grand Canyon region that were monotonous lowlands at the close of Cretaceous deposition became an uplifted, dissected landscape characterized by north- and east-flowing, sediment-choked streams. Developing topography included the elevated Laramide plateaus and high parts of folds, as well as step-bench topography.

Chapin and Cather (1983) presented evidence for an Early Eocene northeastward reorientation of Laramide compressive stresses within the Colorado Plateau region. This caused 60 miles (100 km) of north–northeast translation of the Colorado Plateau along right-lateral, strike-slip faults that partially decoupled the Colorado Plateau from the North American continent along the future Rio Grande rift. The Early Eocene reorganization of stresses appears to have resulted in minor development, or reactivation, of northwest-trending monoclines in the Grand Canyon region. Northward crowding of the Colorado Plateau into the Wyoming Foreland Province was accommodated by crustal shortening manifested as thrust faulting and regional folding in Wyoming (Chapin 1983) . The result was the east- and southeast-trending basins and ranges in Wyoming. The southernmost of these was the east-trending Uinta uplift bounded both to the north and south by thrust faults dipping under the range. Bernaski (1985) summarized data which reveals that the Uinta uplift began to rise in Early Eocene time. Thus, Laramide structures outlined the eastern and northern boundaries of the Colorado Plateau. The Rio Grande rift along the eastern boundary became better defined and more strikingly decoupled from the North American craton as a result of extension beginning in Late Oligocene time.

## Grand Canyon Monoclines

Most Laramide monoclines in the Grand Canyon region formed in the Paleozoic and Mesozoic sedimentary cover in response to reverse movements along favorably oriented faults in the Precambrian basement (Fig. 14.5). Three lines of evidence demonstrate that most faults under the monoclines were inherited from Precambrian time: (1) juxtaposition of crystalline rocks having different lithologies and fracture-foliation fabrics that cannot be restored by removal of Laramide offsets; (2) juxtaposition of Precambrian Supergroup strata that cannot be restored to prefault conditions by removal of Laramide offsets; and (3) presence of the Precambrian synorogenic Sixtymile Formation along the west side of the Butte fault in the eastern Grand Canyon.

The maximum offset across a Grand Canyon monocline is at least 2500 feet (750 m) along the East Kaibab monocline. The regional trends of the monoclines are generally north–south, but they are characterized by great sinuosity. The longest is the East Kaibab monocline, which is ~190 miles (~300 km). East–west spacings between the monoclines in the Grand Canyon region vary from 7 to 30 miles (11 to 50 km).

Total crustal shortening resulting from deformation within the monoclines was less than 1 percent across the region (Davis 1978). The reasons for this low percentage are as follows: Spacings between the monoclines are large in comparison to local shortening across them, and the dips of the underlying faults are steep.

## Monocline Trends

The trends of the Laramide monoclines are sinuous, and they tend to branch (Fig. 14.4). Branching is well-developed along the East Kaibab monocline. Here, prominent northwest-trending branches such as the Phantom–Grandview segment splay from the main fold. The Hurricane monocline bifurcates southward into two parallel branches. Branching also yields en echelon patterns such as those observed between the various segments of the East and West Kaibab monoclines. Some monoclines are segmented with the intervening gaps exhibiting no discernible deformation. An example is the Fossil, Monument, and Eremita segments, which together constitute a detached western extension of a weakly developed branch of the East Kaibab monocline. Changes in trend and complicated branching are linked directly in outcrops on the floor of the Grand Canyon to Precambrian fault patterns which have been reactivated (Huntoon 1993).

## Monocline Profile Geometry

Most segments of the Grand Canyon monoclines are developed in the Phanerozoic section over a single, high-angle reverse fault in the Precambrian basement

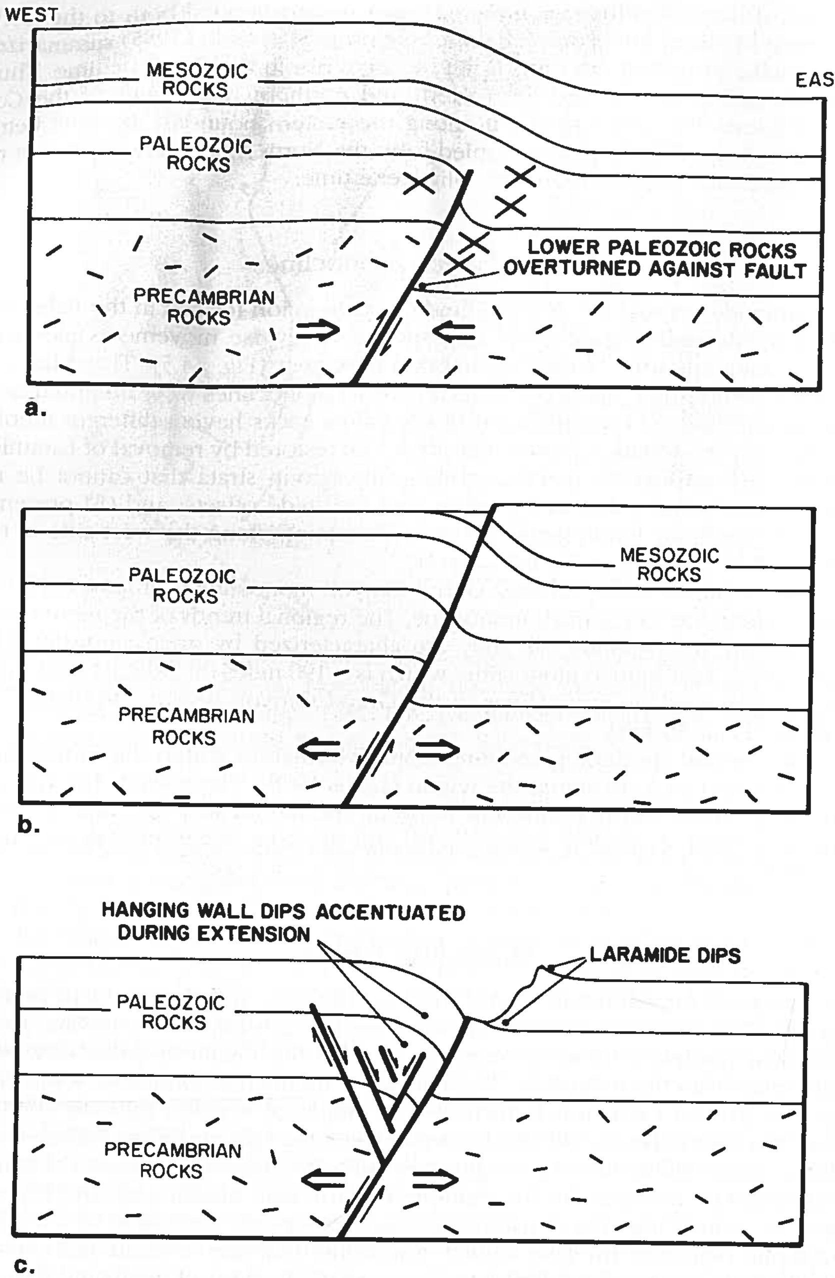

**Figure 14.5.** Stages in the development of a typical monocline-fault zone, Grand Canyon region, Arizona. (a) Laramide folding over reactivated Precambrian fault; Precambrian fault was normal. (b) Late Cenozoic normal faulting. (c) Late Cenozoic configuration after continued extension.

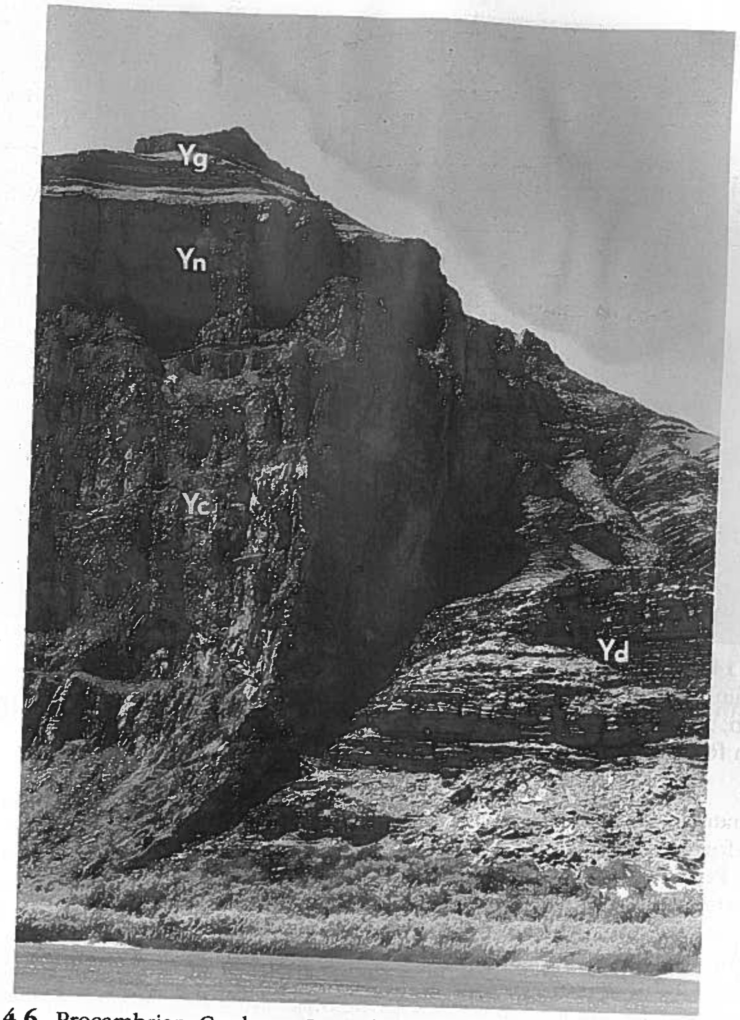

**Figure 14.6.** Precambrian Cardenas Lava (Yc) displaced down in normal fashion against older Dox Formation (Yd) along the west-dipping basement fault underlying the East Kaibab monocline as viewed northward from Tanner Rapid, eastern Grand Canyon, Arizona. The fault was reactivated in Laramide time with approximately 600 feet of reverse (left up) offset to cause monoclinal folding of overlying Paleozoic and younger rocks at this location. Yn, Nankoweap Formation, Yg, Galeros Formation.

(Fig. 14.6). Laramide displacements along the fault generally produced an abrupt offset at the top of the Precambrian basement. The dip of the fault typically is between 60 and 70 degrees. In profile, the anticlinal and synclinal axial surfaces in the monocline converge downward on, and terminate against, the underlying fault at or below the Precambrian–Cambrian contact. Consequently, the dips of the strata increase and the width of the fold decreases with depth in a monocline. The height to which the fault propagated into the overlying Paleozoic strata is proportional to the offset at the Precambrian–Cambrian contact. The dis-

**FIGURE 14.7.** Mechanical crowding within the Cambrian Tapeats Sandstone at the synclinal hinge of the East Kaibab monocline, south wall of Chuar Canyon, eastern Grand Canyon, Arizona. Notice almost vertical dips at this level in the fold. Arrow points to man for scale.

placement on the fault gradually attenuated with elevation largely through ductile deformation of the Paleozoic rocks so that it rarely extends above the top of the Pennsylvanian–Permian Supai Group. Deformation in close proximity to the coring fault includes: (1) minor horizontal shortening folds and kink bands in the footwall block, (2) highly localized drag folding adjacent to the fault surface, and (3) numerous conjugate sets of minor thrust faults.

Shortening across a monocline at all levels is equal to the heave of the Precambrian–Cambrian contact across the underlying reverse fault. Severe crowding developed in the basal Paleozoic rocks in the vicinity of the synclinal hinge (Fig. 14.7). These rocks commonly are riven with conjugate thrusts that mechanically thickened the strata in the syncline and operated to move material out of the syncline away from the fold. The basal Cambrian beds are commonly overturned and highly attenuated adjacent to the coring fault.

The thicknesses of the Cambrian through Pennsylvanian rocks between the anticlinal and synclinal axial surfaces in the East Kaibab monocline are attenuated between 30 and 60 percent (Fig. 14.8). This contrasts with comparatively gentle dips of less than 15 degrees with virtually no attenuation at the level of the Permian strata (Fig. 14.9). The Permian rocks occupying the anticlinal hinge are rarely thinned by brittle failure in the form of downward propagating grabens because of space-compensating horizontal shortening across the monocline.

The Precambrian–Paleozoic contact in the footwall block to the east of the East Kaibab monocline is broadly flexed for 3 to 5 miles (5 to 8 km) in the area immediately north of the Grand Canyon. This flexing adds 1000 feet (300 m) of structural relief to the fold where it is best developed.

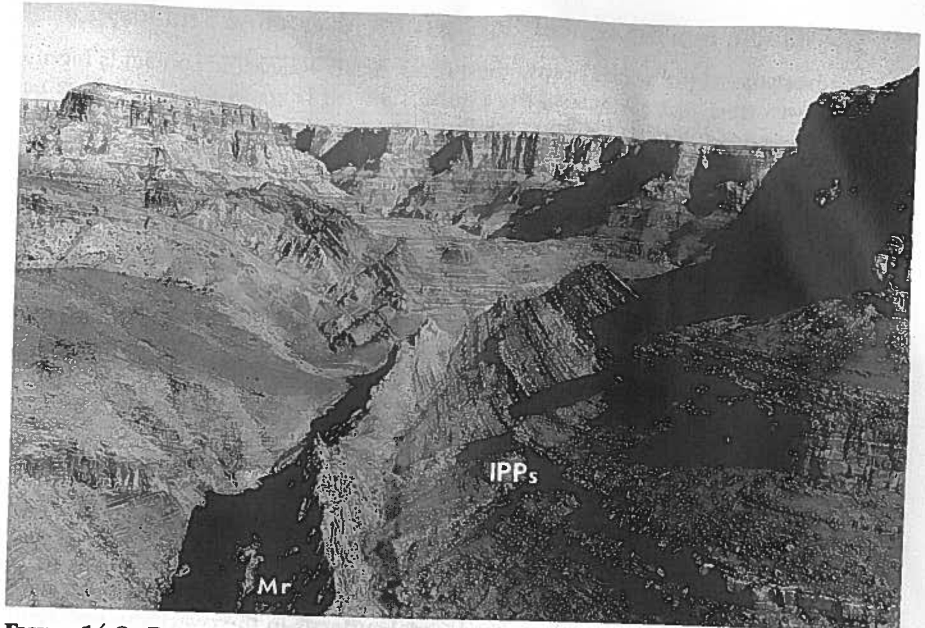

**FIGURE 14.8.** East Kaibab monocline at Chuar Butte, eastern Grand Canyon, Arizona. Ductile thinning of Supai Group (IPPs) and Redwall Limestone (Mr) in center is obvious. Note increasing steepness of dips with depth. View is toward the north, Kwagunt Butte to left.

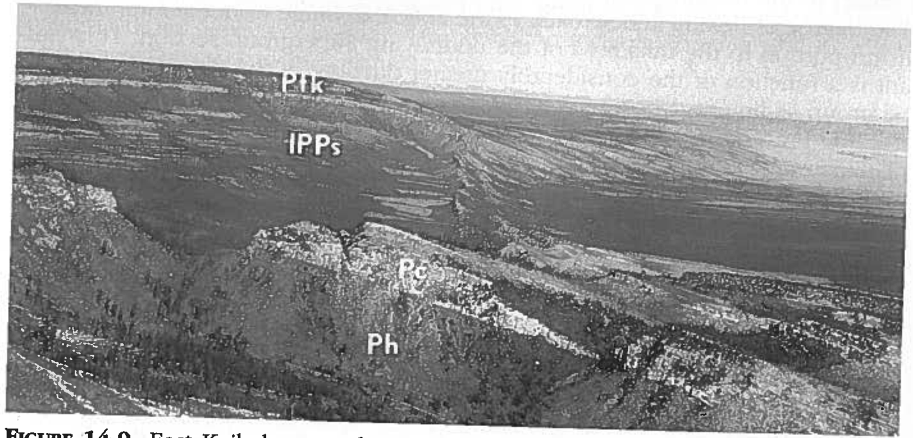

**FIGURE 14.9.** East Kaibab monocline north of the Grand Canyon, Arizona. Dips in the upper Paleozoic section are moderate at this stratigraphic level. Plateau surfaces are comprised of the Permian Kaibab Formation. Ptk, Kaibab and Toroweap Formations, Pc, Coconino Sandstone, Ph, Hermit Shale, IPPs, Supai Group. View is toward the north, Cock's Comb in the center.

## Influence of Basement Strength on Monocline Profiles

The composition of the rocks below the Precambrian–Paleozoic contact is highly variable from west to east across the Grand Canyon (Fig. 14.2). The Paleozoic rocks were deposited directly on crystalline rocks to the west, whereas they are deposited on increasingly thicker sections of progressively younger Precambrian Supergroup rocks to the east. The strength of the unfaulted crystalline rocks tends to be reasonably isotropic. (Isotropy implies that the strength of the rocks was the same regardless of direction prior to failure.) However, the Supergroup sediments are highly anisotropic as a result of bedding, especially the thick Galeros and Kwagunt formations of the Chuar Group. These rocks are ductile, particularly when saturated. Consequently, the presence of the Supergroup sediments causes variations in monocline profiles.

Profile variations are most easily observed by the degree of folding of the Precambrian–Cambrian contact in the hanging wall block, as well as by the level within the fold where the anticlinal axial surface converges on the reactivated basement fault. The ideal monocline in the Grand Canyon region used here as a standard for comparison is one developed over a single reactivated fault that dips 60 degrees, and it is contained wholly within isotropic, rigid, crystalline rocks. Examples include the Hurricane, northern part of the Meriwhitica, and southern part of the Crazy Jug monoclines. Reactivation of the fault under the monocline produced a step-like offset at the Precambrian–Cambrian contact (Fig. 14.10a). Both the anticlinal and synclinal axial surfaces in the overlying fold converge downward on the intersection between the Precambrian–Cambrian contact and the fault surface on the respective sides of the structure. Thus, the Precambrian–Cambrian contact remains planar and the fold does not extend down into the Precambrian crystalline basement.

In contrast, the Precambrian–Cambrian contact in the hanging wall is folded down toward the reactivated fault in locations where Grand Canyon Supergroup strata are preserved in the hanging wall block (Fig. 14.10b). This occurs along the East Kaibab, Grandview–Phantom, and Crazy Jug monoclines. Dips of the contact in the hanging-wall block adjacent to the fault range up to 20 degrees. The degree of flexing and setback of the anticlinal hinge from the fault increase in proportion to the thickness of the underlying Supergroup section. This variant is a function of the considerably greater ductility of the Grand Canyon Supergroup sediments in contrast to the rigidity of the crystalline rocks.

The Precambrian–Cambrian contact in the footwall block remains essentially planar until it very closely abuts the reactivated fault regardless of whether or not sections of the Grand Canyon Supergroup are present in the footwall block. Consequently, the synclinal axial surface always converges on the intersection between the contact and the fault surface in the footwall block in the Grand Canyon monoclines.

## Causative Stresses

Hubbert (1951) used basic mechanical principals and experimental results to demonstrate that faults tend to develop in intersecting conjugate sets (pairs of faults with parallel trends but opposing dips). His analysis assumes that the rock was brittle and reasonably isotropic with respect to structural strength prior to failure. The relationship between the orientations of the causative principal stresses and the angles of fracture is summarized as follows. The axis of the maximum principal stress bisects the acute angle formed by the intersecting shear planes; the axis of the minimum principal stress bisects the obtuse angle. In environments where vertical stresses dominate, the maximum principal stress is vertical, and the faults are predicted to dip between 60 and 62.5 degrees. In contrast, horizontal compression results in horizontal maximum principal stresses and the development of thrust faults that theoretically dip between 27.5 and 30 degrees.

The stress regime responsible for the development of the monoclines involved east–northeast-oriented horizontal maximum principal stresses and vertical minimum principal stresses. Orientations of the maximum principal stresses have been deduced from conjugate shear fractures in both Precambrian and lower Paleozoic rocks at numerous locations along the monoclines (Huntoon 1993). The conjugate shears occur at all scales from microscopic to mesoscopic, and they appear as intersecting second-order thrust faults. A larger-scale example is shown on Figure 14.11. These observations corroborate those of Reches (1978b), who used a variety of stress indicators to determine that the average orientation of the maximum principal stress was N67°E along the Palisades segment of the

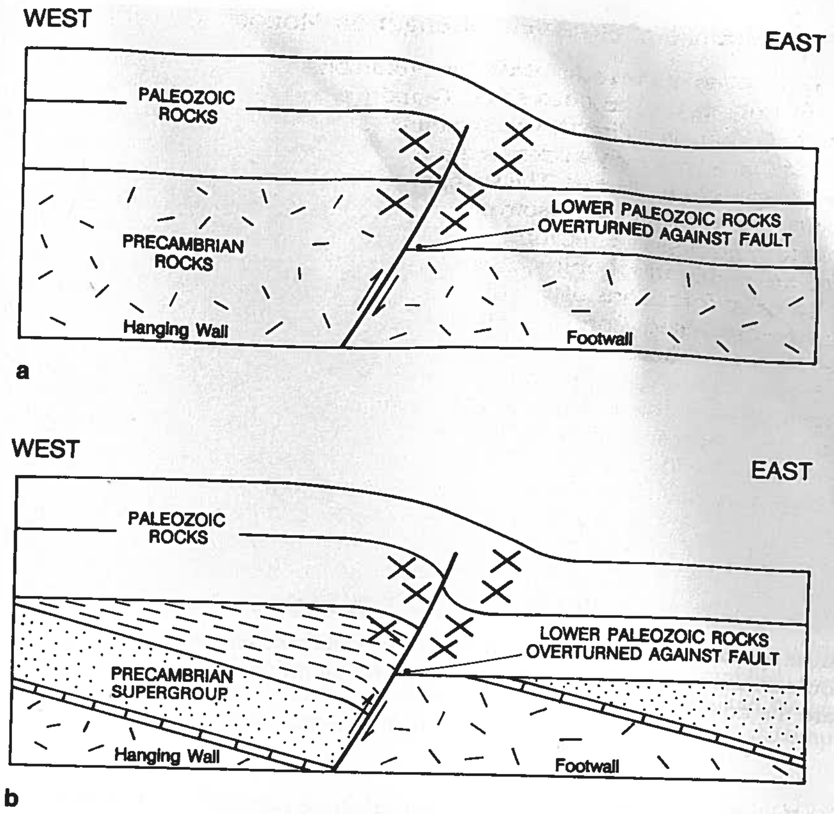

**Figure 14.10.** Idealized composite profiles of Grand Canyon monoclines contrasting those with and without the ductile Precambrian Grand Canyon Supergroup in the hanging wall of the underlying reactivated fault. Small crosses represent small scale conjugate thrust faults. (a) Precambrian crystalline rocks in hanging wall. (b) Precambrian sedimentary rocks in hanging wall.

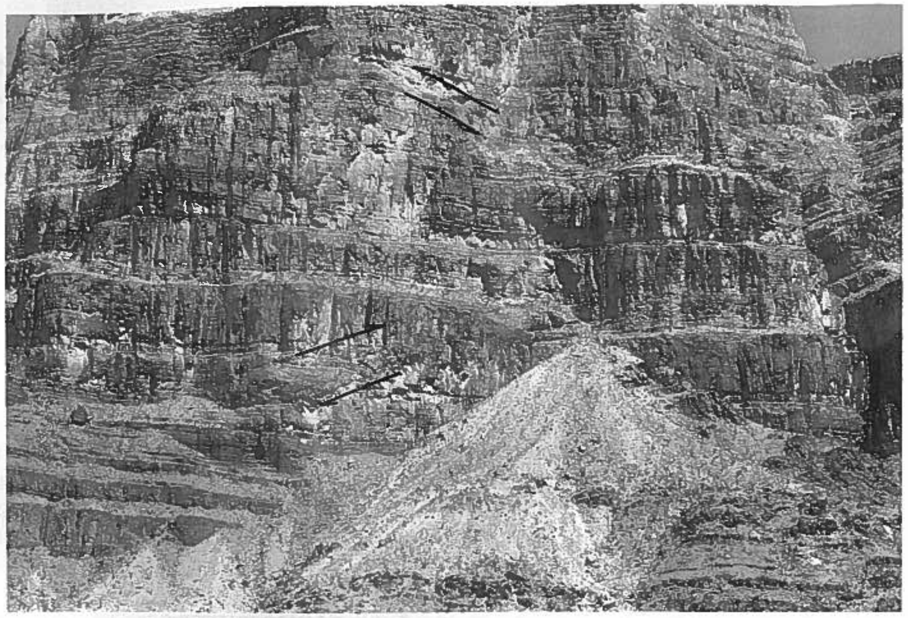

**Figure 14.11.** Conjugate thrusts in the lower Paleozoic limestones east of the Lone Mountain monocline at Granite Park, western Grand Canyon, Arizona. View is toward the northeast.

East Kaibab monocline. His analysis utilized stress orientations deduced from the Paleozoic rocks from calcite twinning, minor faults, kink bands, and minor folds.

In contrast to the second-order thrusts, the basement failed along steeply dipping first-order Precambrian normal faults that were already in place to accommodate Laramide strain. What became the upthrown block after Laramide displacement had been the downdropped block in Precambrian time. The presence of these weaknesses rendered the rocks anisotropic, which destroys the relationship between the principal stress and fracture orientations predicated by Hubbert. Consequently, the dips of the reactivated faults do not reveal information about Laramide stress regime.

We had to find a monocline that did not develop over a preexisting basement fault if we were to use the dips of basement faults to deduce the causative stresses. Huntoon (1981) found a segment of the Meriwhitica monocline which satisfied this criterion. It developed over a six-mile-wide block of unfaulted crystalline basement lying between two reactivating Precambrian faults. The unbroken basement block had to fail along a new fault for the monocline to develop through the area. The block did fail, and the basement exposures lying west of Milkweed Canyon shown on Figure 14.12 reveal that the fault dips between 17 and 27 degrees as anticipated. East–northeast horizontal compression was confirmed as the cause.

A similar thrust fault in an embryonic stage of development underlies an incipient monocline in the south wall of Diamond Canyon 1.5 miles (2.4 km) east of the Hurricane fault. In this case, the southwest-dipping fault crosscuts well-developed north–northeast striking vertical foliation showing no regard for that preexisting fabric. Once again, horizontal compression is implied.

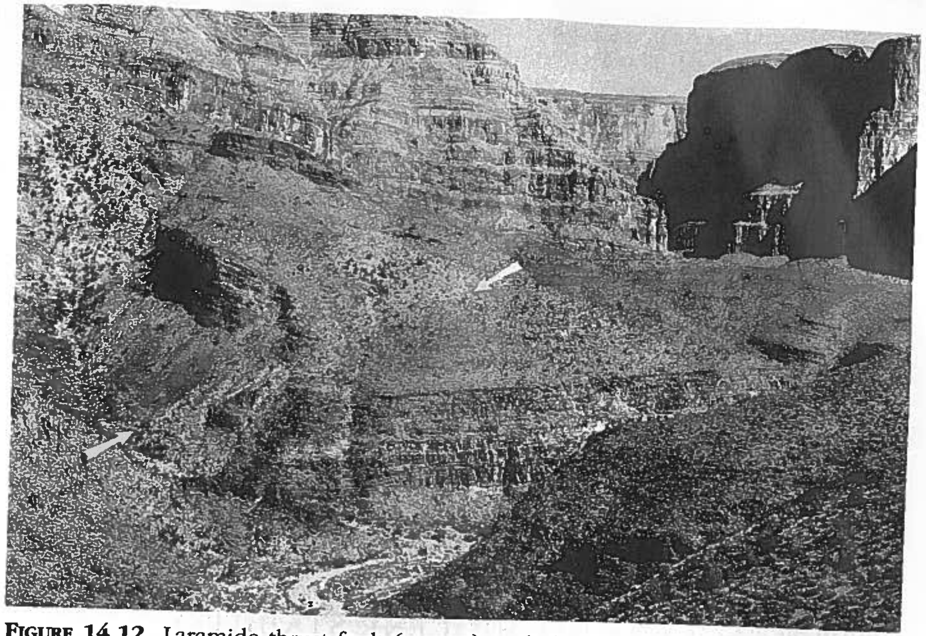

**Figure 14.12.** Laramide thrust fault (*arrows*) underlying the Meriwhitica monocline in a small canyon to west of the junction of Milkweed and Spencer canyons, western Grand Canyon, Arizona. Thrust fault developed in previously unfaulted Precambrian crystalline basement in response to horizontally oriented Laramide maximum principal stresses.

Davis and Tindall (1996) deduced that there is a component of right-lateral strike-slip motion along the basement fault underlying the northern part of the East Kaibab monocline. Their findings are based on the orientations and motions along minor faults in the Cretaceous rocks within the fold. They estimated that lateral slip was as much as three times the vertical offset at that location. This is consistent with the motion expected along a reactivated basement fault that was not oriented perpendicular to the maximum principal stresses.

## Age of Monoclines

It is difficult to establish the timing for the inception of monoclinal folding in the Grand Canyon using stratigraphic evidence because the Late Cretaceous section has been eroded from the region. However, Late Cretaceous rocks containing unconformities are present in the southern high plateaus of Utah and elsewhere in the Rocky Mountain region, and these establish a Maastrichtian initiation for Laramide deformation (Anderson et al. 1975; Dickinson et al. 1987).

The presence of angular unconformities between the Late Cretaceous Kaiparowits, Campanian–Paleocene(?) Canaan Peak, Paleocene(?) Pine Hollow, and Paleocene–Eocene Wasatch formations described by Bowers (1972) reveals that folding was occurring in the southern Utah basins during Laramide time. The Grand Canyon region and areas to the south were undergoing concurrent uplift. Laramide erosion in the Grand Canyon area removed most of the remaining Mesozoic strata from the Permian surface east of the Aubrey monocline

(Fig. 14.1) and Paleozoic strata as low as the upper part of the Cambrian Muav Limestone to the west. The Meriwhitica, Hurricane, and southern segment of the Toroweap monoclines were beveled during this erosional event prior to deposition of Paleocene–Eocene rocks on the Laramide erosion surface. The beveling of the monoclines indicates that the monoclines were developing concurrently with the regional warping that produced the Late Cretaceous and Paleocene unconformities in Utah.

Young (1979) made a case for late-stage recurrent folding along the Meriwhitica monocline. He found Eocene(?) lacustrian limestones that are restricted to Laramide paleocanyons on the hanging-wall block upstream from the monocline. He concluded that renewed folding caused the axis to rise sufficiently to pond water in the channel. The ponded sediments represent the youngest episode of Laramide folding documented in the Grand Canyon region to date.

An analysis of fission track data collected from Grand Canyon rocks led Naeser et al. (1989) to conclude that Laramide uplift and monoclinal folding commenced about 60 million years ago followed by a second pulse of uplift beginning in Late Eocene time between 40 and 35 million years ago. These findings are consistent with the timing of tectonism deduced from the incomplete stratigraphic record.

## EOCENE TO MIOCENE STABILITY

Rapid Laramide rates of oceanic crustal subduction in trenches along the west coast slowed about 45 million years ago, causing the descent angles for the oceanic slab to steepen under the North American plate (Dickinson 1981). The result was a return of arc magmatism to the southern cordillera and a significant relaxation of east–west compressive stresses across the region which had deformed during Laramide contraction. Deformation ceased in the Grand Canyon region as a consequence.

Tectonic quiescence at shallow crustal levels prevailed in the Grand Canyon region from about Late Eocene through Early Miocene time, longer than in the Basin-Range to the west and south. The southwestern part of the Colorado Plateau remained undifferentiated from the Mogollon Highlands to the south. Drainage was toward the northeast in valleys that originated in the highlands and terminated in basins on the plateau or possibly exited from the plateau to the north. The rapid, early Tertiary erosion that accompanied Laramide uplift waned. This left a regional northeast-sloping erosion surface that was beveled across successively older rocks toward the highlands.

### Inherited Laramide Erosion Surface

The major structural uplifts and basins that currently characterize the Colorado Plateau around the Grand Canyon were in place at the close of Laramide time, including the Shivwits and Kaibab plateaus and the Cataract basin. Appreciable relief existed across these features, and erosion by streams had already deeply dissected canyons into the elevated areas and removed large quantities of Mesozoic and Paleozoic sediments from the surfaces. Step-bench topography was present, with the largest step being the southwest-facing Mogollon escarpment in the Permian strata. It trended northwest–southeast across the western Grand Canyon at a location not far south of its present slightly retreated position along the Shivwits Plateau and Aubrey Cliffs.

The Laramide erosion surface is still preserved over much of the Grand Canyon region behind the canyon rims. It occupies a position on successively younger strata from west to east because the Hurricane, Toroweap, and Aubrey monoclines progressively stepped the Paleozoic strata down to the east, so the Laramide surface was beveled across successively younger strata in that direction. Cambrian rocks formed the surface to the west, whereas Permian and Triassic rocks formed the surface to the east.

At Long Point, at the southern edge of Cataract basin, Young (1999) documented Paleocene–Eocene lacustrian deposits resting on the Kaibab Formation. These lake deposits indicate that the Laramide erosion surface was virtually flat at that location. He attributed the ponding to the development of Cataract basin adjacent to the rising Kaibab uplift during the last stages of Laramide deformation.

### Laramide Drainage System

Remnants of the Laramide drainage system are preserved as hanging valleys west of the Toroweap monocline and south of the Colorado River (Young 1999). The meandering courses of the oldest paleovalleys in the vicinity of what is now the Hurricane fault reveal that gradients were gentle at the time they formed. Remnants of the Laramide erosion surface preserved under Miocene volcanics in the vicinity of the Meriwhitica monocline on the Hualapai Plateau indicate that the monocline was beveled to very low relief. Strata as low as the upper part of the Cambrian Muav Limestone were stripped from the monocline. Hindu Canyon, one of the paleovalleys, crossed the fold with little regard for its presence despite structural offset of about 1000 feet (300 m). The floors of the paleovalleys, as well as the oldest sediments preserved in them, probably date from Late Cretaceous(?) and Paleocene(?) time. Northward flow is revealed by channel slope, imbricated pebbles, and increasing Precambrian clast concentrations toward the south within the stream deposits.

The Music Mountain Formation, an early Tertiary arkose, filled the oldest Laramide valleys in the vicinity of Peach Springs canyon. It then spread over the adjacent plateaus. The unit is characterized by abundant Precambrian clasts, rarity of volcanic clasts, deeply weathered profiles, and a deep, red appearance in many outcrops (Koons 1948). The aggregation indicates that the climate was wet and that paleoslopes in the channels were extremely gentle to flat. The weathering reveals that the surface was long-lived.

The channel filling, followed by uplift during late Laramide time, first caused meander cutoffs and then deep incision of the Peach Springs paleovalley in the vicinity of the Hurricane fault zone (Fig. 14.13). The resulting canyon was cut over 1600 feet (500 m) below the Laramide surface. Unresolved is where the stream in it exited the region. One plausible scenario is that it turned eastward or merged with an eastward flowing river that occupied a Laramide canyon superimposed on the Uinkaret and Kaibab uplifts which discharged northeastward into the intercontinental basins of Utah and beyond. In this view, the inferred canyon was a precursor to the Grand Canyon that late in Cenozoic time was reoccupied and deepened into the modern Grand Canyon by the oppositely flowing Colorado River. Another popular scenario proposed by Young and Brennan (1974) is that the Peach Springs drainage continued northward between the Shivwits and Kaibab plateaus over what is now the north rim of the Grand Canyon. Their model requires that the northward tilt of the southwestern part of the Colorado Plateau had to be between 0.5 and 1 degree greater than at present. The additional tilt is needed for the steam to have cleared the present north rim dur-

**FIGURE 14.13.** Deeply incised Laramide paleovalleys in the Peach Springs Canyon area, western Grand Canyon, Arizona. The two meander loops (*small arrows*) are older and less deeply incised than the Peach Springs paleocanyon (*large arrows*), which is colinear with the Hurricane fault. Offset Early Tertiary rocks along the floor of Peach Springs Canyon reveal that Late Cenozoic normal faulting postdated incision of both channels. Arrows show paleocurrent directions. (U.S. Geological Survey photograph.)

ing the period of maximum canyon incision near the mouth of Peach Springs Canyon.

The onset of Oligocene–Miocene arc volcanism to the southwest of the Colorado Plateau was heralded by increased amounts of volcanic and pyroclastic fragments deposited in the upper part of the Eocene–Miocene Buck and Doe Conglomerate. The unit was depositing in the then-aggrading canyons on the Hualapai Plateau. It is overlain by basalt flows and the ~18.5-million-year-old Miocene Peach Springs Tuff (Young and Brennan 1974). The volcanic activity was a harbinger of extensional tectonism that would impact the region strongly.

## LATE CENOZOIC EXTENSIONAL TECTONISM

Initiation of normal faulting in the Grand Canyon region in Middle(?) to Late Miocene time was the outgrowth of complex plate tectonic interactions along the western continental margin that began in Late Oligocene time. Figure 14.14 illustrates the sequence of events. The description that follows is summarized from Dickinson (1981, p. 129).

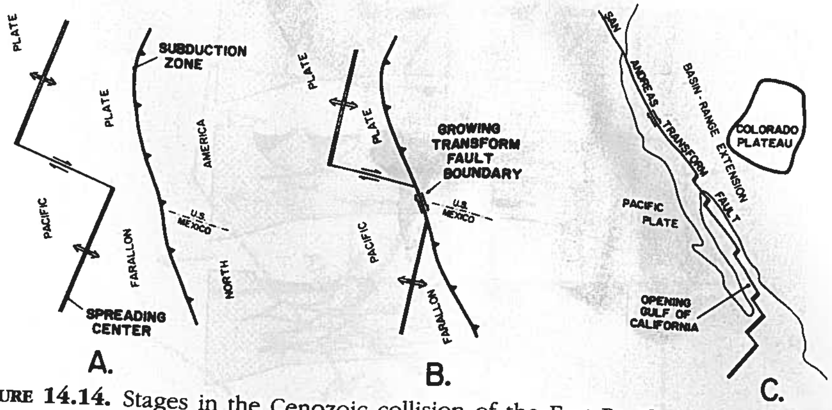

**FIGURE 14.14.** Stages in the Cenozoic collision of the East Pacific spreading center and Farallon subduction zone, western North America. (a) Spreading center and subduction zone converge during Early Tertiary time. (b) Spreading center begins to subduct near U.S.–Mexican border in Late Oligocene time, and interplate motion is accommodated along transform fault that grows north and south at continental margin as Farallon plate continues to subduct. (c) Remaining part of Farallon plate subducts between Late Oligocene and Late Miocene time, resulting in annihilation of both the spreading center and subduction zone; interplate motion accommodated by San Andreas transform fault beginning in Pliocene time and continuing to present.

The Pacific–Farallon ridge and the Farallon–American trench obliquely converged upon each other near the border of the United States and Mexico during Late Oligocene time. The result was annihilation of the ridge and trench at the point of contact, along with the mechanical substitution of right-lateral transform faulting along the area of contact. The transform fault progressively grew northward and southward as the trench-ridge system continued to converge. Transform faulting successively stepped inboard onto the continent during this period. The San Andreas fault emerged as the principal transform fault along the plate boundary near the beginning of Pliocene time. These events caused the cessation of subduction, eventual termination of arc magmatism, and widespread extensional tectonism in the region bordering the San Andreas fault. The result was wholesale extension within the Basin–Range during Late Oligocene through Middle Miocene time, along with east–west opening of the Rio Grande rift beginning in Late Oligocene time (Fig. 14.1).

The major phase of Basin–Range extension along the lower Colorado River area began in Late Oligocene time, considerably earlier than the first surface manifestations of normal faulting on the Colorado Plateau. Detachment faulting in the Whipple Mountains was characterized by east–northeast-dipping, low-angle faults in which the upper plate glided down slope to the northeast on an unextended lower plate (Davis et al. 1980). Similar extension also may have begun at middle and lower crustal levels under the southwestern part of the Colorado Plateau during this period.

Speculations regarding Late Oligocene–Late Miocene extension at deep crustal levels under the plateau and at shallower levels in the Basin–Range ap-

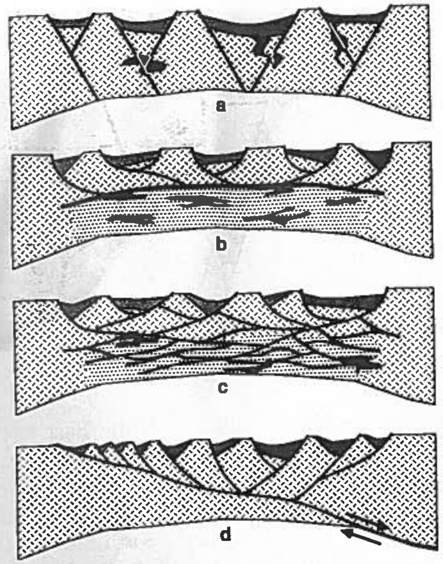

**Figure 14.15.** Summary of models used to explain extension in the Basin–Range Province west and southwest of the Colorado Plateau, Arizona (a) Classic horst-graben model. (b) Subhorizonal decoupling zone model. (c) Shear zone bounded lens model. (d) Crustal penetrating shear model. Either models c or d could have produced crustal thinning and subsidence along the southwestern Colorado Plateau in Late Oligocene–Early Miocene time. (From Allmendinger et al. 1987, Fig. 7.)

pear to be served best by invoking either a gently northeasterly dipping, crustal-penetrating normal fault or slip between shear-bounded lenses, respectively illustrated in Fig. 14.15c and 14.15d. Either allows for: (1) tectonic thinning of the crust under the western part of the plateau from about 25 to 19 miles (40 to 30 km), (2) slight down-to-the-southwest subsidence of the southwestern corner of the plateau, (3) structural differentiation of the plateau from the Basin–Range in Miocene time, and (4) progressive tectonic erosion of the southwestern and western edges of the plateau. Motion of the Colorado Plateau had to include a slight clockwise rotation of 2 to 4 degrees owing to the southward widening of the Rio Grande rift (Fig. 14.16). Extrusion of lower plate rocks from under the western part of the plateau possibly accompanied rotation. Thus the Colorado Plateau was rotating into extensional space created within the Basin–Range Province at all crustal levels.

Figure 14.17 illustrates that northwest-striking blocks calving off the thin, trailing edge of the plateau could account for tectonic erosion of its western and southwestern margins. The upper plate blocks now comprise the Hualapai, Cerbat, Juniper, Aquarius, and Peacock ranges. These northeasterly tilted mountain blocks probably rest in tectonic contact on lower plate rocks, such as observed in the Whipple Mountains.

By Miocene time, the upper part of the crust along the western margin of the Colorado Plateau was undergoing the first significant crustal extension to affect the surface since late Precambrian time. By about mid-Pliocene time, the Grand Canyon region began to experience east–west extension that first caused down-to-the-west normal faulting along many of the Laramide monoclines; and,

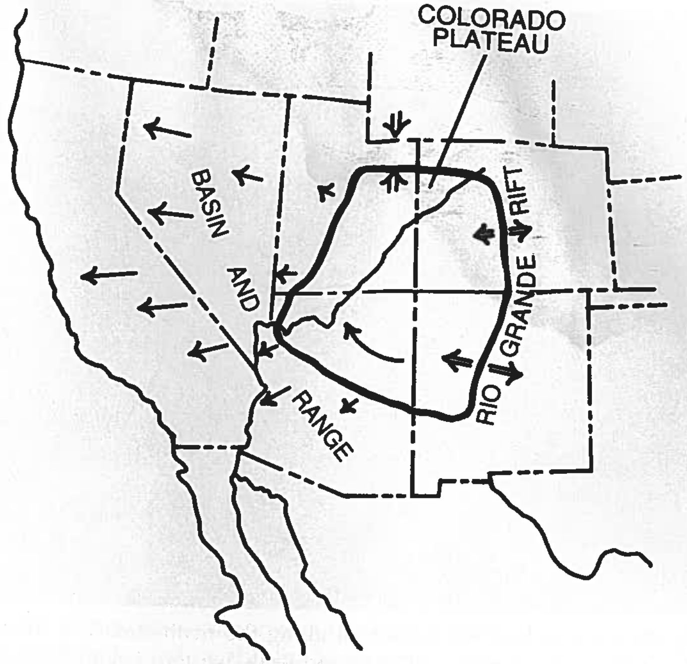

**Figure 14.16.** Clockwise rotation of the Colorado Plateau into extensional space created in the Basin–Range during Late Oligocene–Early Miocene time. Arrows in the Basin–Range schematically illustrate that all rocks within the province moved away from the Colorado Plateau at rates which increased to the west as the crust within the Basin–Range simultaneously extended.

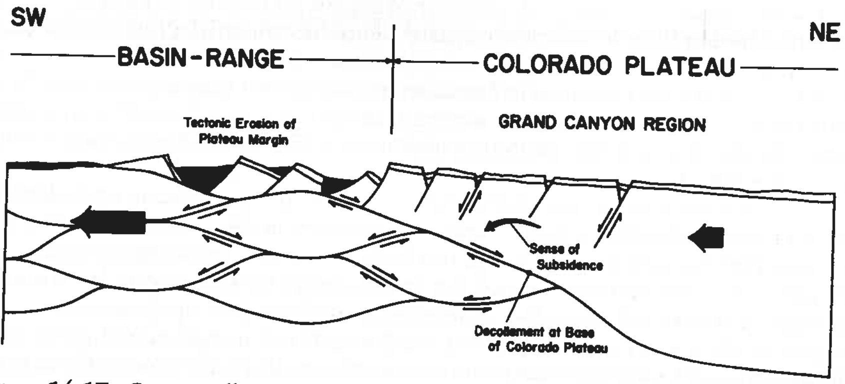

**Figure 14.17.** Cartoon illustrating tectonic erosion and subsidence along the southwestern edge of the Colorado Plateau over extending shear-bounded lenses in Late Oligocene–Early Miocene time. Lens concept from Hamilton (1982). Heavy arrows show absolute motions within the Basin–Range and Colorado Plateau provinces. Fine arrows show relative motions between shear surfaces. Notice that the motion between the lenses causes the crust to both thin and lengthen. Vertical scale greatly exaggerated, particularly at top.

**Figure 14.18.** View toward the northeast along the main strand of the Late Cenozoic Hurricane fault from the top of Diamond Peak, western Grand Canyon, Arizona. Arrows point to the Cambrian Tapeats Sandstone on the respective sides of the fault. The east (right)-dipping Laramide Hurricane monocline is not developed in this reach.

more recently, the onset of internal fragmentation of the intervening blocks by normal faulting coupled with the development of extensional basins.

## Age of Onset of Faulting

Definitive timing for the inception of late Cenozoic normal faulting in the eastern Grand Canyon has eluded researchers because Tertiary sedimentary and volcanic rocks that could be used to bracket the onset of faulting are missing. More information is available from the western Grand Canyon, where Tertiary rocks such as those shown in Fig. 14.18 provide insights. Figure 14.19 summarizes what is now known.

The earliest Cenozoic normal faulting occurred along the listric west-dipping Grand Wash fault, which is the western boundary of the Colorado Plateau in Arizona. The maximum offset along the fault in the vicinity of the mouth of the Grand Canyon has been estimated by Lucchitta (1979, Fig. 13) to be down to the west 10,000 ft (3000 m). Downdropping, accompanied by down-to-the-east rotation of the western block, created the Grand Wash trough, which filled with the Miocene and younger clastic and evaporite rocks of the informally named Rocks of the Grand Wash Trough (Billingsley et al. in press). It appears that the initial faulting was synchronous with the latter part of the major phase of Basin-Range extension to the southwest, which Hamilton (1982) assigned to Late Oligocene through Late Miocene time. Young and Brennan (1974) observed that eruption of the ~18.5-million-year-old Peach Springs Tuff predated most of the offset along the southern part of the fault. They based their findings on slight pre-tuff, southwestern-facing scarp development along the fault, and the fact that the tuff is tilted on ranges comprising the hanging wall blocks to the west that were later partially buried by the Rocks of the Grand Wash Trough. Therefore, major movement occurred along the fault after eruption of the tuff, but prior to deposition of the upper part of the Rocks of the Grand Wash Trough. These relationships bracket the major offset within Middle Miocene-Late Miocene time, findings consistent with those of Faulds et al. (1997) for the similar Red Lake basin, which is the next structural basin along the Grand Wash fault to the south.

**Figure 14.19.** Two down-to-the-west, Late Cenozoic normal faults sever the east (left)-dipping Lone Mountain monocline south of Parashant Canyon (foreground), western Grand Canyon, Arizona. Faulted surface is the top of the Permian Esplanade Sandstone.

Young minor displacements along the fault appear to account for some of the folding of the Miocene–Pliocene Hualapai Limestone, as well as for minor faulting of a gravel deposit located 3.5 miles (5.5 km) south of the Diamond Bar Ranch (Lucchitta 1967) and scarps in the alluvium north of Lake Mead in the vicinity of Grand Gulch and Squaw canyons (G.H. Billingsley, personal communication, 2000).

The Hurricane fault is the southern, waning extension of the Wasatch fault, which in Utah comprises the physiographic boundary between the Colorado Plateau and Basin-Range Province. The maximum offset across the Hurricane fault zone in the Grand Canyon is in excess of 2600 feet (800 m) at Three Springs Canyon.

Billingsley (2000) found that basalts dated at about 3.5 million years in the Mt. Trumbull–Bundyville area north of the Grand Canyon rest on the same erosion surface developed on Chinle strata on either side of the fault, allowing him to conclude that the offsets along the Hurricane and Toroweap faults are younger than 3.5 million years in the Grand Canyon region. The implications of this are profound because it reveals that the major Cenozoic faults observed in the western Grand Canyon largely, if not totally, postdate erosion of the canyon.

Based on the scanty data available in the Grand Canyon region, it appears that normal faulting is migrating eastward into the Colorado Plateau with time. The record for this is well-documented in south central Utah (Rowley et al. 1981). Jackson (1990) supports this view by making the case that activity along the younger faults, such as the Toroweap fault, is waxing whereas activity along the faults to the west is waning.

**FIGURE 14.20.** Two prominent Late Cenozoic normal faults offset the Permian Esplanade Sandstone down to the northeast. These faults comprise the southwestern boundary of a graben and occur four miles southeast of the mouth of Whitmore Canyon, western Grand Canyon, Arizona.

**FIGURE 14.21.** Quaternary basalt (right of cone) and alluvium displaced down to the west along the Toroweap fault in Prospect Valley south of the Colorado River, western Grand Canyon, Arizona. Notice that the offset of the basalt is greater than that of the alluvium. View is toward the southeast.

## Normal Faulting Along Preexisting Monoclines

The strain resulting from Pliocene to recent east–west extension in the Grand Canyon region was first accommodated along reactivated Precambrian faults such as the Hurricane fault (Fig. 14.18). Normal faults severed the Laramide monoclines, displacing the west block down opposite to Laramide downfolding to the east (Fig. 14.19). This produced continuous faulting along most of the monoclines lying west of the East Kaibab monocline. Prominent local northwest, north, and northeast fault trends developed, reflecting local trends along the reactivated basement faults. The faults in the western Grand Canyon propagated laterally beyond the ends of the Laramide monoclines as extension continued, a situation that is well-expressed along the southern part of the Hurricane fault and various segments of the Toroweap fault.

New faults developed in the rocks adjacent to the reactivated basement faults as extension progressed (Huntoon et al. 1981). In some locations, the faults are arranged in two, or even three, intersecting sets and break the surface into a mosaic of fault-bounded blocks. Each of the sets contains conjugate faults that converge downward, thus producing numerous grabens (Fig. 14.20). The net effect is east–west lengthening as well as vertical thinning of the Paleozoic section, culminating in the development of extensional sag basins in the most densely faulted areas. The presence of numerous faults with different orientations allowed the Paleozoic rocks to deform without significant tilting of many of the fault-bounded blocks. This style of deformation has been treated theoretically by Reches (1978a) and is well-exposed along the Hurricane fault zone where a predominance of dip-slip displacement is revealed by near vertical slickenlines (Hamblin 1965).

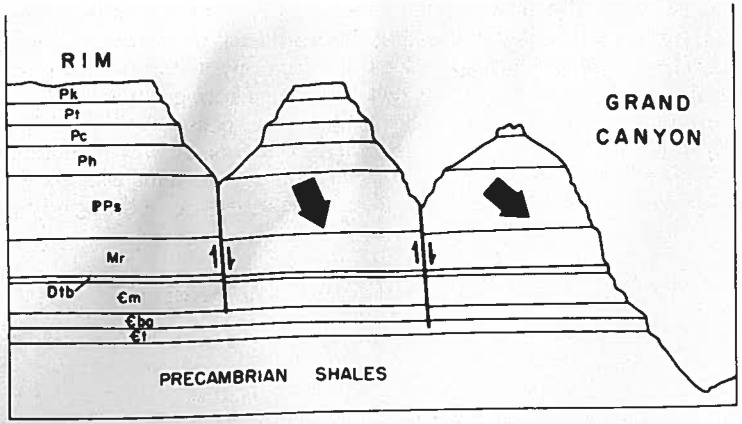

**FIGURE 14.22.** High-angle gravity faults develop across a ridge between deep canyons as the buttes settle into the ductile Bright Angel Shale, Grand Canyon, Arizona. Pk, Kaibab Formation; Pt, Toroweap Formation; Pc, Coconino Sandstone; Ph, Hermit Shale; IPPs, Supai Group; Mr, Redwall Limestone; Dtb, Temple Butte Formation; Cm, Muav Limestone; Cba, Bright Angel Shale; Ct, Tapeats Sandstone.

## Subsidiary Faults and Extensional Basins

Continued extension has resulted in the emplacement of several laterally extensive faults internal to the blocks lying between the Laramide monoclines. Some of these, such as the Bright Angel fault in the eastern Grand Canyon, were produced by reactivation of Precambrian faults that had not been reactivated during Laramide compression (Huntoon and Sears 1975). Others undoubtedly are the result of new faulting within the extending basement rocks.

Basins caused by densely spaced intersecting faults have developed in areas where extension has been particularly great. Some occur along the major reactivated fault zones such as the area between the Toroweap and Hurricane faults along the Colorado River, as well as along the Hurricane fault zone in the area centered on Parashant Canyon (Huntoon et al. 1981). Closely spaced faulting in the latter area has progressed sufficiently to create a 10-mile (16-km)-diameter structural basin with approximately 600 feet (180 m) of structural closure. Evidence that development of these basins is geologically young is the fact that incision of the canyon has not kept pace with subsidence so the Colorado River does not flow on bedrock across them, but rather on late Tertiary and younger sediments.

Two notable extensional basins occur interior to the blocks between the reactivate Laramide fault zones: (1) the 320 square miles or 320 miles$^2$ (820 square kilometers or 820 km$^2$) north-trending Blue Springs basin with about 1000 feet (300 m) of closure centered around Blue Springs in the Little Colorado Canyon (Cooley et al. 1969, Plate 1) and (2) the more than 600 square miles or 600 miles$^2$ (1500 square kilometers or 1500 km$^2$) Markham fault zone in Cataract basin. The high-angle normal faults allowing for subsidence in the Blue Springs area are exceptionally well-exposed in three dimensions in the Little Colorado gorge.

The predominately northwest trending faults in the Markam fault zone are intersected by a few northeast-trending grabens. In addition, a cluster of northwest-trending normal faults, most down to the west, also occurs at Rose Well Camp, 10 miles (16 km) to the west of the Markam fault zone. The youthfulness of both the Markham and Rose Well faulting is revealed by closed topography and active sedimentation along the downthrown sides of many of the faults. The Kaibab bedrock along one of the faults crossing the northeastward flowing Rogers Wash in the Rose Well zone is offset up to the north, thereby damming the channel and producing somewhat more than 30 feet (10 m) of topographic closure at Sink Tank. The total offset across the fault could not be measured owing to burial of the downthrown southern block by modern sediments. However, neither recent sedimentation south of the fault nor incision of the resistant Kaibab Formation north of the fault has kept pace with subsidence of the downdropped block.

## Increased Fault Densities with Depth

Fault densities in the Paleozoic section increase with depth within the major fault zones. Excellent examples of this can be observed in the Hurricane, Toroweap, and Eminence zones (Huntoon et al. 1981, 1996). This geometry implies that the subsidiary faults propagated upward from shallow levels within the upper part of the Precambrian basement or, in some cases, from the brittle lower Paleozoic carbonate section. The displacements along individual faults attenuate with elevation in the Paleozoic section through ductile deformation within the Pennsylvanian and Permian sediments.

## Extensional Sag

Infolding toward faults of the Paleozoic strata in the hanging wall is a common feature along many large-displacement normal faults in the region. This phenomenon has been called reverse drag. It occurs along faults in which the dip of the fault surface decreases with depth. The cause is creation of space as the hanging-wall block pulls away from the footwall block. The space fills by infolding of the strata from the hanging wall. The phenomenon is well-developed along the Bright Angel fault at Grand Canyon Village. In this case, the dip of the fault surface is 70 degrees in the Paleozoic section, which contrasts with 60 degrees on the reactivated part of the fault in the Precambrian basement.

Similarly, the dips of the folded strata in the hanging wall of a faulted monocline become progressively accentuated as extension continues. Here also, the cause is a fault surface along which the dip diminishes with depth (Fig. 14.5C). Hamblin (1965) demonstrated that successive Cenozoic lava flows that cross the Hurricane monocline are each less steeply infolded than those below. It is clear, therefore, that the degree of infolding is proportional to the amount of displacement across the fault.

The distinction between a faulted monocline and a fault exhibiting reverse drag is that in the case of the faulted monoclines, the strata in the footwall are upturned toward the fault. If the dips in the hanging wall block are appreciably greater than those in the upturned footwall block, extensional sag has taken place along the faulted monocline.

## Recurrent Faulting

The most spectacularly exposed and complete records of late Cenozoic faulting in the Grand Canyon region occur along the Hurricane and Toroweap faults. The resolution of the number and timing of Pliocene and Quaternary displacements is constrained only by the number of such young rock units deposited across the faults. Highlights from outcrops along the Hurricane fault near Whit-

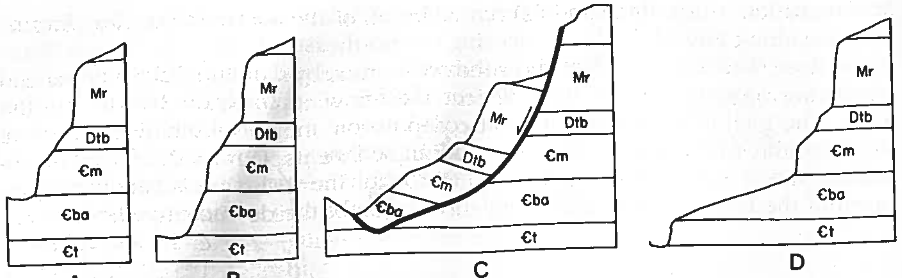

**FIGURE 14.23.** Stabilization of a Redwall cliff profile through detachment of a rotational slide, Grand Canyon, Arizona. (a) Channel floor has not exposed the ductile Bright Angel Shale so cliff profile is stable. (b) The channel has begun to cut into the Bright Angel Shale; and as it deepens, the shale slope is too steep to buttress the load of the cliff. (c) The rocks comprising the Redwall cliff fail. (d) Erosion of debris results in stable cliff profile. Mr, Redwall Limestone; Dtb, Temple Butte Formation; Cm, Muav Limestone; Cba, Bright Angel Shale; Ct, Tapeats Sandstone.

more Wash serve to illustrate the quality of the record. The Paleozoic rocks are offset approximately 1000 feet (300 m), whereas older Pleistocene basalt flows that fill an old channel of Whitmore Wash to a depth of about 600 feet (180 m) are displaced only 75 feet (23 m). A slightly eroded scarp in Whitmore Wash extends 8 miles (13 km) north from the Colorado River and offsets by 50 feet (15 m) a stage IV Pleistocene basalt flow that cascaded into the canyon from the east. The same scarp also displaces younger alluvium by only 15 feet (5 m). With only these four units, we are able to bracket a minimum of four faulting events. Fenton (1998), using cosmogenic dating, has expanded these findings and constrained the timing of specific increments of displacement along both the Hurricane and Toroweap faults.

Scarps in Pleistocene(?) alluvium along the Aubrey, Toroweap (Fig. 14.21), and Hurricane faults demonstrate Quaternary activity in the western Grand Canyon region. Some of this activity is Holocene (Jackson, 1990). Holm (1987) presents evidence for Quaternary faulting at the northeastern edge of the San Francisco volcanic field immediately to the southeast of the Grand Canyon. Although Holocene offsets have not been proven in that area, Akers et al. (1962) found a fresh scarp in a Quaternary gravel that they suspected might be Holocene in age.

## Disruption of Drainage

The western margin of the Colorado Plateau is demarcated by the west-facing Grand Wash fault scarp from the area north of the Utah state line southward around the entire Hualapai Plateau to a terminus south of the Cottonwood Mountains. Displacement was sufficient to sever the northward flow of streams across that province boundary by late Early Miocene time. Young and Brennan (1974) place the timing of final drainage disruption at about the time the Peach Springs Tuff erupted. Their interpretation is based on the fact that sediments preserved above the tuff on the Hualapai Plateau do not contain clasts derived from the region south of the plateau. Severing of the northward flowing streams across the Mogollon escarpment took place as early as Oligocene time in the region south and east of the eastern Grand Canyon (Peirce et al. 1979). Two other processes operated to further disrupt these streams from crossing onto the Colorado Plateau: (1) extensional subsidence and fragmentation of the headlands in the Basin and Range Province and (2) partial burial of the southern plateau margins by Miocene volcanics.

Concurrent subsidence of the southwestern margin of the Colorado Plateau allowed for eventual establishment of the west-flowing Colorado River across the region in earliest Pliocene time following deposition of the Miocene–Early Pliocene Hualapai Limestone in the Grand Wash trough. One popular model for establishment of the modern Colorado River through the Grand Canyon is headword erosion of a gully from the Grand Wash cliffs across the Kaibab Plateau where it captured the ancestral Colorado River (Hunt 1969; Lucchitta, Chapter 15, this volume). This mid-Tertiary river, for which no trace exists, was postulated to exit the plateau to the southeast of the Grand Canyon region or to have ponded in Miocene Lake Bidahochi playa in northeastern Arizona, prior to capture.

An emerging, alternative model is that as the late Cenozoic climate got wetter, the Colorado River prograded southwestward from its source in the Rocky Mountains by filling the basins before it with sediments and overtopping their lowest margin. A modern analogue is the recent downstream progradation of the Mohave River which has become integrated across several formerly isolated structural basins in eastern California, and which now discharges into Death Valley. Upon reaching the Grand Canyon region, the Colorado River reoccupied a Laramide canyon already superimposed across the Kaibab and Uinkaret plateaus, and it prograded westward through structural and topographic lows on the old Laramide erosion surface lying just south of the Laramide Mogollon escarpment in the western part of the canyon. Regardless of how the Colorado River got here, the first sediments from it did not reach the Grand Wash Trough until Pliocene time. It excavated the Grand Canyon to within 50 feet (15 m) of its present depth by early Pleistocene time (McKee et al. 1968).

## Near-Surface Structural Localization of Volcanism

Basalts ranging in age from Late Miocene through Holocene erupted through vents on the plateaus immediately adjacent to the Grand Canyon. Best and Brimhall (1970) note the following relationships between volcanism and structure on the Uinkaret Plateau. (1) Normal faulting and volcanism have operated simultaneously throughout most of Late Cenozoic time, although the inception of faulting predates basaltic volcanism. (2) A shift in fault activity from the Grand Wash to the Hurricane–Toroweap zones has been paralleled in time by an eastward shift in volcanism. (3) Vents throughout the region lie between fault lines and are independent of them with but a few exceptions. (4) Many of the basalts carry mantle-derived peridotite inclusions, indicating that the magma originated from the upper mantle. Dutton (1882) and Koons (1945) observed the tendency for cones on the Uinkaret Plateau to align parallel to faults but to occur in the areas between them. For example, the Hancock Knolls are comprised of 11 centers in a 9-mile (14-km) alignment 6 miles (10 km) west of, and parallel to, the Supai monocline and fault. Three Pleistocene basalt plugs form a second parallel alignment in exposures on the Esplanade bench 2 miles west of the Supai monocline.

Deeply eroded outcrops of dike swarms on or below the Esplanade surface in the central and western Grand Canyon indicate that the dikes are localized along fractures and minor faults that parallel nearby normal faults. For example, a small dike swarm exposed in the inner gorge between two plugs in the alignment 2 miles west of the Supai monocline reveals that extensional fissures deep in the Paleozoic section served as feeders to the discontinuously spaced plugs higher in the section. Other examples include (a) dike swarms a mile west of the Hurricane fault and south of the mouth of Whitmore Canyon and (b) another swarm in the walls of Tincanebitts and Dry canyons. The fact that vents do not preferentially occur along the principal late Cenozoic faults indicates that, in general, upward movement of magma was independent of the faults at great depths. Rather, the dikes and vents tended to localize on extended fractures in the Paleozoic section in close proximity to the surface. The parallelism between the intruded fractures and nearby faults implies that late Cenozoic extension either created or opened the fractures.

## MODERN GEOPHYSICAL SETTING

Although the Grand Canyon is situated on the western edge of the Colorado Plateau physiographic province, the modern geophysical properties of the crust under it appear to be transitional in character between those of the stable interior of the plateau and the extending Basin–Range Province to the west. For example, the thickness of the crust is 25 miles (40 km) or more under most of the plateau, but the crust tapers to about 19 miles (30 km) thick from the easternmost Grand Canyon to the Grand Wash fault (Smith 1978). The crust is only 15 miles (24 km) thick in southern Nevada and western Utah.

Heat flow through the plateau interior typically is 1.5 heat flow units (1 heat flow unit = $10^{-6}$ calorie/centimeter-second), but from east to west across the Grand Canyon it rises to two units (Blackwell 1978). Increased heat flow in the western Grand Canyon appears to be substantiated by a warming of groundwater discharged from springs west of Kanab Canyon. Temperatures of waters from springs in the lower Paleozoic section in the eastern Grand Canyon range from 50°F to 73°F, whereas those sampled from the same rocks to the west range from 64°F to 86°F (Loughlin and Huntoon 1983).

The intermountain seismic belt coincides with the crustal transition zone between the Basin–Range and Colorado Plateau provinces. The seismic belt is characterized by high seismicity and tectonic extension. Seismicity associated with it extends as far east as the West Kaibab fault zone (Smith and Sbar 1974). Fault plane solutions for earthquakes within the belt in southern Utah reveal that east–west extension is occurring and that focal depths are shallow, most at depths of less than 10 miles (16 km). The faults have steep dips, and motion on them tends to be near vertical. Smith and Sbar (1974) report that an earthquake on November 11, 1971, near the Hurricane fault north of Cedar City, Utah, produced three north-trending fractures in alluvium. The longest exhibited horizontal east–west extension and could be traced for half a mile. Focal depths during the quake were from near surface to slightly over a mile (1.6 km) deep.

Citing a combination of seismic refraction, reflection, low resistivity, and pressure wave velocity data, Keller et al. (1975) postulated and the presence of a mantle upwarp that occupies a band at least 50 miles (80 km) wide under the transition zone. The upwarp extends approximately 30 miles (50 km) eastward under the Colorado Plateau. Its eastern limit appears to correlate with a lateral change in crustal magnetization reported by Shuey et al. (1973).

The coincidence between the postulated mantle upwarp and the intermountain seismic belt led Keller et al. (1975) to speculate:

> The presence of the upper crustal low-velocity layer may be related to the mechanism of Cenozoic faulting and seismicity. Thus the presence of (a low-velocity layer) east of the Wasatch front could provide an explanation for the presence of Cenozoic block faulting east of the province boundary. The shallow seismicity characteristic of the intermountain seismic belt also extends east of the Wasatch front and is roughly coincident with the easternmost zone of Cenozoic normal faulting.

Late Cenozoic basaltic volcanism also characterizes much of this same region, a finding that is consistent with extensional tectonics.

## GRAVITY TECTONIC STRUCTURES

The extreme topographic relief of the Grand Canyon produces huge stress gradients within the canyon walls. The associated failure of the rocks yields valley anticlines, high-angle gravity faults, and rotational landslides that are unrelated to deep-seated processes. The rates of motion involved in the development of these structures is probably almost imperceptible in human terms. All classes of structures discussed here are actively forming someplace in the canyon now.

### Valley Anticlines

A valley anticline whose axis parallels the Colorado River is present between Fishtail and Parashant canyons. Identical valley anticlines also occur in the principal tributary canyons to this sixty-mile reach including Kanab and Tuckup canyons. The coincident trends of the sinuous anticlines and the canyons reveal a genetic link between the two. Huntoon and Elston (1980) deduced that the anticlines formed by lateral flowage of the saturated shaly parts of the Cambrian Muav Limestone and underlying Bright Angel Shale from under the canyon walls. The floor of the canyon arches up in response to the compression across it. The huge lithostatic load under the 2100-foot (640-m) canyon walls drives the flowage (Sturgul and Grinshpan 1975).

The limbs of the typical valley anticline dip away from the canyon at angles of up to 60 degrees, and the folding extends over 800 feet (270 m) into the canyon walls. Numerous sets of minor, low-angle, conjugate thrust faults parallel the axis of the anticline in the Muav Limestone. The intersecting thrusts dip both toward and away from the river, and they are particularly numerous and have larger offsets where the Muav Limestone is steeply folded. However, they occur in beds dipping as little as two degrees. The thrusts serve to thicken and shorten the beds in the floor of the canyon perpendicular to the trend of the river.

### Gravity Faults

High-angle gravity faults occur across narrow ridges between deep canyons in which the Bright Angel Shale is exposed. They represent brittle failure of the rocks overlying the shale as those rocks founder above the ductile shale (Fig. 14.22). The faults are steeply dipping to near vertical, and displacements die out with depth. They do not penetrate below the Bright Angel Shale.

This class of faults is important in the morphologic evolution of canyon scenery. Once formed, erosion proceeds along them, segmenting what was formerly a ridge between two canyons into a chain of buttes. As erosion continues, the buttes segregate and, ironically, the faults vanish.

**Figure 14.24.** Former channel of the Colorado River that was blocked by a Pliocene(?) rotational slide that fell from the south side of Cogswell Butte (right), Grand Canyon, Arizona. View is downstream.

## Rotational Slides

Rotational slides are a most important factor in canyon widening. As shown in Fig. 14.23, they are massive blocks or rows of blocks that detach from the canyon wall and glide into the canyon. The detachment surface is an upward-facing concave normal fault. As the block glides toward the canyon, it rotates backward against the curved fault surface.

There are two common settings for rotational slides in the Grand Canyon. The largest failures involve the Redwall cliff inclusive of the Cambrian Bright Angel Shale upward through the Permian Esplanade Sandstone. This section is commonly 1600 feet (490 m) or more thick. Smaller rotational slides involve the 250- to 400-foot (75- to 120-m)-thick Cambrian Tapeats Sandstone that detaches above the ductile Precambrian Galeros Formation in the eastern Grand Canyon.

The cliffs fail because oversteepened slopes on the shales do not provide sufficient buttressing to support the lithostatic loads under the cliff when the Colorado River or its tributaries first incise into the shale. Huge tiers of blocks calve off the canyon wall until the slope on the shale is wide enough to support the rocks above it. Huntoon (1975) proposed that a stable canyon profile is attained through a series of catastrophic rotational slides shortly after the shale is exhumed. The unusually large setback of the north rim along the east side of the Walhalla Plateau in the eastern Grand Canyon was caused by progressive calving of the rocks above the Galeros Formation. Those cliffs have retreated almost to the western margin of the Galeros substrate.

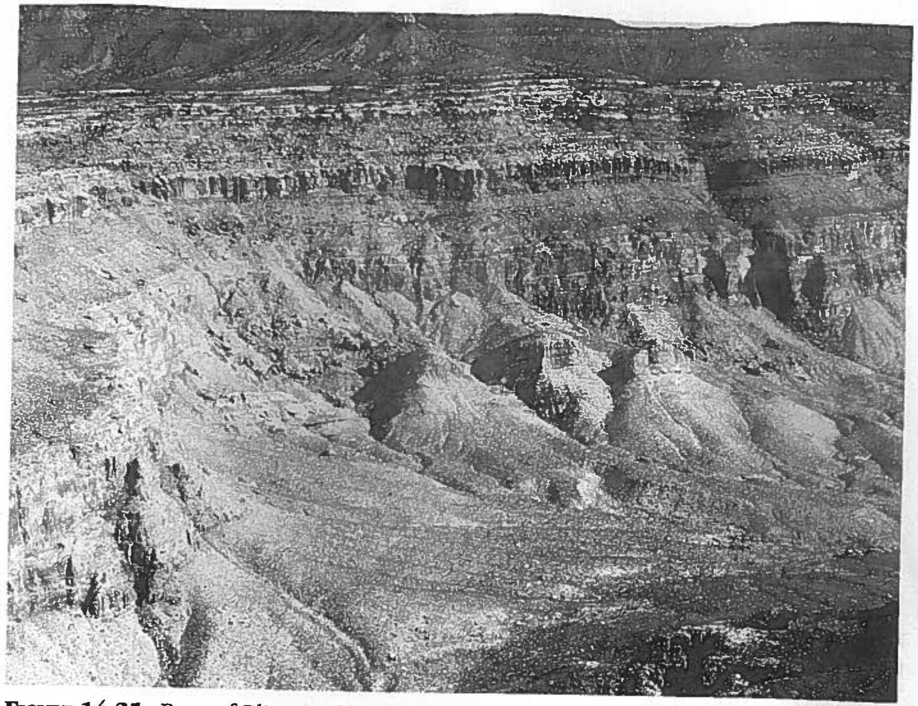

**Figure 14.25.** Row of Pliocene(?) rotational slide blocks that detached from the Redwall cliff, Surprise Valley, Grand Canyon, Arizona. A second, closer row is buried by alluvium in the center of the valley.

Spectacular examples of geologically young rotational slides involving failure of the Redwall cliff line the Colorado River between Deer and Fishtail canyons. A tier of huge blocks calved off the north wall and completely filled a one-mile reach of the Colorado channel. The blockage displaced the river 0.3 miles (0.5 km) to the south where it cut a parallel channel. The elevation of the blocked channel is the same as the modern channel attesting to the youth of the slide. Sediments ponded in the temporary lake behind the slide are preserved in thick deposits on the south side of the river two miles upstream from Deer Canyon.

A much older rotational slide off the south side of Cogswell Butte blocked the Colorado River halfway between Deer and Tapeats canyons. The buried channel there lies 210 feet (70 m) above the modern river (Fig. 14.24). The river carved the narrows to the south as it bypassed this blockage. Similarly, an even older slide from the south wall preserves a remnant of the Colorado channel lying 540 feet (175 m) above current river level upstream from Tapeats creek.

The courses of tributaries were also buried and displaced by equally large rotational slides. Paleochannels at the mouth of Deer Canyon record that the

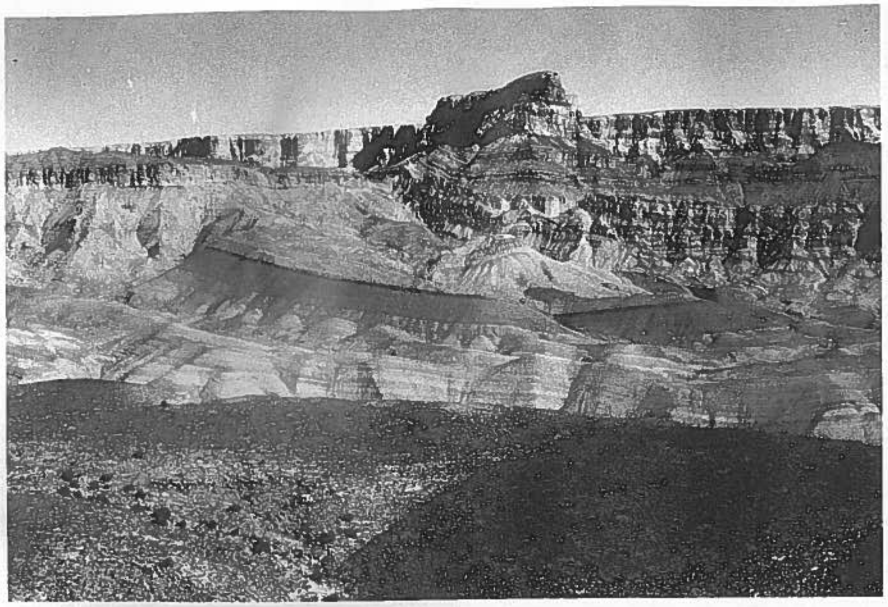

**Figure 14.26.** Carbon Butte, the small left-dipping butte in the center, detached from the ridge to the left and glided one mile down a valley tailing in its wake blocks of Tapeats Sandstone torn from its base, eastern Grand Canyon, Arizona. View is toward the northeast, with Chuar Butte in the background.

stream was first displaced west by a slide off the west side of Cogswell Butte, then east by a slide from the west side of Deer Canyon. The scenic narrow slot behind the falls at the mouth of the Deer Canyon which lies between the older paleochannels is the most recent displaced position of the creek.

The oldest slides occur in Surprise Valley, which contains two or more rows of huge rotational blocks (Fig. 14.25), some which displaced the mouth of Tapeats Canyon to the east. The buried paleochannel of Tapeats Canyon lies about 900 feet (290 m) above the Colorado River. The fact that this channel remnant lies one-fifth of the depth of the Grand Canyon above the modern canyon floor hints at the great antiquity of that slide. The paleochannel could date from Tertiary time.

Large, young rotational slides are common in the western Grand Canyon downstream from Whitmore Wash. The most notable is a 1.2-mile-long detachment from the west that blocked the Colorado River near 205-Mile Canyon. It displaced the river eastward along its entire length.

Carbon Butte is the farthest traveled rotational slide block in the Grand Canyon (Ford et al. 1970). The butte (Fig. 14.26) includes rocks from the Bright Angel Shale up through the Redwall Limestone, and it occupies a position between the east and west forks of Carbon Canyon in the eastern Grand Canyon. The butte detached from the Redwall cliff on a listric fault bottoming between the Cambrian Tapeats Sandstone and the underlying Kwagunt Formation. The mass slid southward, trailing behind it large chucks of Tapeats Sandstone torn from its base. The block came to rest one mile (1.6 km) and 1800 feet (550 m) below its starting point. The track it followed was a valley eroded on resistant Precambrian strata along the south-plunging axis of a Precambrian syncline.

# POSTSCRIPT

Late Precambrian time in the Grand Canyon region was characterized by erosional beveling across an uplifted, block-faulted mountainous terrane produced by extensional tectonism. That same stress regime has been reimposed on the region. The outcome is fairly well assured. The plateaus surrounding the Grand Canyon will continue to fragment by extensional faulting. Erosion will continue to wash the elevated rocks to the sea. The canyon will gradually disappear. Someday the seas will return and deposit new rocks here. Perhaps Ecclesiastes (1:9) said it best: "The thing that hath been, it is that which shall be; and that which is done is that which shall be done: and there is no new thing under the sun."