NATURAL REGIONS OF THE UNITED STATES AND CANADA

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Cover design from a photograph by John S. Shelton.

The photograph shows an aerial view of compound alluvial fans, east side of Death Valley, California.

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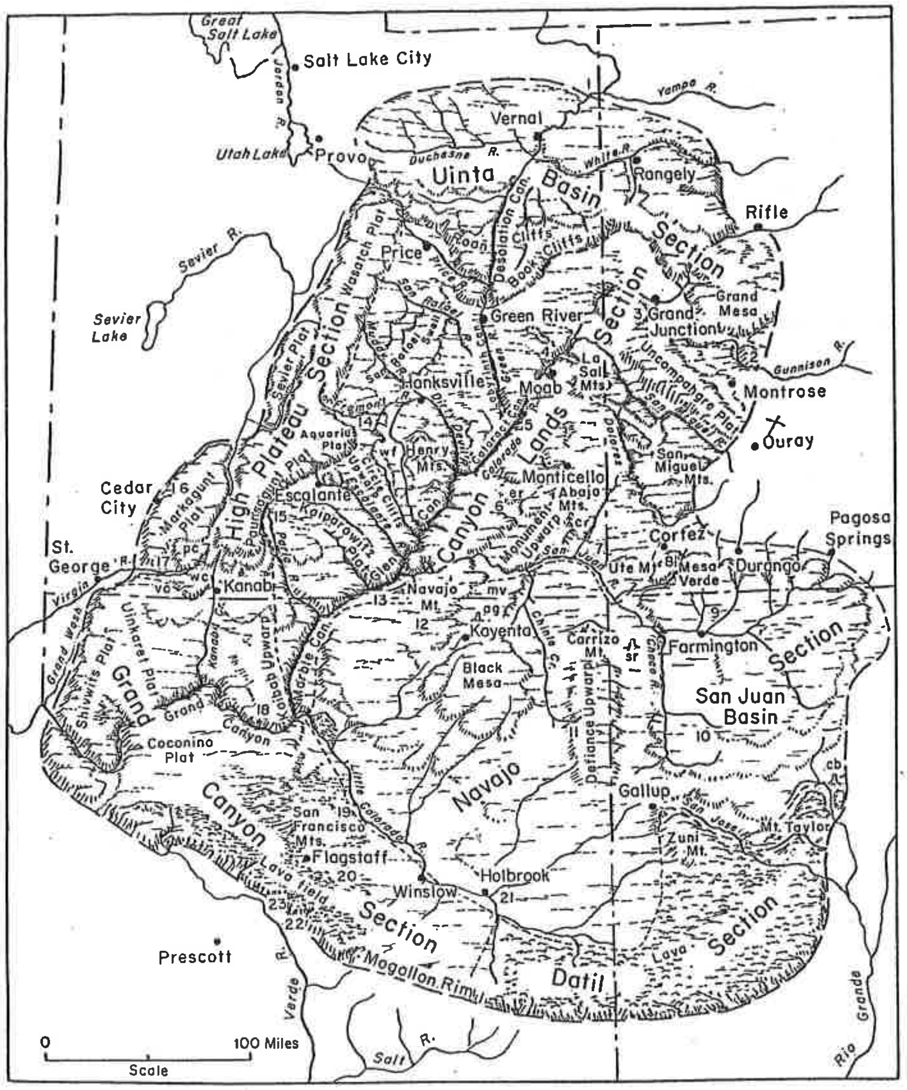
COLORADO PLATEAU—LAND OF COLORS AND CANYONS

The Colorado Plateau (Fig. 15.1), covering about 130,000 square miles between the Rocky Mountain and Basin and Range provinces, is easily the most colorful part of the United States. It is not just desert; it is Painted Desert with spectacular canyons, high plateaus, volcanic mountains, sand deserts, and shale deserts with grotesque badlands. And along the canyon walls are cross sections of geologic history. These geologic features may be seen in more than a dozen national parks and monuments created expressly for the purpose. It is an area of unusual archeological interest too, and another dozen national parks and monuments protect some of the better known examples of the cliff dwellings and other ruins of the prehistoric Anasazi, ancestors of the Pueblo Indians. Those of special geomorphic, geologic, or archeologic interest are indicated in Figure 15.1. In addition to these there are national recreational areas along the Colorado River at Lake Mead, which extends into the lower part of Grand Canyon, and at Lake Powell in Glen Canyon. Two national monuments of historical interest are El Moro (Inscription Rock) and Pipe Spring.

Outstanding physiographic features of the Colorado Plateau are its:

1. Structural geology, which consists of
   A. extensive areas of nearly horizontal sedimentary formations;
   B. structural upwarps that form striking topographic features;
   C. igneous structures, including some large central-type volcanoes, numerous cinder cones and volcanic necks, high lava-capped plateaus and mesas, and dome mountains caused by intrusion of stocks and laccoliths;
   D. and the whole plateau uplifted as much as 3 miles since the Cretaceous.
2. Great altitude; the general plateau surface is higher than 5,000 feet; some plateaus and several peaks reach to 11,000 feet.
3. Drainage system, which is deeply incised and forming steep-walled canyons, most of which have brilliantly colored walls.
4. Aridity and shortage of water.
5. Extensive areas of bare rock.



National Parks and Monuments

1. Dinosaur Nat. Mon.
2. Black Canyon of the Gunnison Nat. Mon.
3. Colorado Nat. Mon.
4. Arches Nat. Mon.
5. Canyonlands Nat. Park
6. Natural Bridges Nat. Mon.
7. Hovenweep Nat. Mon.
8. Mesaverde Nat. Park
9. Aztec Ruins Nat. Mon.
10. Chaco Canyon Nat. Mon.
11. Canyon de Chelly Nat. Mon.
12. Navajo Nat. Mon. (Betatakin and Kiet Seel)
13. Rainbow Bridge Nat. Mon.
14. Capitol Reef Nat. Mon.
15. Bryce Canyon Nat. Park
16. Cedar Breaks Nat. Mon.
17. Zion Nat. Park
18. Grand Canyon Nat. Park
19. Wupatki and Sunset Crater Nat. Mons.
20. Walnut Canyon Nat. Mon.
21. Petrified Forest and Painted Desert Nat. Mon.
22. Montezuma Castle Nat. Mon.
23. Tuzigoot Nat. Mon.

Escarpments at South End of High Plateaus

pc Pink Cliffs
wc White Cliffs
vc Vermilion Cliffs

Other Prominent Features

wf Waterpocket Fold
er Elk Ridge
cr Comb Ridge
mv Monument Valley
ag Agathla Peak
sr Shiprock
cb Cabezon Peak

Figure 15.1 *Physiographic map of the Colorado Plateau.*

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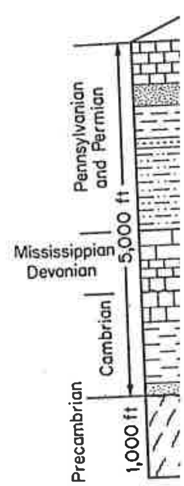

Figure 15.2 *Blo*
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6. Sparse vegetation and sparse population (about a half million, an average of about four persons per square mile).

7. Brightly colored and highly varied desert scenery.

Structural Framework

The Colorado Plateau consists of the part of the continent's stable platform that lies west of the Southern Rocky Mountains; the western edge of the Plateau coincides with the ancient flexure along which the platform ended and the basement rocks plunged downward under the late Precambrian, Paleozoic, and early Mesozoic geosynclines from which the Basin and Range Province evolved. The Plateau marks the western edge of the Upper Cretaceous trough, or geosyncline, whose axis was along the site of the Southern Rocky Mountains; the western shore of the Upper Cretaceous sea was at or near the western edge of what is now the Plateau.

This major break in the continental structure is not difficult to see. Grand Canyon, for example, exposes the entire section, only 4,000 feet thick, of Cambrian to Permian epicontinental marine formations that were deposited on the platform (Fig. 15.2). To considerable degree the thickness of this section is typical of the platform all the way eastward to the Appalachian Plateau. Yet just to the west, in the broken-up Basin and Range Province, these formations greatly thicken, and so do the late Precambrian and early Mesozoic formations. At Death Valley the late Precambrian, Paleozoic, and Triassic formations total almost 100,000 feet in thickness.

From the Appalachian geosyncline westward to the Colorado Plateau, the Precambrian basement rocks have formed a stable platform for the Paleozoic and younger formations. This platform was interrupted only by the trough of the Upper Cretaceous geosyncline that crossed it obliquely at the site of the Southern Rocky Mountains. The platform had been stable for about 500 million

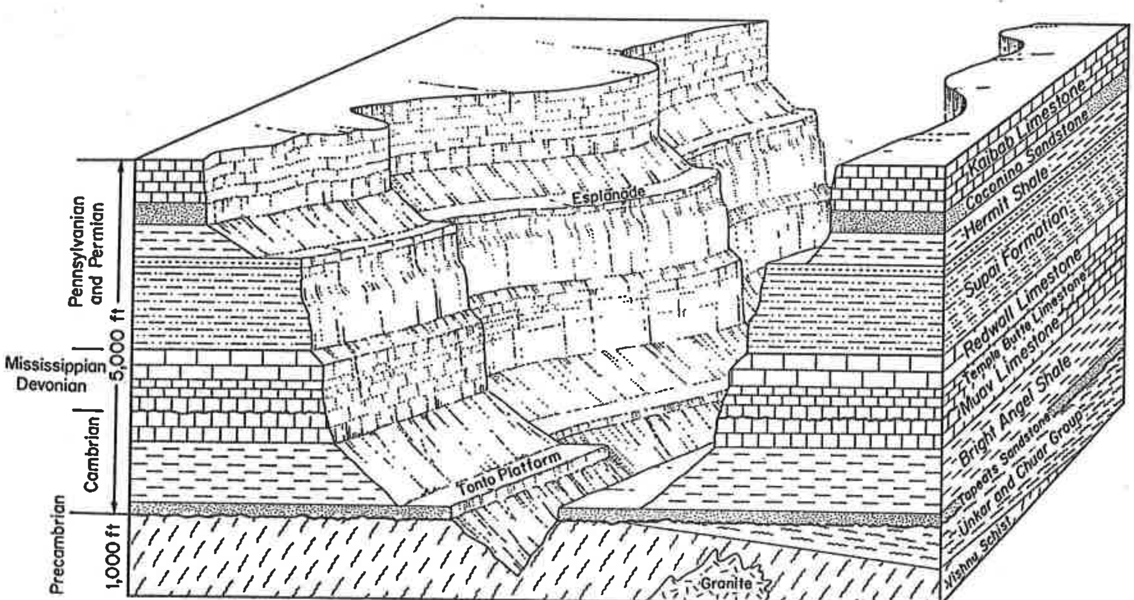

Figure 15.2 *Block diagram illustrating the formations in the Grand Canyon. Vertical scale exaggerated; the canyon is a mile deep, and the rims are 10 to 12 miles apart. In addition to the downcutting of about a mile at the canyon, a thickness of about 2 miles of Triassic, Jurassic, and Cretaceous rocks have been eroded from above the Kaibab Limestone.*

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Figure 15.3 *Geol*
[From U.S.G.S. P

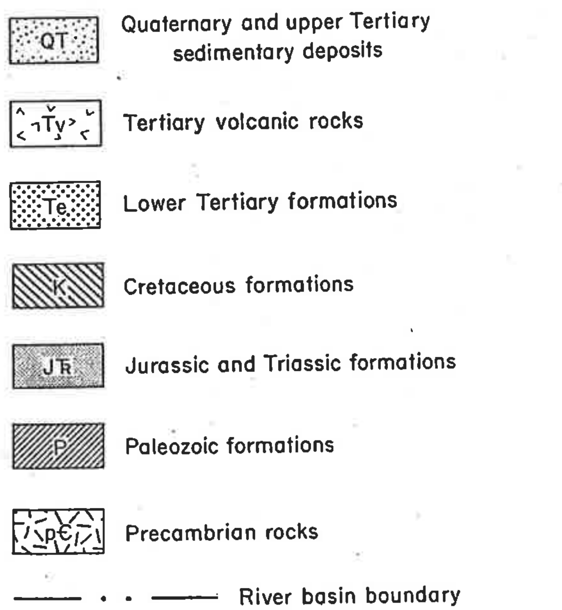

Figure 15.3 *Geologic map of the Colorado Plateau. [From U.S.G.S. Prof. Paper 669.]*

years during the Paleozoic and early Mesozoic. Moreover, the Precambrian rocks exposed in the Colorado Rockies include extensive areas of granitic batholiths like those on the Canadian Shield, whereas under the Colorado Plateau the Precambrian includes a high percentage of geosynclinal sedimentary rocks, as in the Northern and Middle Rockies. Apparently during the late Precambrian a northerly trending trough or geosyncline developed at about 45 degrees to those that had formed on the Shield and around it. The east edge of this old geosyncline extended southward across what is now the Colorado Plateau; its eastern boundary may have played a part in controlling the position of the boundary between the Colorado Plateau and the Southern Rocky Mountains.

The Colorado Plateau has the general structure of a stack of saucers, tilted toward the northeast. Curiously, the plateau adjoins the Rocky Mountains along the low northeastern part of the structure. As a consequence of this structure, young rocks (Tertiary) crop out in basins on the north and east sides of the plateau, and old rocks (Paleozoic and Precambrian) crop out along the southwest rim (Fig. 15.3), overlooking the much lower Basin and Range Province. The formations are listed and described in Table 15.1.

Although the major structural elements that define the Colorado Plateau are inherited from ancient Cretaceous and older continental structures, the Plateau itself is the product of Cenozoic earth movements and igneous activity. The Plateau and the Southern Rocky Mountains are the high part of a tremendous Cenozoic arch—a geanticline that extends from the central United States westward nearly to the Pacific Coast. The Great Basin, a block-faulted area, is the collapsed western flank of the arch. The Colorado Plateau is a mildly faulted segment of this flank that remains structurally attached to the Rocky Mountain geanticline. This Cenozoic history is summarized on pages 440 to 445. We look next at the structural units that were developed during that history and at the topographic effects that have been produced by the accompanying erosion.

Table 15.1

Geological Formations on the Colorado Plateau

System	*Series*	*Lithology and Thickness*
Tertiary	Holocene	Alluvium, colluvium, sand dunes; mostly less than 50 feet thick.
	Pleistocene	Glacial moraines, outwash, terrace gravels, alluvium; periglacial deposits, avalanche deposits; mostly less than 100 feet thick.
	Pliocene	Bidahochi Formation (Little Colorado River valley): playa and fluviatile deposits of calcareous clay and sand with tuff and interbedded lavas, 400 feet thick; *conglomerate in Castle Valley,* at foot of LaSal Mountains, 1,000 feet; Bishop Conglomerate and Browns Park Formation: north side of Uinta Basin, fluviatile deposits (Miocene or Pliocene), 1,500 feet thick; Sevier River and Parunuweap Formations, in High Plateaus Section, conglomerate and lacustrine or alluvial silt mixed with volcanics. 200 feet; age uncertain; *gravel on Kaibito Plateau,* Navajo Reservation, may be late Miocene, gravel deposited by ancestral San Juan River, 50 feet; Datil Formation, in the Datil Section, interbedded volcanics and sandstone 2,000 feet thick, age uncertain.
	Miocene	Muddy Creek Formation: fill in ancient canyon at Peach Springs, Arizona, interbedded fluviatile sediments and volcanics, dated at 18.3 million years, more than 100 feet at that locality but much thicker westward in Basin and Range Province; Brian Head Formation, in High Plateaus, limestone, volcanic ash, and volcanic agglomerate, 500 to 1,000 feet thick, age uncertain; Chuska Sandstone, eastern Navajo Reservation, 700 feet, age uncertain. Gravel on Mogollon Rim.
	Oligocene	Duchesne River Formation: Uinta Basin, playa deposits grading to fanglomerate, may be late Eocene.
	Eocene	In Uinta Basin: Uinta Formation: fluviatile deposit 1,000 feet thick. Bridger Formation: fluviatile deposit like Uinta, 1,000 feet. Green River Formation: oil shale and other lake deposits, 3,000 feet. Colton and Wasatch Formations: fluviatile deposits that grade laterally to lake beds of the Green River formation, 2,000 feet.
	Paleocene	Flagstaff Limestone, Wasatch Plateau, lacustrine limestone, 1,000 feet thick; Tuscher Formation and Ohio Creek Conglomerate, conglomeratic sandstone in eastern part of Uinta Basin, 400 feet thick; upper part of North Horn Formation (see below); Nacimiento Formation in San Juan Basin, fluviatile beds of brown conglomerate interbedded with red and gray shale, 1,000 feet.
Upper Cretaceous		In High Plateaus and Western Uinta Basin: North Horn Formation: lower part (see above): fluviatile and lacustrine deposits of shale, sandstone, conglomerate, and limestone, 2,000 feet. In San Juan Basin: Animas Formation: fluviatile conglomerate overlain by shale and sandstone, high proportion of volcanic material, 2,000 feet. Ojo Alamo Sandstone: cross-bedded conglomeratic sandstone, 100 feet. McDermott Formation: lenticular shale, sandstone, and conglomerate containing much volcanic debris, 300 feet.

System
Upper Cretaceous (*Continued*)
Jurassic
Triassic

System	Series	Lithology and Thickness
Upper Cretaceous (*Continued*)		In San Juan Basin: (*Continued*) Fruitland Formation and Kirtland Shale: deltaic deposits of sandstone, shale, and coal, increasing shale upward, 1,300 feet. Pictured Cliffs Sandstone: littoral sandstone, 250 feet. Lewis Shale: mostly marine shale, 1,500 feet, thins southward by basal beds grading to Mesaverde Formation. Mesaverde Formation: deltaic, littoral, and coastal plain deposits of sandstone, shale, and coal, 1,000 feet, upper and lower parts grade northward to marine shale. Mancos Shale: marine shale, 2,000 feet thick in north, thins southward by intertonguing with Mesaverde Formation. Dakota Sandstone: littoral sand 100 feet thick. In Canyonlands Section, High Plateaus, and Uinta Basin: Mesaverde Formation: deltaic, littoral, and coastal plain deposits, 2,500 feet thick, grades eastward to marine shale. Mancos Shale: mostly marine shale but includes tongues of deltaic and littoral deposits that grade eastward to marine shale, 4,000 feet thick. Dakota Sandstone: littoral sandstone, 100 feet thick.
Jurassic		Morrison Formation: fluviatile deposits of clay and shale, variegated, sandstone, conglomerate, and locally gypsum and limestone, 500 feet. San Rafael Group: Summerville Formation: evenly bedded, reddish brown sandstone and sandy shale, 250 feet, estuarine (?). Curtis Formation: marine, evenly bedded gray sandstone and shaly sandstone, 200 feet. Entrada Sandstone: thick bedded, cross-bedded buff sandstone, thinner bedded and earthy northward, 500 feet. Carmel Formation: thin-bedded red sandstone, shaly sandstone and shale, thin limestone and locally thick beds of gypsum, 500 feet.
Triassic		Glen Canyon Group: Navajo Sandstone: tan to light gray, massive cross bedded sandstone, eolian (?), 600 feet; may be Jurassic. Kayenta Formation: sandstone and shaly sandstone, minor amounts of red shale and green clay, fluviatile (?), 300 feet. Wingate Sandstone: massive, cross-bedded, cliff-forming sandstone, 300 feet. Chinle Formation: variegated sandstone, shale, limestone, and conglomerate, well-bedded but beds lenticular, 500 feet. Shinarump Conglomerate: cross-bedded sandstone and conglomerate, much petrified wood, 100 feet. Moenkopi Formation: red and buff sandstone and red shale, some limestone, abundant ripple marks, 600 feet.

(Continued)

Table 15.1 *(Continued)*

System	*Series*	*Lithology and Thickness*	
		Southwest sequence	*Northeast sequence*
Permian		Kaibab Limestone: white buff and light gray limestone and limy sandstone, 800 feet. Coconino Sandstone: light colored sandstone, 300 feet. Hermit Shale: red beds, 400 feet.	Cutler Formation: bright red sandstone and lighter red or pink grit and conglomerate alternating with sandy shale or sandy limestone, generally about 1,000 feet.
Pennsylvanian		Supai Formation: red sandstone and shale, 1,000 feet; upper part Permian.	Rico Formation: dark maroon sandstone, and conglomerate alternating with sandy shale and sandy limestone, 300 feet. Hermosa Formation: shale, limestone, evaporites, generally about 2,500 feet but in salt anticlines thickens to 14,000 feet. Molas Formation: red calcareous shale, limestone, 100 feet.
Mississippian		Redwall Limestone: bluish gray crystalline limestone, 600 feet.	Pre-Pennsylvanian Paleozoic rocks, 2,000 feet.
Devonian		Temple Butte Limestone: purple and cream colored limestone and sandstone, 100 feet.	
Cambrian		Tonto Group: Muav Limestone: mottled limestone, 450 feet. Bright Angel Shale: marine shale, 375 feet. Tapeats Sandstone: brown slabby crossbedded sandstone, 275 feet.	
Precambrian		Grand Canyon Series: Chuar Group, sandstone, shale, basalt, minor limestone, 5,000 feet. Unkar Group, quartzite, shale, limestone, conglomerate, 2,500 feet. - - - - - - - - Unconformity - - - - - - - - Vishnu Series, schist, quartzite, and metavolcanics, 25,000 feet.	

STRUCTURAL AND TOPOGRAPHIC UNITS

GRAND CANYON SECTION. The high southwest part of the Colorado Plateau is called the Grand Canyon Section. The oldest rocks there are complexly deformed Precambrian formations. These are overlain by about 4,000 feet of Paleozoic formations. The Precambrian and Paleozoic formations (Table 15.1) are exposed in the Grand Canyon (Fig. 15.2) and along the southwestern edge of the Plateau. The topography of Grand Canyon is illustrated in Figures 15.4 and 15.5.

The western part of the Grand Canyon Section is divided into a series of blocks by the northerly trending Grand Wash, Hurricane, and Sevier faults (Fig. 15.6). Along each of these faults

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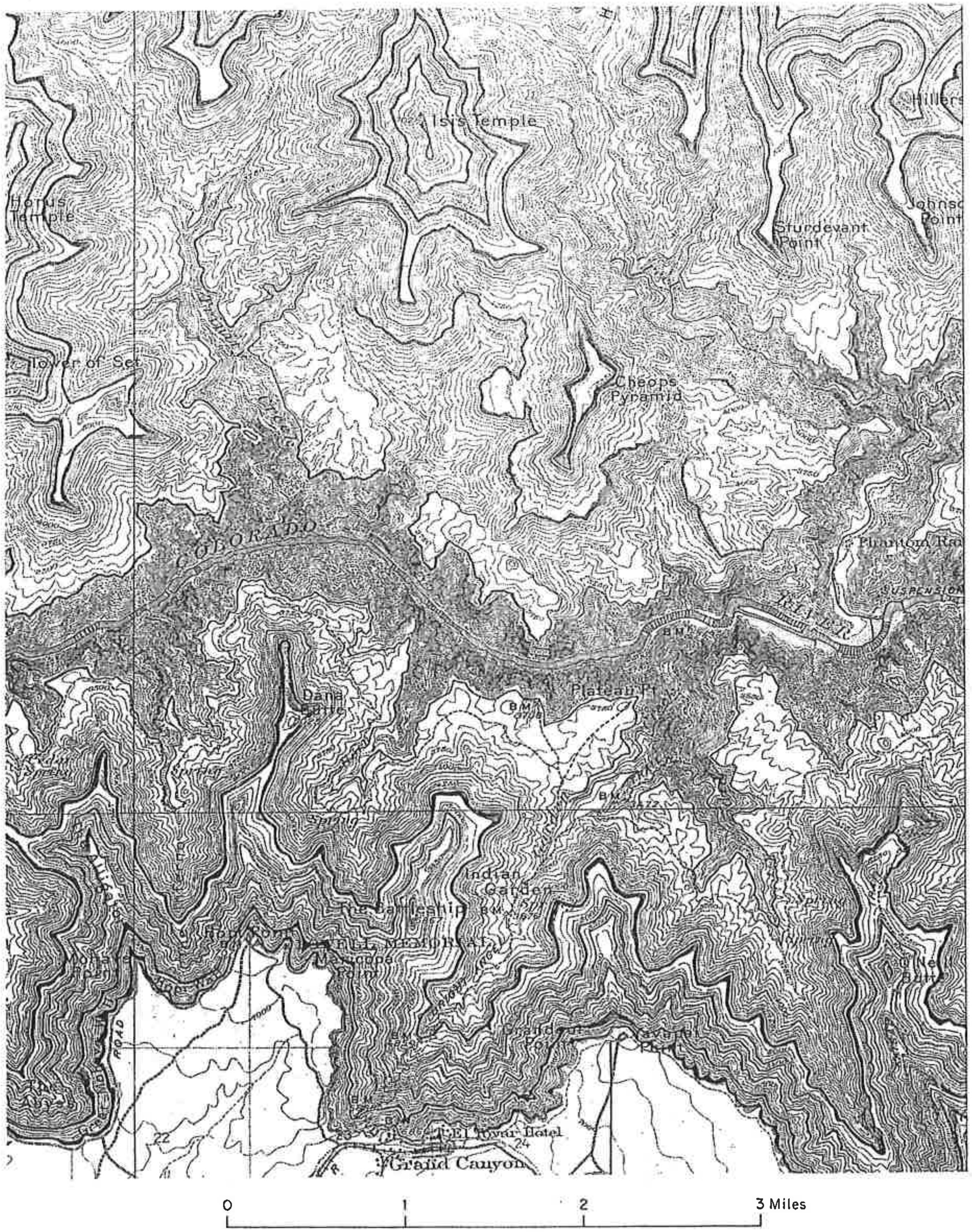

Figure 15.4 *Topographic map of Grand Canyon.* [From *U.S.G.S.*]

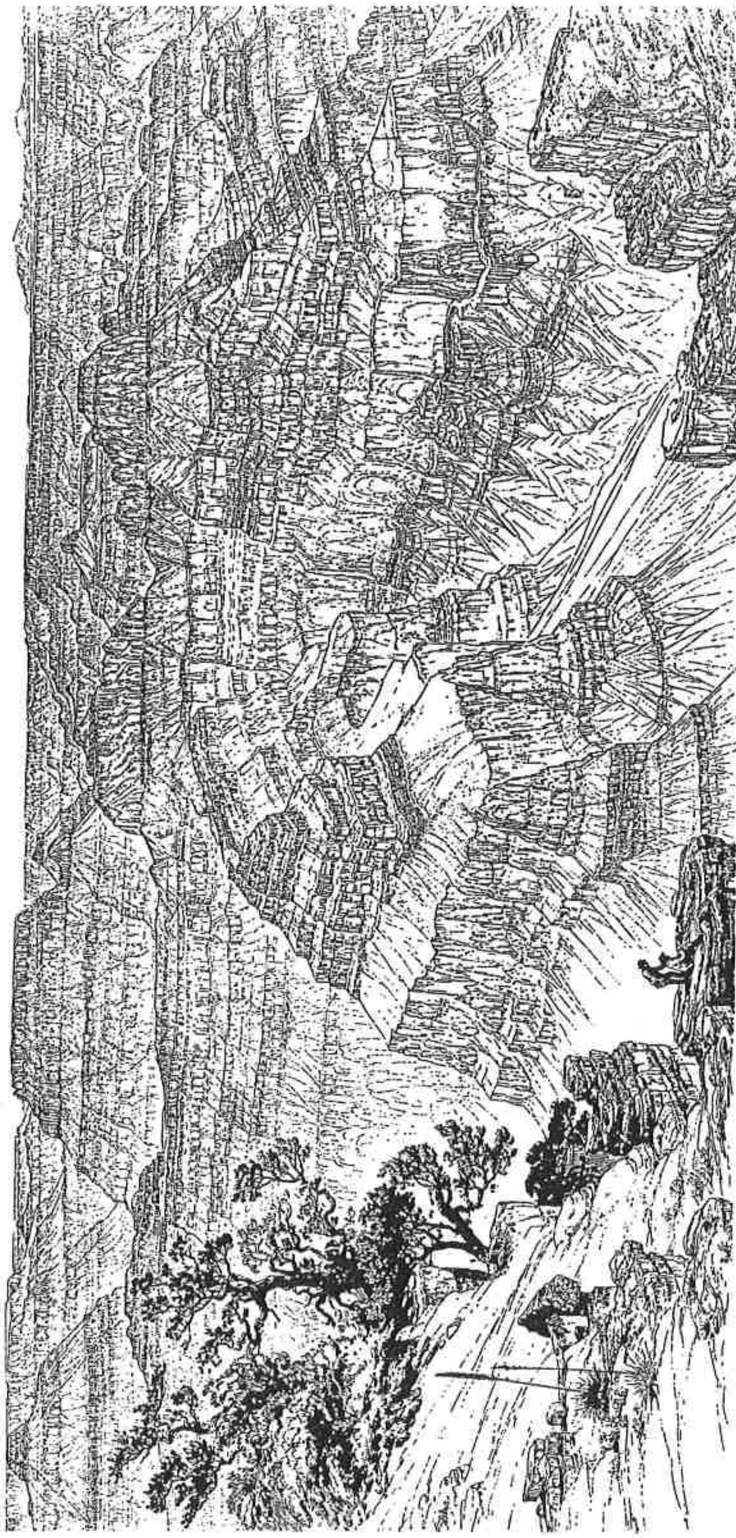

Figure 15.5 Powell's antecedent Colorado River in Grand Canyon, as seen from Point Sublime, looking east. The sketch is by W. H. Holmes, whose artistic ability for drawing landscapes realistically and showing their geology accurately was appreciated and encouraged by Powell, who provided opportunity for Holmes to use his great talent.

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the blocks to the west have dropped downward relative to the blocks to the east. This structure is transitional between the Colorado Plateau, which in general is little faulted, and the much-faulted Basin and Range Province.

In general, the formations in these fault blocks and those farther east dip northeastward, but about 75 miles from the rim, the northeast dip is interrupted by the Kaibab Plateau (Fig. 15.6) Upwarp, one of several upwarps that characterize the Colorado Plateau. These upwarps are asymmetric anticlines with gently dipping west flanks and steeply dipping east flanks. They represent a mile or more of vertical structural displacement. These folds may be the surface expression of faults deep in the crust.

About a third of the Grand Canyon Section is covered by Tertiary and Quaternary lavas from the San Francisco Mountain volcanic field and from some isolated volcanoes north of Grand Canyon. These lavas unconformably overlie Paleozoic and later formations, which had been faulted, folded, tilted northeastward, and exposed by erosion long before the earliest lavas (Tertiary) were erupted. Enough time elapsed after the deformation and before the eruptions to permit the removal by erosion of thousands of feet of Mesozoic formations that once extended across this part of the Colorado Plateau.

The ancestral river had already cut deeply into Grand Canyon by the time the first lavas were erupted, and some of the later lavas poured down the walls and into the bottom of Grand Canyon. Radiometric dating of the lavas indicates that the Grand Canyon was within 50 feet of its present depth about 1.5 million years ago.

One of the most recent eruptions on the Colorado Plateau took place in about the middle of the eleventh century A.D. at Sunset Crater, east of San Francisco Mountain. Volcanic cinders from the eruption buried a Pueblo Indian village very much in the way that Vesuvius buried Pompeii.

DATIL SECTION. The south rim of the Colorado Plateau in New Mexico and eastern Arizona is known as the Datil Section (Fig. 15.1), an extensive area covered by thick lavas. The earliest lavas there probably are of middle Tertiary age, but the volcanism continued intermittently into Holocene times. One Late Pleistocene or Holocene lava flow in the San Jose Valley is so fresh that it still looks hot. Santa Fe Railroad conductors tell yarns about being on the last train through before the lava covered the tracks!

Principal structural features in this section are the upwarp at the Zuni Mountains, the large central-type volcano at Mount Taylor, the numerous smaller volcanic centers and volcanic necks (Fig. 15.7) around it, and the extensive lava-covered mesas and valleys to the south. The lavas at Mount Taylor, among the oldest in this section, unconformably overlap the tilted formations on the southern flank of the San Juan Basin. The folding, much older than the volcanism, is early Tertiary in age.

Erosion of the high mesas has, in some places, exposed natural cross sections of the lavas, the volcanic cones, and the feeder vents (Fig. 15.7,A). Elsewhere, continued erosion has completely exposed and isolated the plugs that filled the vents to form volcanic necks (Fig. 15.7,B). The surface onto which these lavas erupted was about 2,000 feet higher than the present surface; thus the surface there has been lowered that much by erosion since the earliest volcanism in that area.

These lavas extend southward into the Basin and Range Province, and consequently that boundary of the Colorado Plateau is arbitrary. Along the eastern edge of the Datil Section, the Basin and Range Province extends northward along the Rio Grande depression to the Southern Rocky Mountains, and the boundary between this depression and the uplifted Colorado Plateau is sharply defined by the westernmost faults of the depression.

NAVAJO SECTION. North of the Grand Canyon and Datil Sections is a structural depression referred to as the Navajo Section, about half of which is in the Navajo Indian Reservation. The deepest part of the depression, the San Juan Basin, forms an embayment in the southwest

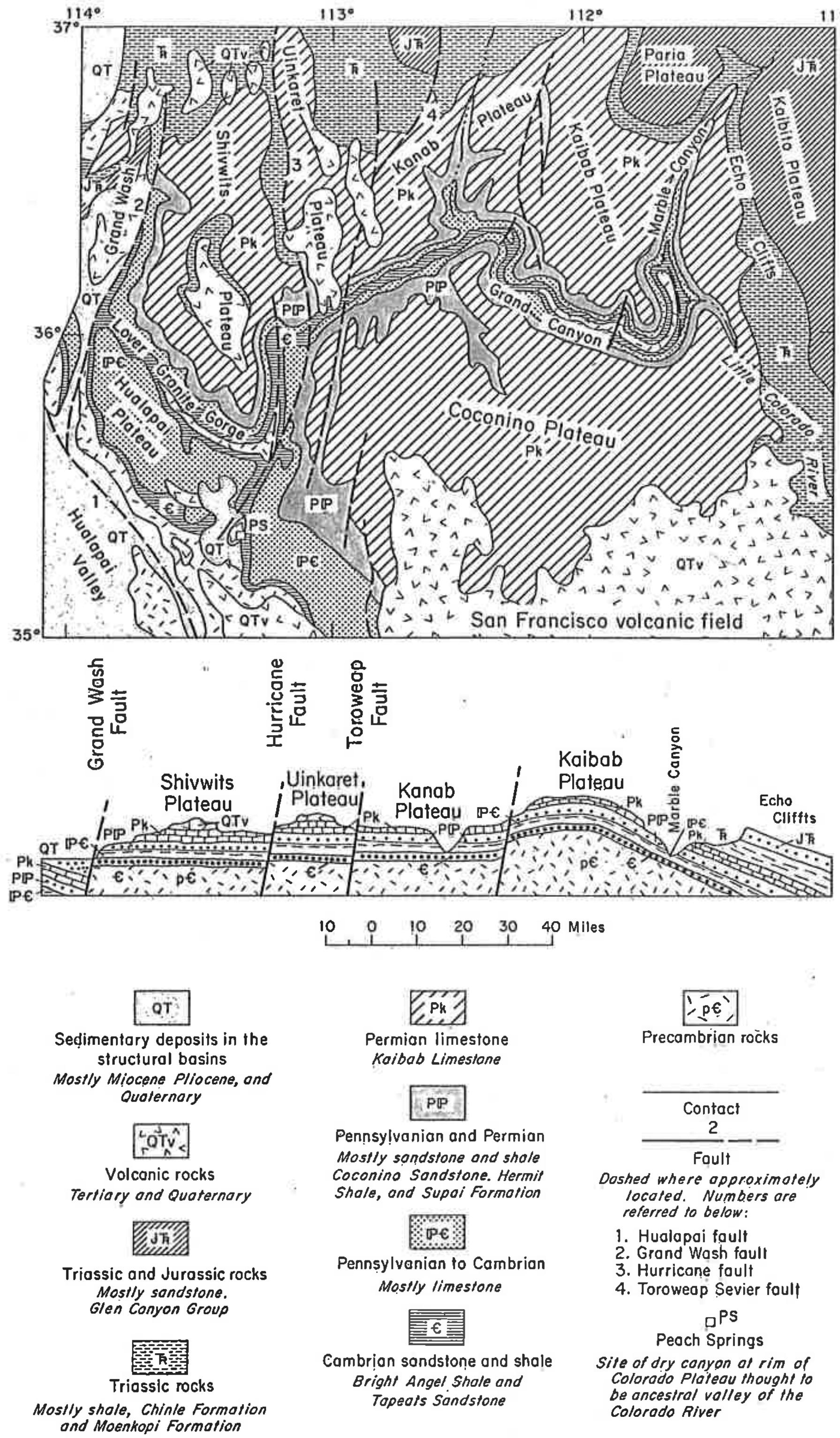

Figure 15.6 *Geologic map and cross section at Grand Canyon. [From U.S.G.S. Prof. Paper 669.]*


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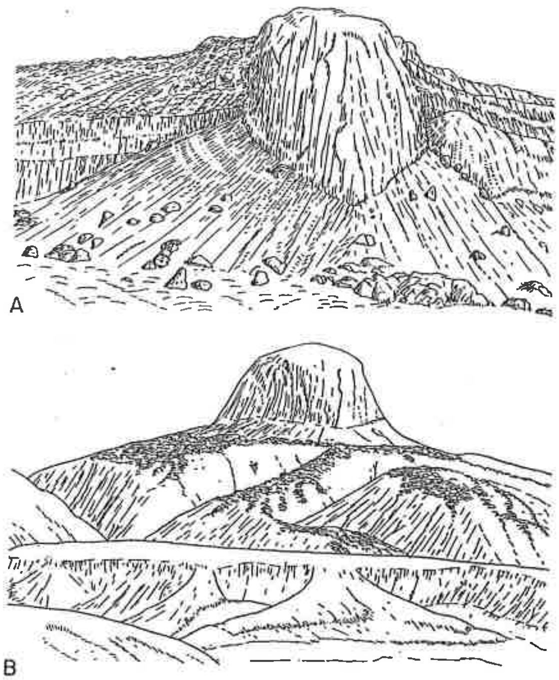


Figure 15.7 *(A) Natural cross section of a volcano and of the vent feeding it near Mount Taylor, New Mexico. The half-exposed plug in the vent is 500 feet in diameter and about 1,000 feet high. A cone 400 feet high was built at the surface, and lava flows extend 7½ miles from it. (B) Volcanic neck (Cabezon Peak), also near Mount Taylor. This neck is 2,000 feet in diameter. The benches below are formed by Cretaceous sedimentary formations. The volcanic cone and lava flows have been completely removed by erosion from this volcanic center, and only the plug remains.*

corner of the Southern Rocky Mountains. Structurally, this basin is more than two miles lower than the rim of the Plateau at the southern edge of the Grand Canyon and Datil sections (Fig. 15.16). Paleozoic rocks form the rim of the Plateau, but under the San Juan Basin these same rocks are overlain by more than 5,000 feet of Mesozoic formations and about 5,000 feet of Tertiary formations. The Defiance Upwarp separates the San Juan Basin from a shallower basin that lies to the west under Black Mesa.

The Navajo Section is characterized by broad flats on the shaly formations separated by low cuestas where the more resistant sandstones crop out. Colorful Triassic formations produce the Painted Desert, which extends far northwest of the national monument. In the San Juan Basin, the Tertiary and Cretaceous formations resemble a series of stacked saucers that get progressively smaller toward the top and form cuestas that face outward. Erosion of volcanic formations in the Navajo Section has produced numerous volcanic necks, like the frequently illustrated ones at Shiprock, New Mexico, and Agathla Peak in Monument Valley (see also Fig. 15.7).

CANYON LANDS SECTION. North of the Navajo Section is the Canyon Lands Section of the Colorado Plateau, where, as the name implies, canyons are the dominant feature. This section has four large upwarps: the Uncompahgre Upwarp, the Monument Upwarp, the Circle Cliffs Upwarp (Fig. 15.8), and the San Rafael Swell (Figs. 15.15, 15.16). Between the upwarps are structural basins; there is a big one under the Henry Mountains and another big one between the Kaibab and Circle Cliffs upwarps. Very little faulting is associated with these structural upwarps and basins or with those in the Navajo Section, except in the northwest-trending basin south of and parallel to the Uncompahgre Upwarp. This basin differs from the others in that it contains thick deposits of salt. In the course of the deformation that produced the basin, the salt deposits, of late Paleozoic age, were squeezed around like taffy, and the overlying formations were folded in northwest-trending anticlines and synclines that became faulted.

The canyons in the Canyon Lands Section have been carved mostly in sandstones in the upper Paleozoic and lower Mesozoic formations (Fig. 15.9). Jurassic and Cretaceous formations include thick shale units that form badlands arranged in belts between cuestas and benches formed by resistant beds of sandstone.

Where the resistant, canyon-forming sandstones are turned up steeply along the flanks of the asymmetric, anticlinal upwarps, they form great ridges generally known as hogbacks but referred to locally as "reefs." These form nearly

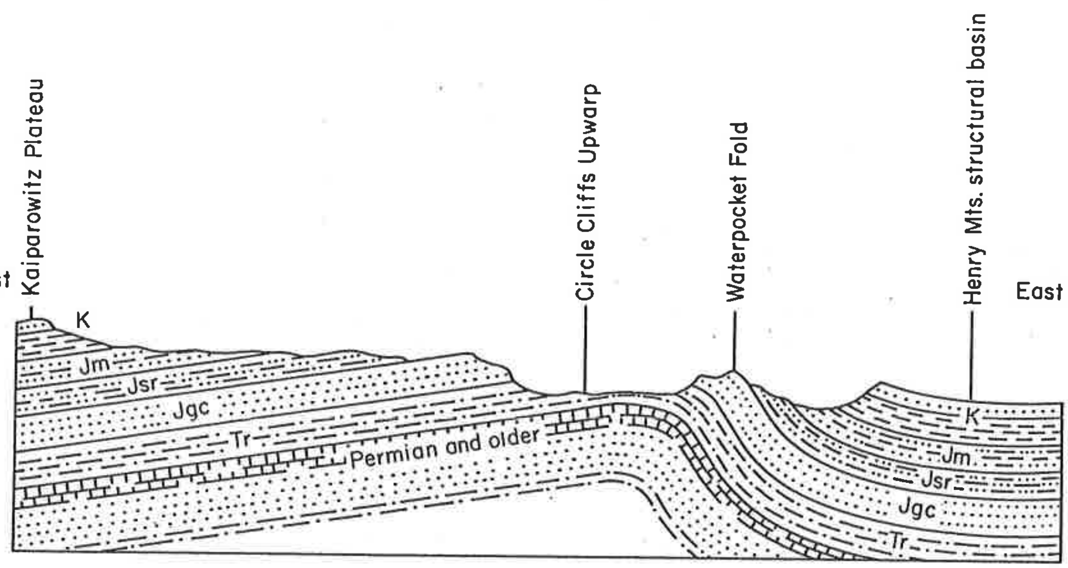


Figure 15.8 *Cross section of the Circle Cliffs Upwarp. Tr, Triassic formations; Jgc, Jurassic, Glen Canyon Group, cliff-forming sandstone formations; Jsr, San Rafael Group; Jm, Jurassic, Morrison formation; K, Cretaceous formations. The structural relief is about 6,500 feet; length of section approximately 40 miles.*

impassable barriers, as do the canyons. The thick sandstones erode into characteristic dome-like forms; Capitol Reef (a national monument) was so-named because its domes are suggestive of the dome on the capitol building in Washington, D.C. Back from the rims of canyons, nearly flat-lying sandstone formations form bare, knobby rock surfaces deeply dissected by narrow, rock-walled gulches or small canyons. Friable and earthy sandstones that extend across broad areas form a sandy desert with dunes.

Other distinctive structural features of the Canyon Lands Section are the laccolithic Henry Mountains (Fig. 15.10), La Sal Mountains, and others. These are structural domes produced by the forceful upward injection of molten igneous rock, which formed stocks. The injection of these plug-like masses domed the overlying rocks and those adjacent to them. As the stocks rose higher, they widened; the wider the stock, the steeper and higher the dome (Fig. 15.11). Where the stocks encountered weak shales, the magma was squeezed sideways into them to form laccoliths. The overlying beds were folded into anticlines radiating from the stocks. Some stocks may have reached the surface and erupted (Fig. 15.12).

During the glacial stages the higher mountains lay within the zone of intensive frost action (p. 461) and are consequently rounded. The lower parts of the mountains faithfully reflect the geologic structure. The contrast reflects the difference in the processes of erosion. Still other erosion forms distinctive of the Canyon Lands Section are the pediments, alcoves, arches, bridges, spires, and pedestal rocks, described later.

UINTA BASIN SECTION. North of the Canyon Lands Section is the Uinta Basin Section, which forms an embayment between the Middle and Southern Rocky Mountains. This, the deepest part of the structural bowl, contains the uppermost of the saucers and is structurally four miles lower than the southwest rim of the Grand Canyon Section (Fig. 15.16). Paleozoic formations under the basin are overlain by about two miles of Mesozoic and another two miles of Tertiary formations. Figure 15.13 shows the formations

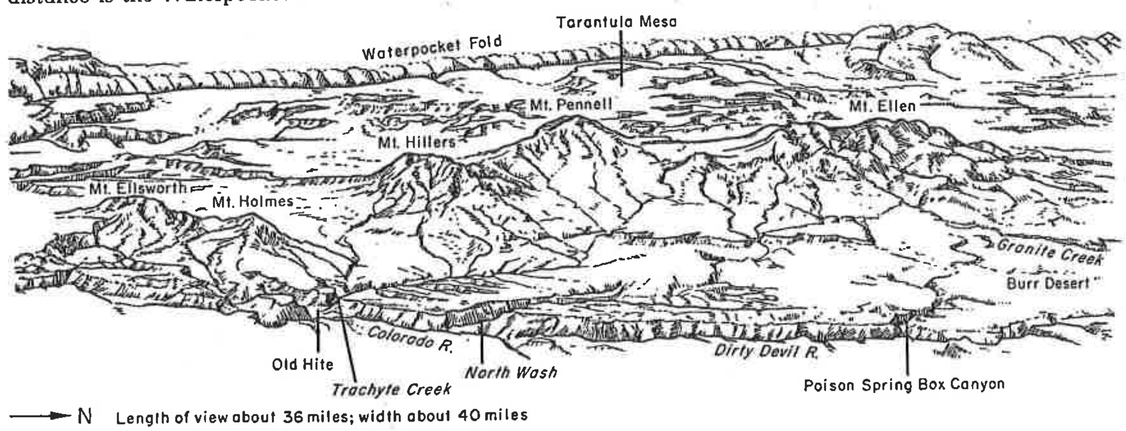
Figure 15.9 *Canyons of the Colorado River, where it crosses an anticline in late Paleozoic and Mesozoic red beds at Canyonlands National Park.*

rising gently southward (to the Canyon Lands Section) and rising steeply northward onto the southern flank of the Uinta Mountains. The Tertiary formations in the Uinta Basin form broad hilly benches that slope north, and form the south-facing escarpment known as the Roan Cliffs (Fig. 15.11). Cretaceous formations, rising southward from under the Tertiary formations, form the south-facing Book Cliffs, an escarpment that is about 2,000 feet high and extends about 100 miles across the southern edge of the basin, overlooking the Canyon Lands.

HIGH PLATEAUS SECTION. At the western edge of the Colorado Plateau is the High Plateaus Section, which consists of northerly trending fault blocks (Fig. 15.14). Many are lava capped and form plateaus, all of which are higher than 9,000 feet and some as high as 11,000 feet. Mesozoic and Tertiary formations underlie the lavas. The plateaus are separated by wide, flat-bottomed structural valleys (grabens) trending north to south. The colorful Tertiary sedimentary formations have been eroded into badlands at Bryce Canyon National Park and Cedar Breaks National Monument. Zion Canyon, at the southern end of the High Plateaus, is similar to many of the canyons in the Canyon Lands Section.

The High Plateaus end southward in three great escarpments that face southward and overlook the Grand Canyon Section. The northern escarpment, the Pink Cliffs, is formed by Tertiary formations (Fig. 15.3). The middle escarpment, the White Cliffs, is formed by upper Mesozoic

Figure 15.10 *Diagrammatic view of the Henry Mountains region, Utah. Mounts Ellen, Pennell, Hillers, Holmes, and Ellsworth are dome mountains produced by intrusion of stocks and laccoliths into the sedimentary formations. In the foreground are the canyons of the Colorado River and its tributary, the Dirty Devil. In the distance is the Waterpocket Fold.*



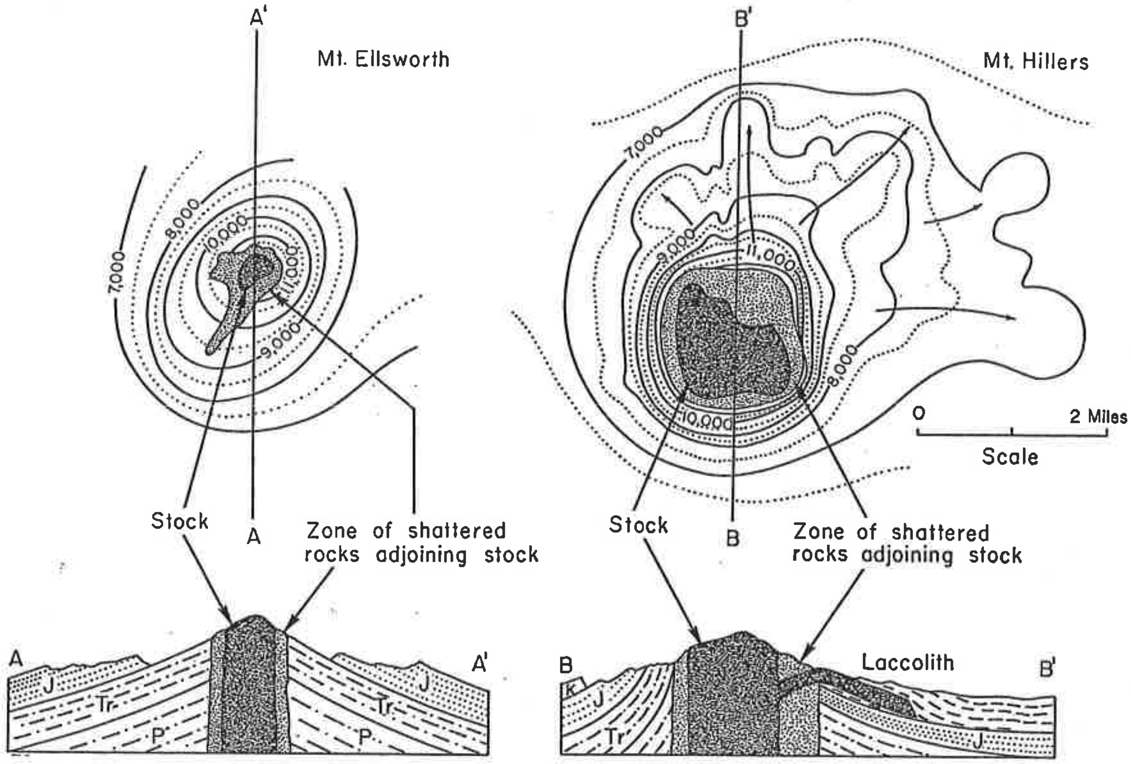


Figure 15.11 *Structure contour maps and diagrammatic cross sections of two laccolithic mountains on the Colorado Plateau. The sedimentary formations (P, Permian; Tr, Triassic; J, Jurrassic, and K, Cretaceous) are turned up steeply around wide stocks like the one at Mt. Hillers (15.9), and where these stocks reached the thick shale formations (K), tongue-like intrusions (laccoliths) were injected laterally between the sedimentary beds, forming anticlines whose axes (represented by arrows) radiate from the stock. Smaller stocks, like the one at Mt. Ellsworth (Fig. 15.9), caused less doming, less shattering of the wall rocks, and produced few, if any, laccoliths.*

sandstone. The southern escarpment, the Vermillion Cliffs, is formed by lower Mesozoic formations. This is known as the Grand Staircase of Utah.

This Section is a structurally high rim of the Colorado Plateau, but it differs from the high southwestern and southern rims in having been raised by faulting (Fig. 15.14). Deformation began in late Cretaceous time and continued intermittently throughout Tertiary and Quaternary time. The recency of some of the faulting, together with the fact that the western edge of the High Plateaus coincides with an active seismic belt (Fig. 2.17), suggests that these fault blocks may still be moving.

CENOZOIC STRUCTURAL AND IGNEOUS HISTORY

In late Cretaceous time, the Colorado Plateau had become a coastal plain, and the Cretaceous sea lay to the east (Fig. 15.15,A). In Paleocene time, folding, which had started much earlier in western Utah, progressed eastward to the area that was to become the Colorado Plateau. Flagstaff Lake (Fig. 15.15,B) developed at the site of the High Plateaus, and the deposits that accumulated in that lake truncate the folded beds of the Circle Cliffs Upwarp. The upwarp had formed in early Paleocene time, and probably the other upwarps began forming early in the Tertiary,

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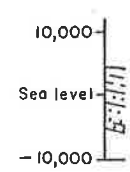
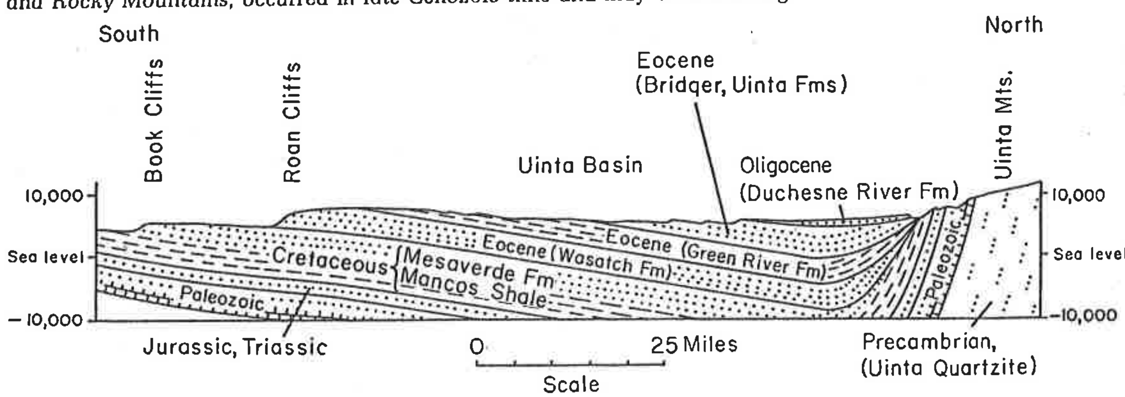


Figure 15.12 *Structural dome at Mount Ellsworth, one of the laccolithic Henry Mountains. Most of the dark rock at the center of the mountain is intrusive igneous rock that has domed the Mesozoic formations. In the distance can be seen one of the big monoclinal folds, the Waterpocket Fold, and on the skyline are the High Plateaus. [Photograph by Fairchild Aerial Surveys for the U.S.G.S.]*

Figure 15.13 *Cross section of the Uinta Basin, showing thick Tertiary formations overlying the Cretaceous and older strata. Toward the south, the Tertiary formations are conformable with one another, but against the steep flank of the Uinta Mountain uplift, unconformities between these formations record a series of structural movements that began in latest Cretaceous time and did not end until sometime after the Oligocene—that is, in middle or late Tertiary time. General uplift of the Uinta Basin, along with the rest of the Colorado Plateau and Rocky Mountains, occurred in late Cenozoic time and may be continuing.*



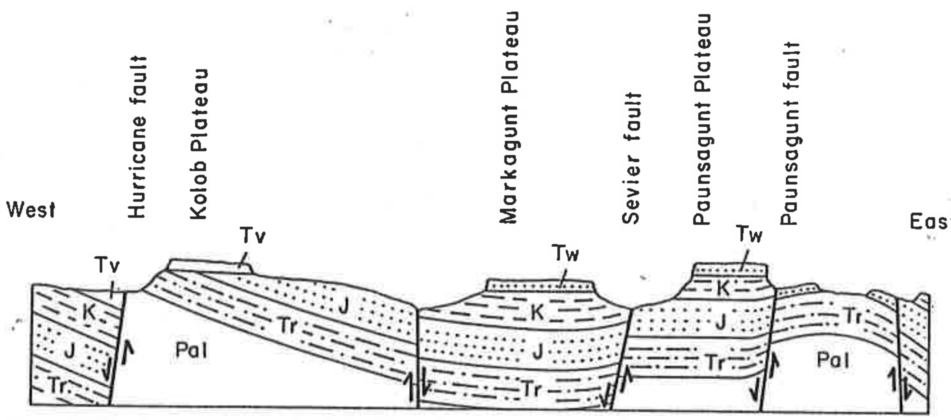


Figure 15.14 *The central part of the High Plateaus Section. The High Plateaus are between the Hurricane and Paunsagunt faults. To the east is the Canyon Lands Section (figure shows north end of the Kaibab Upwarp); to the west is the Basin and Range Province. Pal, Paleozoic; Tr, Triassic; J, Jurassic; K, Cretaceous; Tv, Tertiary volcanics; Tw, Tertiary sedimentary formations. Length of section, about 65 miles.*

including the Uinta Mountains, San Rafael Swell, Kaibab, Monument, Defiance, and Zuni upwarps, and folds at the Zuni Mountains, San Juan Mountains, and Uncompahgre Plateau (Fig. 15.15,B). On many or most of these folds movement was later renewed.

At the San Juan Mountains a pile of volcanic eruptives, probably accompanied by upwarping, had started accumulating in latest Cretaceous time and continued to grow during the Paleocene. This highland shed volcanic sediments (Animas Formation, Table 15.1) southward onto the Plateau in the San Juan Basin. Paleocene formations in the Uinta Basin indicate that mountains were forming to the east and to the west of that basin, and also at the Uinta Mountains. Probably there were mountains of this age in central Arizona that shed sediments northward onto the area of the Plateau. The site of the Colorado Plateau in Paleocene time was a basin, or series of basins, surrounded by newly formed mountains draining into it. The Plateau area must have been at or near sea level.

During the Eocene the downwarping that had formed Flagstaff Lake spread eastward to the foot of the Rocky Mountains at the site of the Uinta Basin, and there was downwarping in Wyoming. This produced Green River Lake (Fig. 15.15,C), in which the tremendous oil shale deposits of the Green River Formation accumulated. Some environmentalists wish this had never happened because of the expected impact on the landscape when production begins. The catchment area of the Colorado Plateau part of the Green River Lake probably was about the same in kind and extent as that of Flagstaff Lake.

Green River Lake came to an end in middle Eocene time, in part perhaps because of uplift and in part because of filling by the 3,000 feet of sediments that had been deposited (Table 15.1). Thereafter, streams deposited some additional thousands of feet of sediments, forming the Bridger and Uinta formations in what is now the northern part of the Plateau. In late Eocene time, uplift of the Uinta Mountains was renewed along an anticline that marks the northwestward extension of the Uncompahgre Upwarp, and probably at the San Rafael Swell. Whether this renewed uplift was synchronous with deposition of the Uinta and Bridger formations is not clear, but the uplift did deform the Green River Formation. The Nacimiento Upwarp in New Mexico was elevated at this time too, and presumably there was uplift at the other folds also.

During the Oligocene the Uinta Basin became a playa, and thereafter the basins began to overflow. At about the same time, block faulting began in the Basin and Range Province south and west of the Plateau; the Basin and Range Province had previously been mountainous and was undergoing erosion while the Colorado Plateau was receiving sediments. Beginning in the Oligocene, conditions reversed. The Colorado Plateau is without Oligocene deposits (except for the Duchesne River Formation in the Uinta Basin) and almost without Miocene deposits. Presumably during Oligocene time the Plateau began being uplifted relative to the basins in the Basin and Range Province, and in places exterior drainage could commence. During Miocene time, however, the Colorado River had been ponded in the Rocky Mountains at such structural basins as the Middle Park, State Bridge syncline, and the basin of the Gunnison River east of the Black Canyon, as already noted (p. 390). Any overflow from those basins probably became contained in the much larger structural basins downstream on the Colorado Plateau—the Henry Mountains structural basin and that of the Kaiparowitz Plateau. The Green River did not cross the Uinta Mountains and join the Colorado River system until after the Browns Park Formation had been deposited—that is, in early Pliocene time. The drainage from the north continued to be ponded.

By middle Miocene time the Colorado Plateau had been uplifted to within 3,500 feet of its present structural height (Fig. 15.16). The evidence for this is the dry canyon that breaks through the southwest rim of the Plateau at Peach Springs, Arizona. The Precambrian rocks forming the floor of that canyon at an altitude of about 3,500 feet must have been above sea level when the canyon was eroded. The sediments partly filling that canyon include volcanic ash dated as 18 million years old (middle Miocene). These relationships also show that the stretch of Grand Canyon just upstream from there had already been eroded to half its present depth by that time.

The stream that did this cutting presumably was the Little Colorado River. Through Miocene time (Fig. 15.15,D) the Little Colorado River collected drainage from mountains in central Arizona that still were attached to the Colorado Plateau. Gravels from these mountains are strewn northward from the present south rim of the Plateau all the way to the Little Colorado. In late Miocene or early Pliocene time those mountains were detached from the Plateau, faulted downward, and the drainage northward from them disrupted. The valley of the Little Colorado River is unique among those on the Plateau in that it is very broad and open with long parallel tributaries from the south and north. It even looks old compared to the young-looking canyons of the streams draining from the north. According to this interpretation, the first half of the canyon cutting at Grand Canyon was by the Little Colorado River before it lost its water sources by downfaulting and breaking away of the highlands south of the Plateau. The later erosion at Grand Canyon occurred when the drainage from the north reached there.

During the middle Miocene, extrusive volcanics began accumulating around the west, south, and east sides of the Plateau, and the laccolithic intrusions, or at least some of them (e.g., La Sal Mountains), formed at this time; some apparently were intruded earlier. At the time the laccolithic mountains formed, the Colorado Plateau was still covered by the Cretaceous formations—a landscape of badlands and mesas. This is indicated by the fact that all the laccolithic mountains intrude the Cretaceous formations, even those on uplifts where the Cretaceous away from the mountains has been removed by erosion. The colorful painted deserts formed by the Jurassic and Triassic were largely restricted to the valley of the Little Colorado River. This provides a measure of the amount of erosion that has occurred on the Plateau since the middle Miocene—namely, a volume about equal to the Cretaceous formations that once extended southward from the Book Cliffs in Utah to Black Mesa in Arizona.

Other evidence of the former Cretaceous landscape is revealed by outcrops along the west rim of the canyon of the north-flowing Dolores

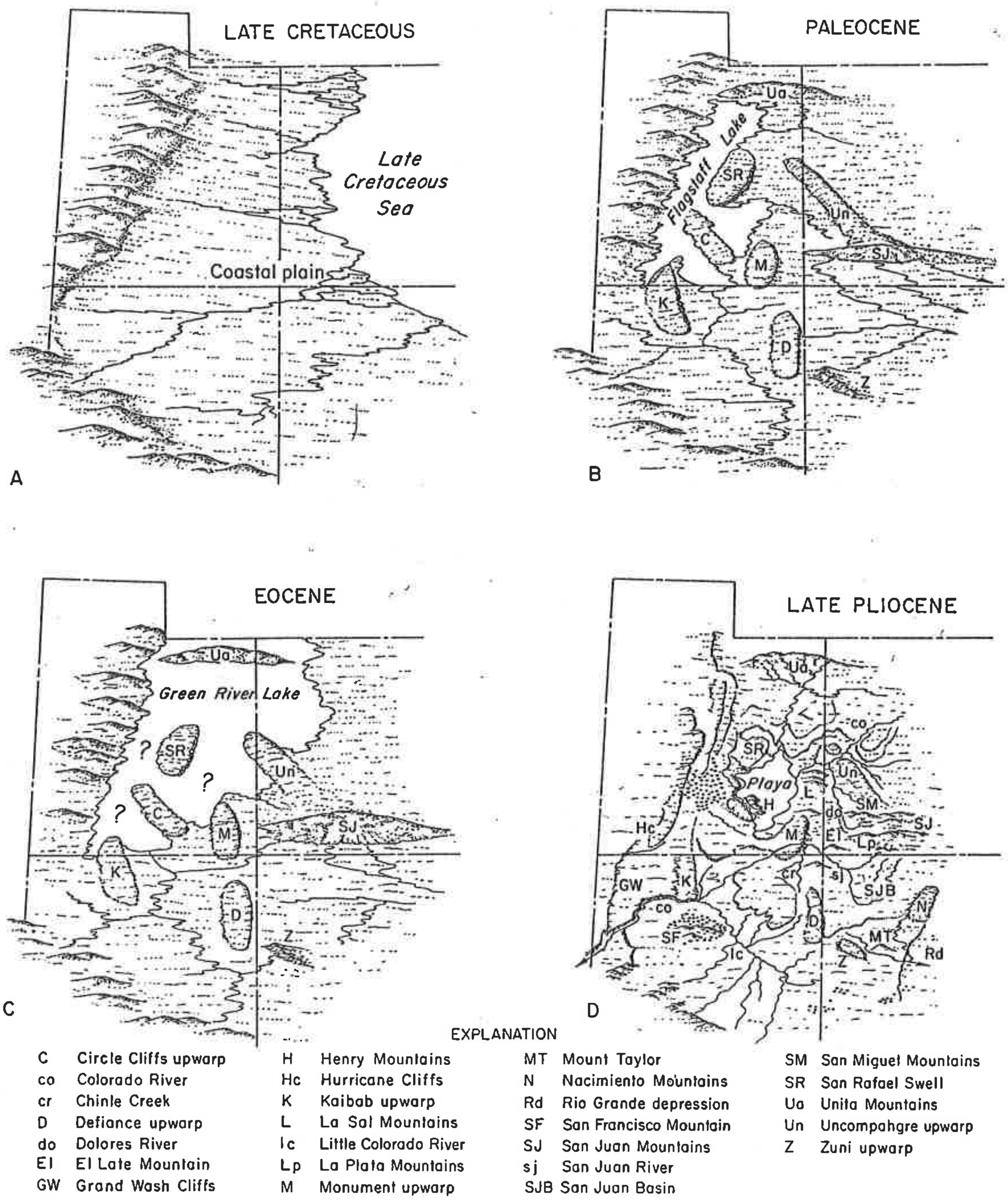


Figure 15.15 *(A) The Colorado Plateau area in Late Cretaceous time. The area was part of a coastal plain that extended eastward from the foot of mountains in central Arizona and central Utah. The edge of the Late Cretaceous Sea was to the east in Colorado. (B) The Colorado Plateau area in Paleocene time. Flagstaff Lake was formed along the western edge of the Plateau area. (C) The Colorado Plateau area in Eocene time.*

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River about west of the San Miguel Mountains (Fig. 15.17). Gravel was deposited on the rim before the river had cut into its canyon, but now the rim drains southwestward to the San Juan River! Clearly, when the Dolores River was at that position, there were hills of Cretaceous shale and sandstone west of there that kept the Dolores flowing north, otherwise it too would have turned southwestward to the San Juan. South of there the Dolores River makes a sharp bend northward as if it originally flowed southwestward to join the San Juan. Such a course could have been interrupted and the river turned northward by the laccolithic intrusions at El Late (Ute) Mountain. Volcanism was extensive during the Pliocene. Evidence that it continued into the Holocene is provided by the fresh-looking lavas in valley bottoms and the eruptives around Sunset Crater.

The compositions of the igneous rocks at the big volcanoes and at the laccolithic mountains average about the same, but for reasons that are obscure the compositions changed in quite different ways as the igneous activity progressed. At the laccolithic mountains, the silica-poor dioritic rocks (Table 2.3) were first to form and the silica-rich rhyolitic rocks the last, whereas at the volcanoes, the silica-rich rocks were the first to form and the silica-poor rocks the last. Perhaps when the volcanic vents reached the surface, pressure was relieved sufficiently to cause the molten magma to froth off the silica rich fraction, like the froth on newly opened ale.

The distribution of igneous centers on the Colorado Plateau (Fig. 15.18) illustrates some important principles about the occurrence of volcanic and other centers of igneous activity. One would suppose that volcanoes would be concentrated where there is much faulting, but instead of being concentrated in the highly faulted neighboring parts of the Basin and Range Province, the volcanic centers are concentrated on the uplifted but otherwise little-deformed rocks of the plateau. Mount Taylor and the basaltic volcanoes around it are on the plateau 25 miles or more west of the highly faulted west edge of the Rio Grande depression. No two of the laccolithic mountains have the same structural setting. The Henry Mountains intruded a structural basin, the Abajos intruded an uplift, the LaSals intruded salt anticlines, Ute Mountain intruded an area of gentle and uniform dips, the La Plata Mountains are at the base of the big uplift at the San Juan Mountains, and the San Miguel laccoliths are high on the flank of that uplift.

Likewise, we have seen that the volcanic field in the Raton Mesa Section of the Great Plains is as extensive or more so than the volcanics in the nearby parts of the Southern Rocky Mountains. The laccolithic intrusions in Montana are numerous on the little-disturbed Missouri Plateau rather than in the nearby much-deformed Rocky Mountains.

Yet from the perspective of outer space it is to be noted that Cenozoic volcanism was concentrated in the western part of the continent; evidence of Cenozoic igneous activity is almost wholly lacking in the central and eastern parts. This distribution tells us something about the structure of the continent, but what? The message is not clear.

Seismic Activity

The Colorado Plateau, which is even now a highly elevated block of the crust, may still be rising, as is suggested by the fact that its edges

Downwarping of the Uinta Basin produced the Green River lake, which covered most of the northern part of the Plateau area. Most of the uplifts, like the San Rafael Swell, probably stood higher than the lake and shed sediments into it. (D) The Colorado Plateau in late Pliocene time. The laccolithic mountains were formed, and there were eruptions at Mount Taylor, San Francisco Mountain, and at the volcanic pile in the central High Plateaus. The main streams were already superimposed on the uplifts, but these streams shifted monoclinally in adjustment to the intrusions. The valley of the Little Colorado River was in about the same position and about as deep as it is today. A considerable canyon had already formed in Grand Canyon. [After U.S.G.S.]

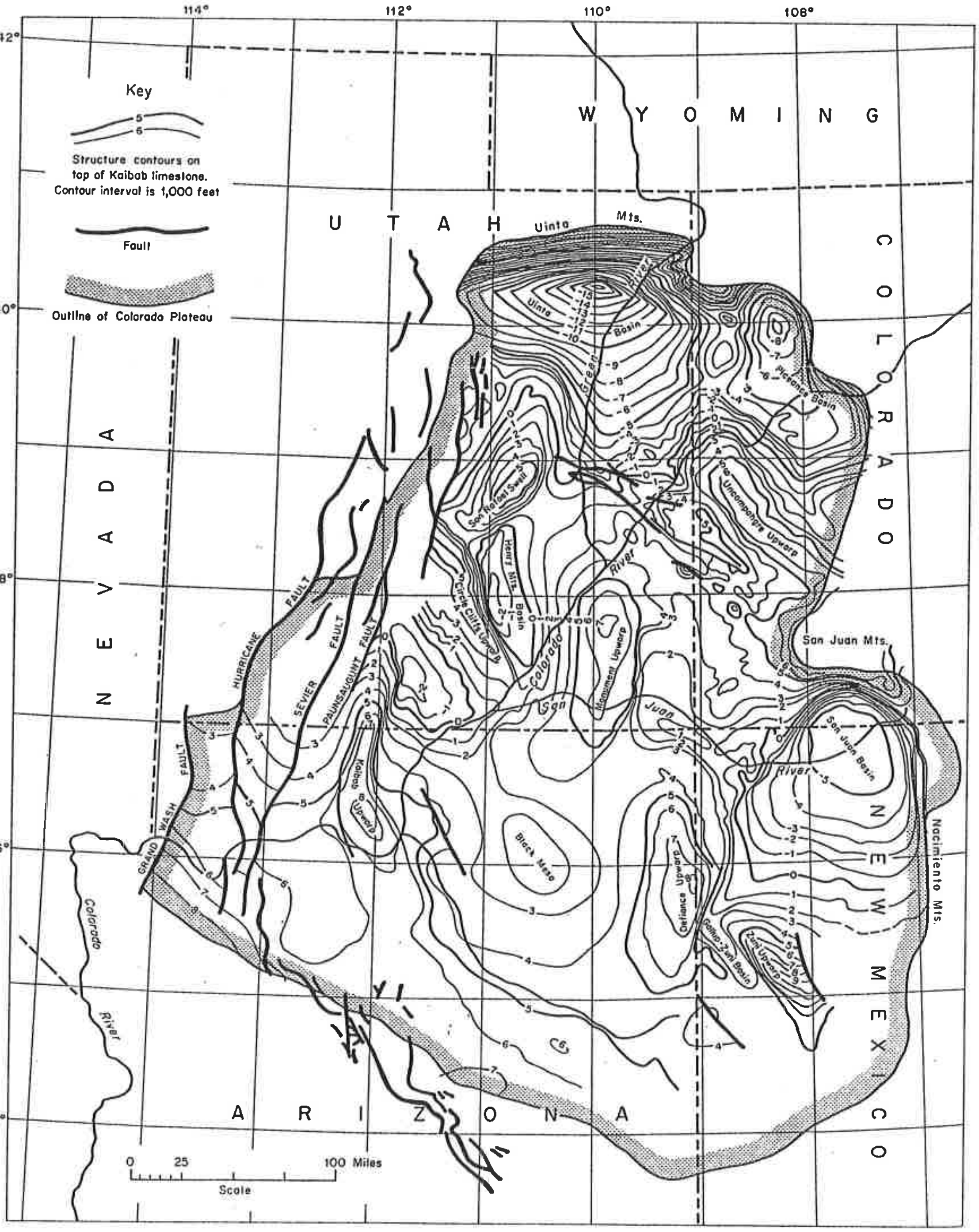

Figure 15.16 *Structure contour map of the Colorado Plateau. Contours drawn on a geologic formation reveal its changes in altitude and dip and bring out the locations, shapes, and dimensions of folds and faults. [After U.S.G.S. Prof. Paper 669.]*

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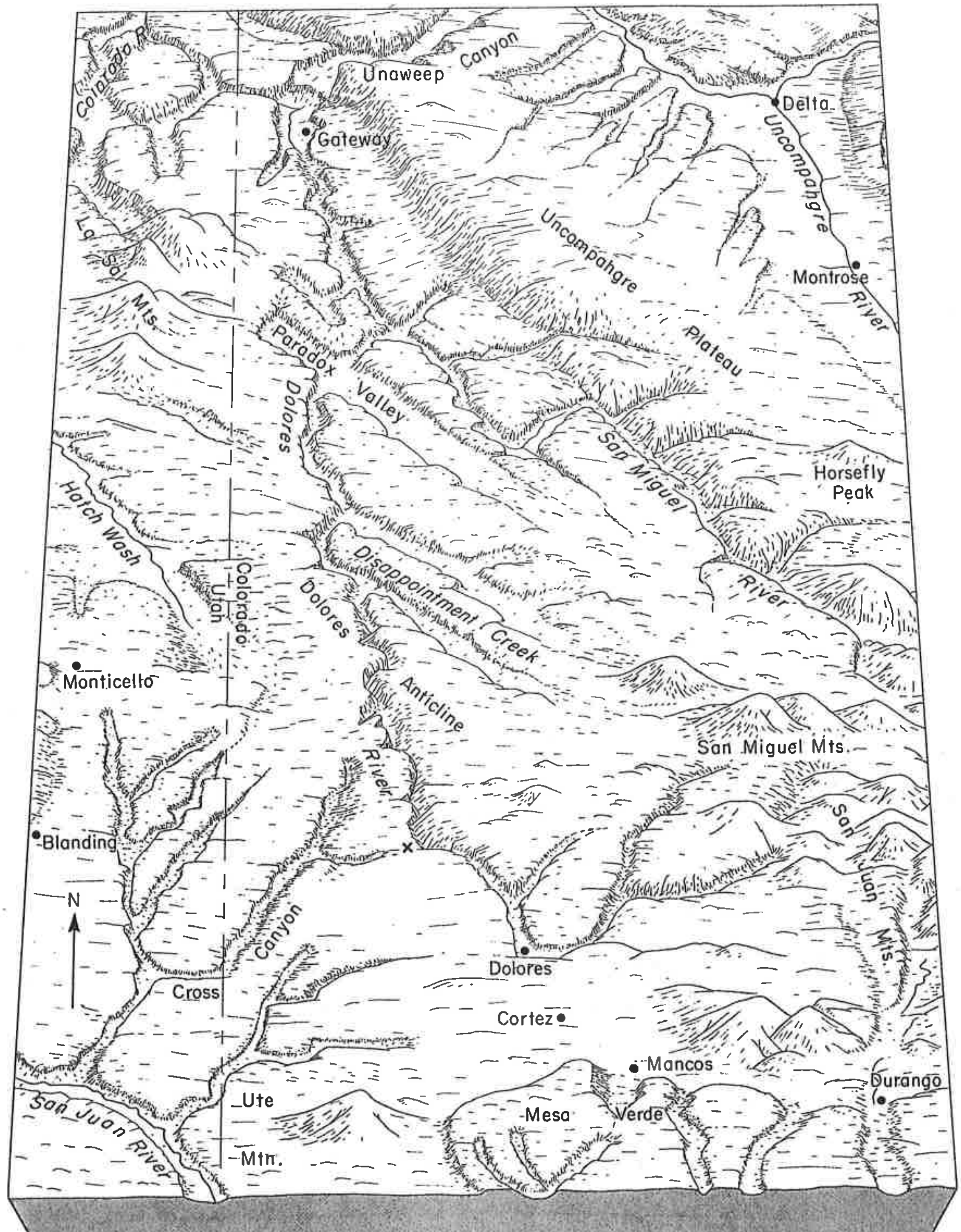

Figure 15.17 *Dolores River drainage basin. The headwaters of the river probably originally flowed southwest from Dolores to join the San Juan River; they may have been turned northward by the early Miocene doming at Ute Mountain. A gravel deposit (N) on the west rim of the north-trending canyon forms the divide between Dolores River and drainage to the southwest. When the Dolores River deposited the gravel, there must have been hills of Cretaceous shale at the site of Cross Canyon and the canyons northwest of it. [After U.S.G.S. Prof. Paper 669.]*

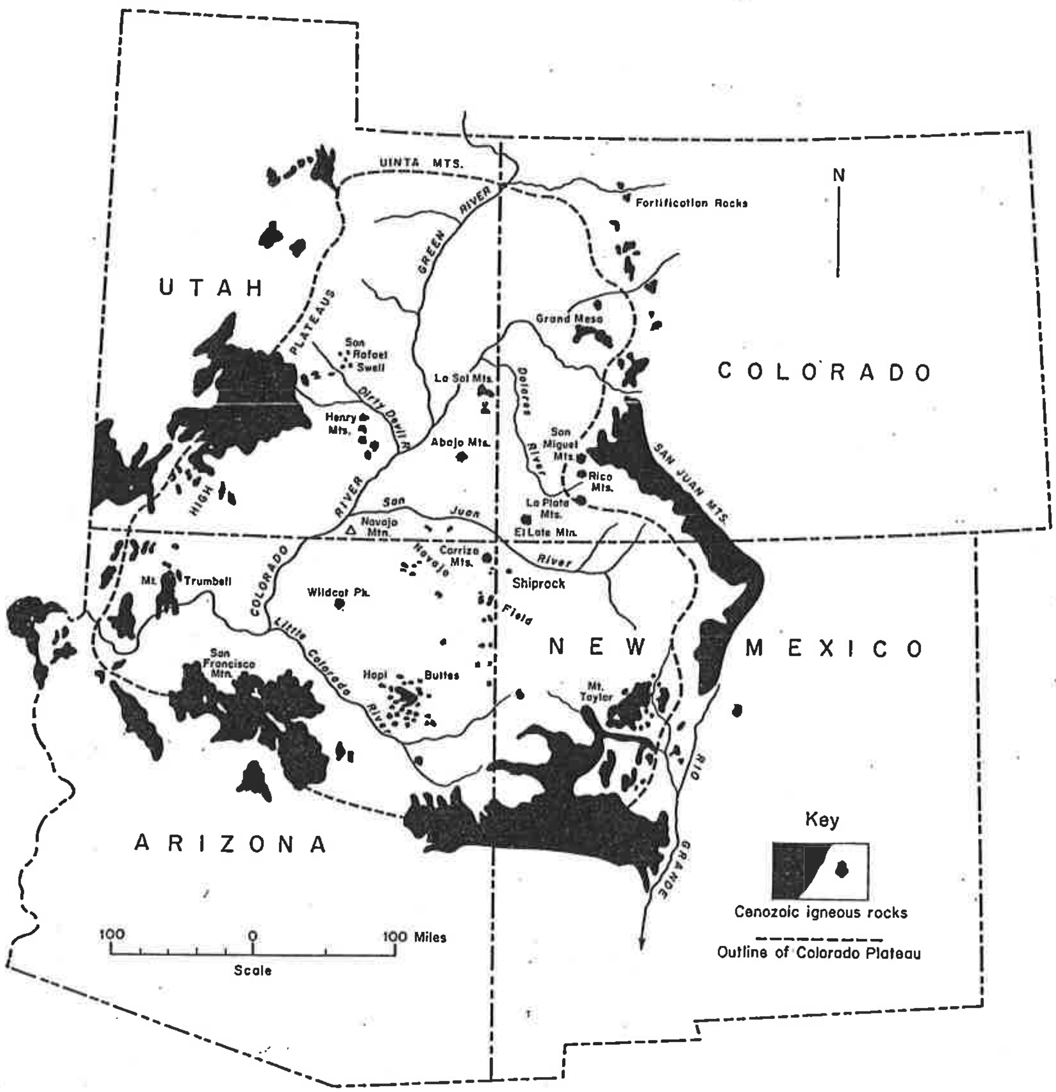

Figure 15.18 *Map illustrating distribution of Cenozoic igneous rocks on the Colorado Plateau. The laccolithic mountains are mostly in the interior of the plateau; the volcanic centers are mostly around the edges of the plateau.*

coincide with belts of more than average seismic activity. The epicenters of major earthquakes are alined along the western edge of the plateau, and along its southeastern edge in the Rio Grande Valley. Epicenters of minor earthquakes also are alined along the southwestern edge of the plateau and along its north and east sides, where it joins the Rocky Mountains. The foci of only a few minor earthquakes have been recorded from beneath the Plateau.

This seismic record, together with the geology, suggests that not much differential earth movement is occurring within the Plateau, but that the province as a whole may be moving with respect

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