Cenozoic Geology of the Colorado Plateau

By CHARLES B. HUNT

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CONTENTS

ILLUSTRATIONS

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ABSTRACT

The pre-Tertiary structural history of the Colorado Plateau undoubtedly controlled its Cenozoic history to considerable extent. The pre-Tertiary history seems to have been one of comparative stability because during most of Paleozoic and Mesozoic time the Colorado Plateau was a shelf area and was without deep geosynclinal basins except during Pennsylvanian time. Thus, the general plateau structure, which is of Cenozoic age, appears to be an inherited feature.

Deposits of early Cenozoic age are well represented on, or adjacent to, the Colorado Plateau, but deposits of late Cenozoic age are scarce. As a result, the early Cenozoic history is known fairly well but there are major gaps in the record for late Cenozoic time. In adjoining parts of the Basin and Range province the reverse is true; there, deposits of early Tertiary age are scarce but deposits of late Tertiary age are extensive.

Paleocene and Eocene deposits in the Uinta Basin and San Juan Basin record that the Plateau area was a basin or trough, probably near sea level, and was surrounded by newly formed mountains. The trough or basin was the product of folding that began in late Cretaceous time and continued intermittently during the first half of the Tertiary. In the lower parts of the trough, several thousand feet of lacustrine and fluviatile sediments were deposited.

After Eocene time, conditions changed markedly. General aggradation of the Plateau area ceased, and general degradation began. Igneous activity, in the form of volcanism and intrusion, became extensive. There was extensive faulting, especially along the west and south edges of the province, and epeirogenic uplift began. The erosion, igneous activity, faulting, and uplift have continued to the present time.

It is inferred that exterior drainage started when the Plateau began to be uplifted, and that the major courses of the streams probably were established before epeirogenic uplift had progressed very far. Also, it is believed that the canyon cutting began when the uplift started and that it has progressed to the present time.

Cenozoic intrusive rocks, believed to be of late Tertiary age, in the Colorado Plateau occur as stocks, laccoliths, and bysmaliths in the dozen or so laccolithic mountains. Upper Tertiary eruptive rocks occur at the large central-type volcanoes at Mount Taylor and San Francisco Mountain and as extensive sheets of basaltic lavas and pyroclastic rocks. The volume of igneous rocks is considerable but is only a percent or so of the volume of eruptive rocks in the San Juan Mountains or of adjoining parts of the Basin and Range province.

As a petrographic province, the Colorado Plateau is high in alkalies and alumina. Four subprovinces can be distinguished within the Plateau. In the interior, in the laccolithic mountains, the percentage of soda greatly exceeds that of potash. In the High Plateaus, soda and potash are about equal. In the Navajo and Tuba volcanic fields, potash exceeds soda. Along the southern edge of the Plateau, soda exceeds potash.

At the end of Cretaceous time the Plateau was a piedmont area extending eastward and northeastward from the foot of mountains that had been built by thrust faulting and folding in the adjacent parts of the Basin and Range province. When the Rocky Mountains were raised the Plateau area became a structural basin or trough.

The orogenic structures on the Plateau are believed to have formed during early Tertiary time. The structures associated with the igneous activity are believed to have been formed while the area was being uplifted epeirogenically in middle or late Tertiary time.

The meandering course of the Colorado River across the various orogenic structures led to the concept of antecedence, and later to that of superposition. Actually, neither theory alone seems adequate to explain all the anomalies of the Colorado River drainage, but a combination of the two processes, for which the term "anteposition" is suggested, offers explanations for many of them. Anteposition refers to arching of a canyon so that a stream becomes ponded and deposits sediment upstream from the arch. When downcutting is resumed, a new superposed course is developed in the stretch represented by the reservoir. But the low point on the rim of the reservoir is the raised portion of the old valley; this becomes the new spillway and downstream from this point the new valley has the aspects of antecedence.

INTRODUCTION

PURPOSE OF REPORT AND ACKNOWLEDGMENTS

Geologically, the Colorado Plateau ranks as one of the better known parts of the United States. Much geological work has been done there and, on the whole, exposures are superb. Yet, despite these favorable conditions, the Cenozoic history of the Plateau is known only very incompletely because datable Cenozoic deposits are few. This report endeavors to summarize what is known about the Cenozoic geology of the Plateau and to present an historical interpretation of the available data. But in view of the scarcity of Cenozoic deposits, much, indeed most, of the historical interpretation must be based on subjective inference, and therefore the history presented is in the form of a hypothesis.

An attempt to summarize and interpret the Cenozoic geology of an area as large as the Colorado Plateau constitutes an ambitious undertaking, in which, of necessity, one must lean heavily on assistance from his colleagues. In particular, I received many suggestions and constructive criticisms from John B. Reeside, Jr., James Gilluly, and Henry G. Ferguson of the Geological Survey, Aaron C. Waters of Johns Hopkins University, and Chester R. Longwell of Yale University. The report was written very largely because of urging by L. C. Craig of the Survey. In acknowledging this assistance, however, it is not to be implied that the individuals agree with the interpretations that are offered.

Because the descriptive data in this report have been abstracted from previous publications, many sentences and, in some instances, entire paragraphs are direct quotations. Quotation marks have not been used but the earlier reports from which the information was taken have been cited.

GENERAL GEOGRAPHIC SETTING OF THE COLORADO PLATEAU

The Colorado Plateau covers above 150,000 square miles in southeastern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado. About 90 percent of this area is drained by the Colorado River and comprises about one-half the drainage basin of the river. Figure 1 shows the outlines of the Plateau and the principal geomorphic subdivisions.

The Colorado Plateau differs from neighboring provinces in stratigraphy, in mode of occurrence and composition of the igneous rocks, and in structure. Its Cenozoic history differed from that of the adjoining provinces. As a result of all these factors, the geomorphic forms on the Colorado Plateau differ from those of the adjoining provinces. And as a result of differences in these factors within the Plateau, there are major differences in the geomorphic forms from one part to another. On the basis of these differences, the Plateau as a geomorphic province has been subdivided into 6 sections (Fenneman, 1928, p. 338–342). (See fig. 1.)

At the north edge of the Plateau is the Uinta Basin, the central part of which is about 6,000 feet above sea level but the surface rises northward to the Uinta Mountains and southward to the rims of the cliffs that face southward and overlook the Canyon Lands. The Uinta Basin resembles the Wyoming Basin to the north but is set apart from it by the Uinta Mountains and by rough topography along a structural arch extending eastward from the mountains. The Uinta Basin is structurally the lowest part of the Colorado Plateau and still retains a thick section of Tertiary rocks. The drainage on these Tertiary rocks accords with their structure and shows no important anomalies. The Duchesne River is an example.

The north edge of the Uinta Basin is along the hogbacks where the formations are turned up at the south foot of the Uinta Mountains and along a structural arch extending eastward from the mountains. The east edge is along the Grand Hogback at the west foot of the White River Plateau. The southern edge is along the southward-facing Book Cliffs, the great southward-facing cuesta of Upper Cretaceous and early Tertiary formations retreating northward off the epeirogenic upwarp in southeastern Utah.

Just south of the Uinta Basin is the Canyon Lands section, a plateau surface most of which is 5,000 to 7,000 feet above sea level. This area has been epeirogenically upwarped, and on top of the upwarp are several huge folds. Throughout this area the drainage is deeply incised in canyons in the pre-Tertiary rocks. Geomorphic features of the area are the elevated plateaus on the upfolds, hogbacks on their flanks, lower plateaus between the upfolds, laccolithic mountains rising above the plateau surfaces, and an intricate set of deep canyons (fig. 2). Among the unusual geomorphic features are the natural bridges (fig. 3) and the related alcove arches (Hunt, 1953) that provide huge shelters along the canyon walls. Except for a few local deposits, like those believed to be of Pliocene age in the salt anticlines, no deposits of Tertiary age remain in the Canyon Lands section. At a prior period, however, there may have been extensive deposits similar to the Browns Park and Bidahochi formations along the main valleys.

Because of the general discordance between the drainage and the orogenic structures it is easy to overemphasize this particular geomorphic feature. Actually, the courses of the Green and Colorado River in the Canyon Lands section are rather accordant with the principal orogenic structures.

The Canyon Lands section ends, at the north, at the foot of the Book Cliffs. On the east, it ends where the formations rise onto the San Juan Mountains. On the west, it ends at the base of the High Plateaus and commonly, but not always, along a fault. On the south, it is bounded by the less folded Navajo section which embraces the basin under Black Mesa and the San Juan Basin. Most of the laccolithic mountains, but almost none of the volcanic rocks, are in the Canyon Lands section.

The Navajo section of the Colorado Plateau is about as high as the Canyon Lands but much less dissected—it is an area of mesas and broad open valleys. The formations are similar to those in the Canyon Lands section, but they have been less folded. Locally, the drainage is deeply incised into the rocks, but examples are few as compared with the Canyon Lands section. The San Juan Basin contains deep Tertiary fill, and the landforms are similar to those in the Uinta Basin.

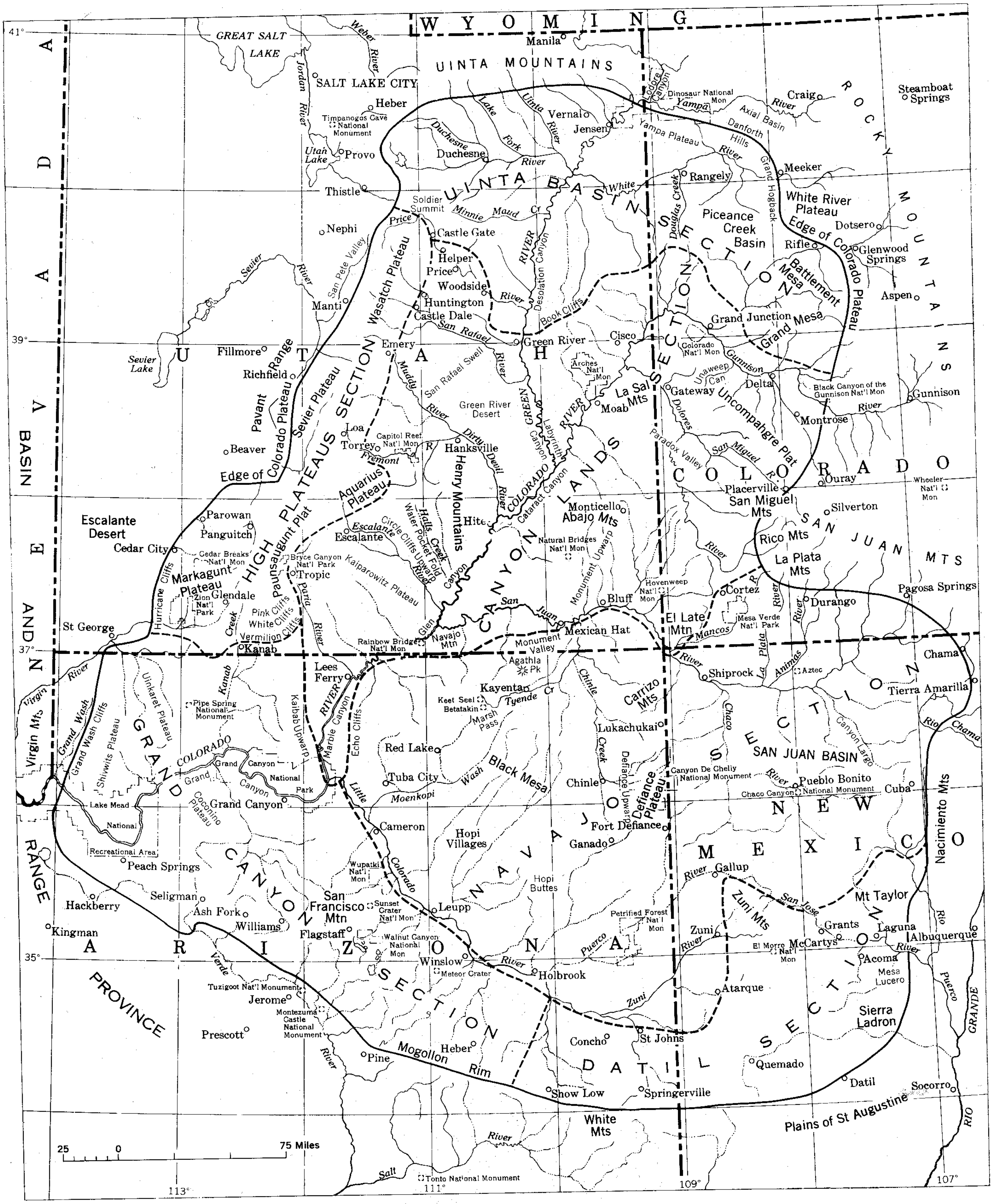
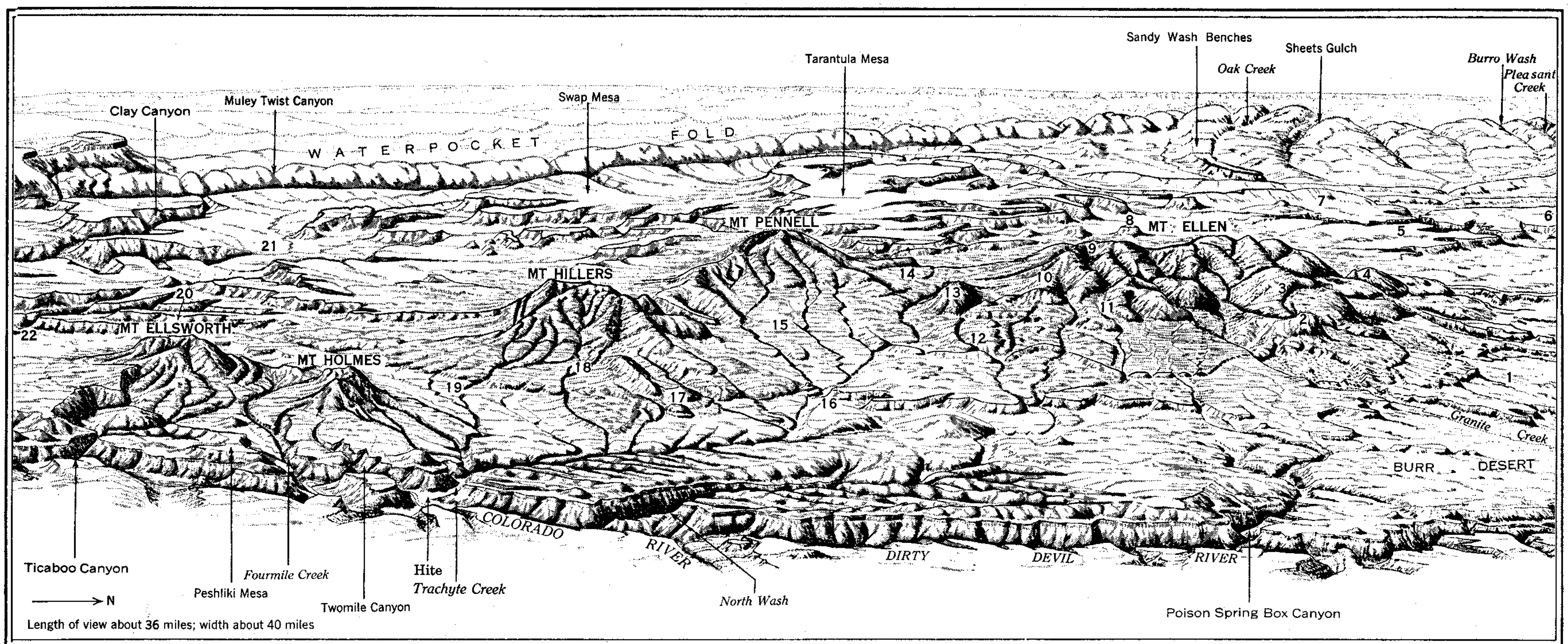


FIGURE 1.—Index map of the Colorado Plateau.



After Hunt, 1954

1 Fairview	5 Stephens Mesa	9 Bromide Basin	13 Ragged Mtn	17 Black Mesa	21 Eggnog
2 Jukes Butte	6 Thompson Mesa	10 Copper Ridge	14 The Horn	18 Gold Creek	22 Lost Spring
3 Horseshoe Ridge	7 Wildcat Mesa	11 Eagle City	15 Straight Creek Benches	19 Star Creek	
4 Table Mtn	8 Steele Butte	12 Maze Arch	16 Trachyte Ranch	20 Shootaring Creek	

FIGURE 2.—Diagrammatic view of the Henry Mountains region, a view that is typical of the Canyon Lands section.

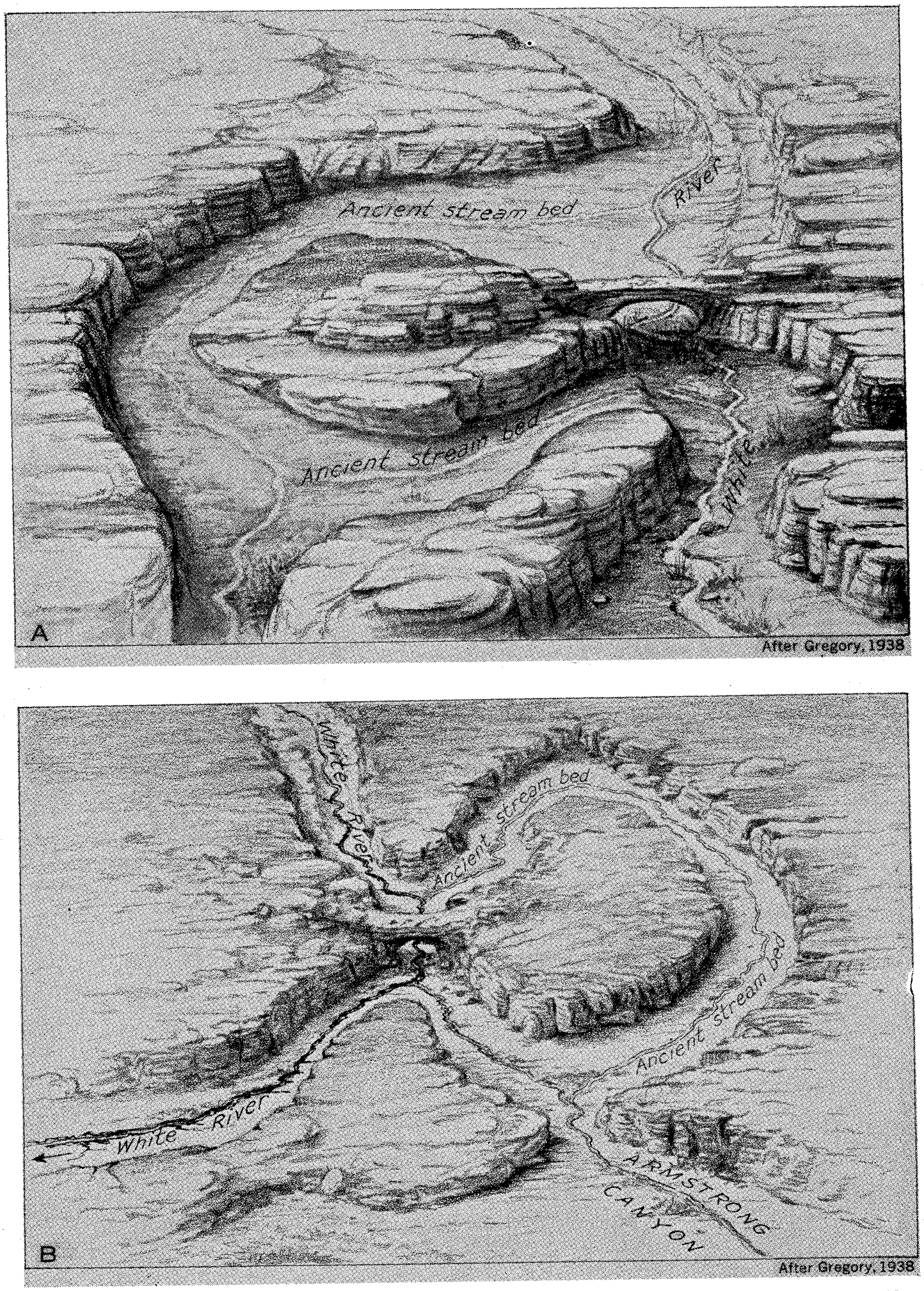


FIGURE 3.—Diagrams showing formation of natural bridges. (A) Sipapu Natural Bridge, (B) Kachina Natural Bridge.

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These basin-folded Tertiary formations, and the basin-folded Mesozoic formations in the Black Mesa area, are bordered by strike valleys, as is the Defiance upwarp (fig. 37). The structures are open, as compared with those in the Canyon Lands section, and the drainage on the whole is well adjusted to them. Whereas the Canyon Lands section is characterized by the laccolithic mountains, the Navajo section is characterized by an abundance of volcanic necks, dikes, and remnants of volcanic cones and small lava flows.

The Navajo section has alcove arches as large as many of those in the Canyon Lands, and some of these, as at Betatakin and Kiet Siel in northern Arizona, were used as sites for cities by the prehistoric Puebloan Indians.

The northern edge of the Navajo section is at the southern limit of the folded rocks of the Canyon Lands section, approximately at the Arizona-Utah Boundary line. The northeast edge is located where the formations rise onto the uplifts at the San Juan and Nacimiento Mountains. To the south and southwest the Navajo section ends about at the north limit of great sheets of lava that characterize the southern and southwestern rims of the Colorado Plateau.

The Datil section, which comprises the southeast rim of the Colorado Plateau, is extensively and deeply covered with lavas. The boundary between the Plateau and adjoining Basin and Range province is sharply defined by the westernmost faults of the Rio Grande depression east of Mount Taylor, but it is highly arbitrary in west-central New Mexico.

Principal geomorphic features of the Datil Section are Mount Taylor, the Zuni Mountains, and the lava-capped mesas and benches to the south. The eruptives are of late Tertiary and Quaternary age; a few are Recent.

The Grand Canyon section is similar to the Datil section in geomorphic and structural form, but the Grand Canyon section is higher and more sharply set apart from the areas about it. It includes the San Francisco Mountain and the extensive lava fields to the south, and the Kaibab upwarp and the faulted blocks to the west. Except for the Colorado River, none of the streams is incised deeply into this part of the Colorado Plateau. This is structurally the highest part of the Plateau, partly because of the Kaibab upwarp and partly because of the southward and southwestward rise of the formations towards the Plateau rim.

The southern boundary of the Grand Canyon section is along the south-facing cliffs of the Mogollon Rim that overlook the belt of faulted and folded pre-Cambrian rocks to the south and along the Grand Wash Cliffs on the west. The Little Colorado River valley separates this section from the Navajo section. A series of plateaus bounded by faults north of Grand Canyon are structurally part of the High Plateaus, but topographically they belong with the Grand Canyon section.

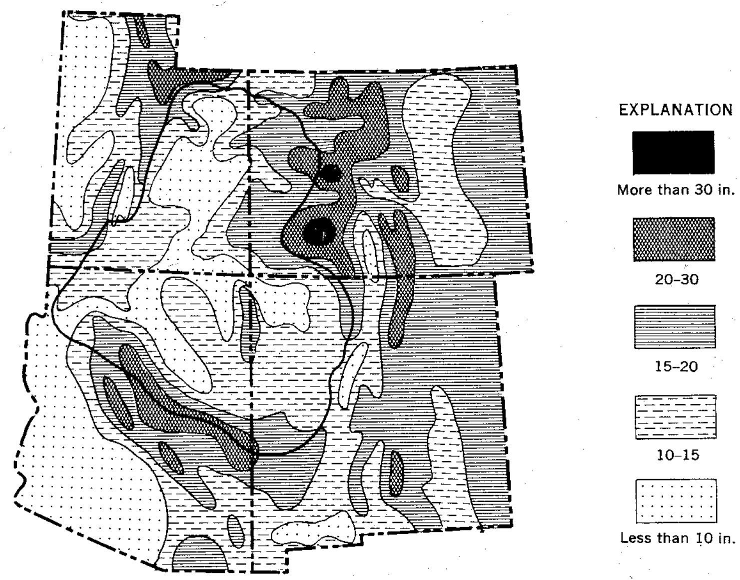
Along the west edge of the Colorado Plateau is the section known as the High Plateaus of Utah, which consists of long, north-trending plateaus, many higher than 9,000 feet and some as high as 11,000 feet. The north and south ends of the High Plateaus are capped by lower Tertiary formations; the central part is capped by volcanic rocks, and the lower Tertiary formations are missing. Between the plateaus are broad, open, north-trending valleys, most of them draining to the Sevier River. The plateaus and intervening valleys are defined by the faults of late Tertiary age. But, although the topography is fault-controlled, some of the escarpments are fault-line scarps where, as at Bryce Canyon, the downthrown block now stands topographically higher than the upthrown block (fig. 51).

Like the Datil and Grand Canyon sections, the High Plateaus are structurally and topographically a high part of the rim of the Colorado Plateau. The major uplift in the High Plateaus section is post-Wasatch and probably is of late Tertiary and Quaternary age.

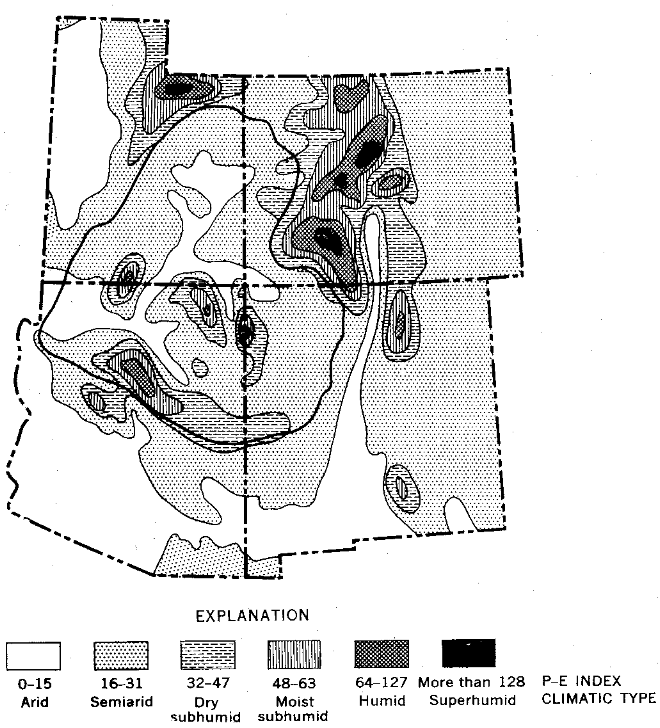
In terms of annual precipitation, most of the Navajo section, the High Plateaus, Uinta Basin, and the higher parts of the Canyon Lands are semiarid (fig. 4). The lowest parts of the Canyon Lands are arid. The Datil and Grand Canyon sections are mostly dry subhumid. The upper parts of many of the mountains throughout the Colorado Plateau are humid, although these areas are too small to show on figure 4. However, the precipitation effectiveness in the Colorado Plateau is low, especially during the growing season (fig. 4). Because of high temperatures and high evaporation the greater part of the Plateau has an arid climate during the growing season.

The natural vegetation on the Plateau consists mostly of northern desert shrub species. The higher parts of the Plateau are wooded or forested; many of the mountain tops and highest plateaus are forested with spruce and fir (fig. 5).

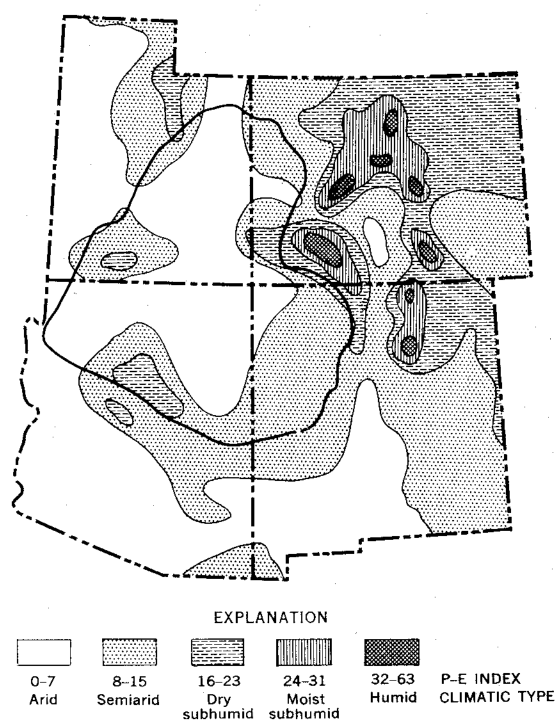
Soils are shallow and mostly Recent gray desert or lithosols that differ greatly in short distances depending on the parent materials (fig. 6). The soils below an altitude of about 8,000 feet are of the pedocal type—that is, they have a limey subsoil. Above 8,000 feet are found acid pedalfer (non-limey) types, including gray-brown podsolic soils. Recent alluvial soils occur along the valleys. Along the Colorado-Utah boundary is



A. Annual precipitation, in inches (from U. S. Weather Bureau)



B. Normal distribution of climatic types on annual basis (after Thornthwaite, 1941)



C. Normal distribution of climatic types during growing season, March through August (after Thornthwaite, 1941)

Note: P-E index is a measure of precipitation effectiveness and is based on a formula that evaluates the effectiveness of precipitation in terms of the temperature at which it fell

FIGURE 4.—Climatic maps of Colorado, Utah, Arizona, and New Mexico. (Colorado Plateau shown by heavy line.)

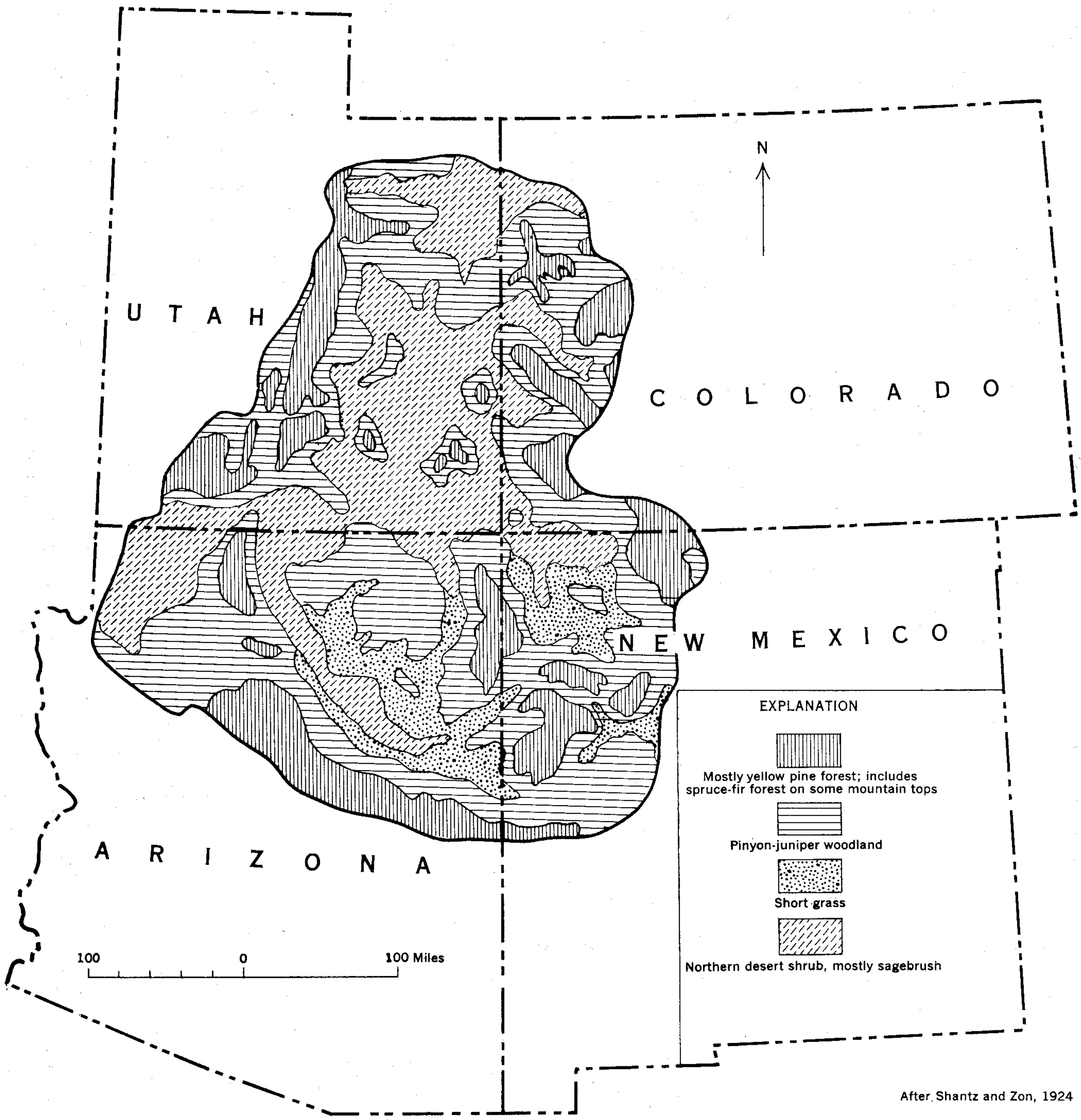


FIGURE 5.—Vegetation map of the Colorado Plateau.

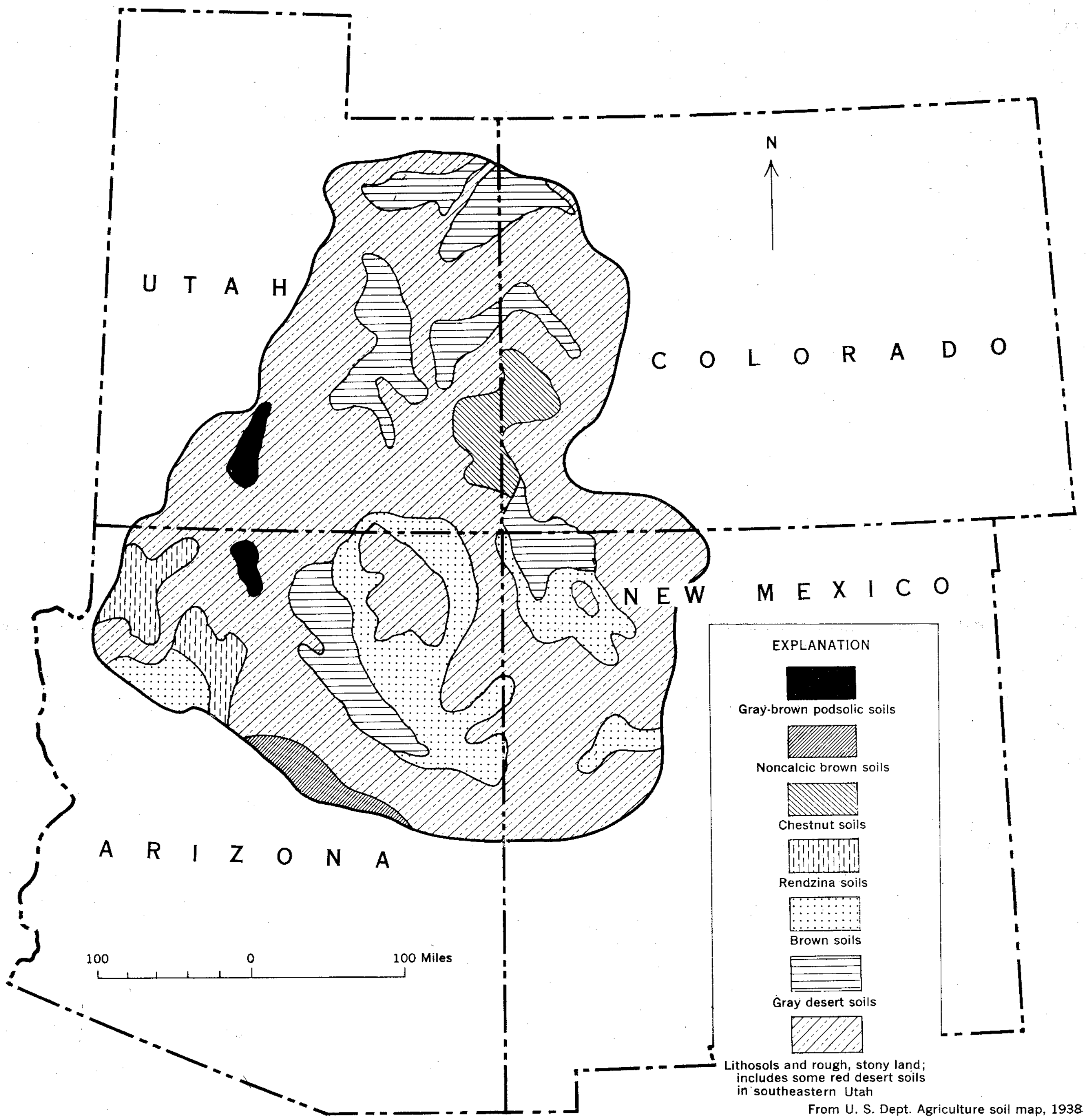


FIGURE 6.—Soil formations on the Colorado Plateau.

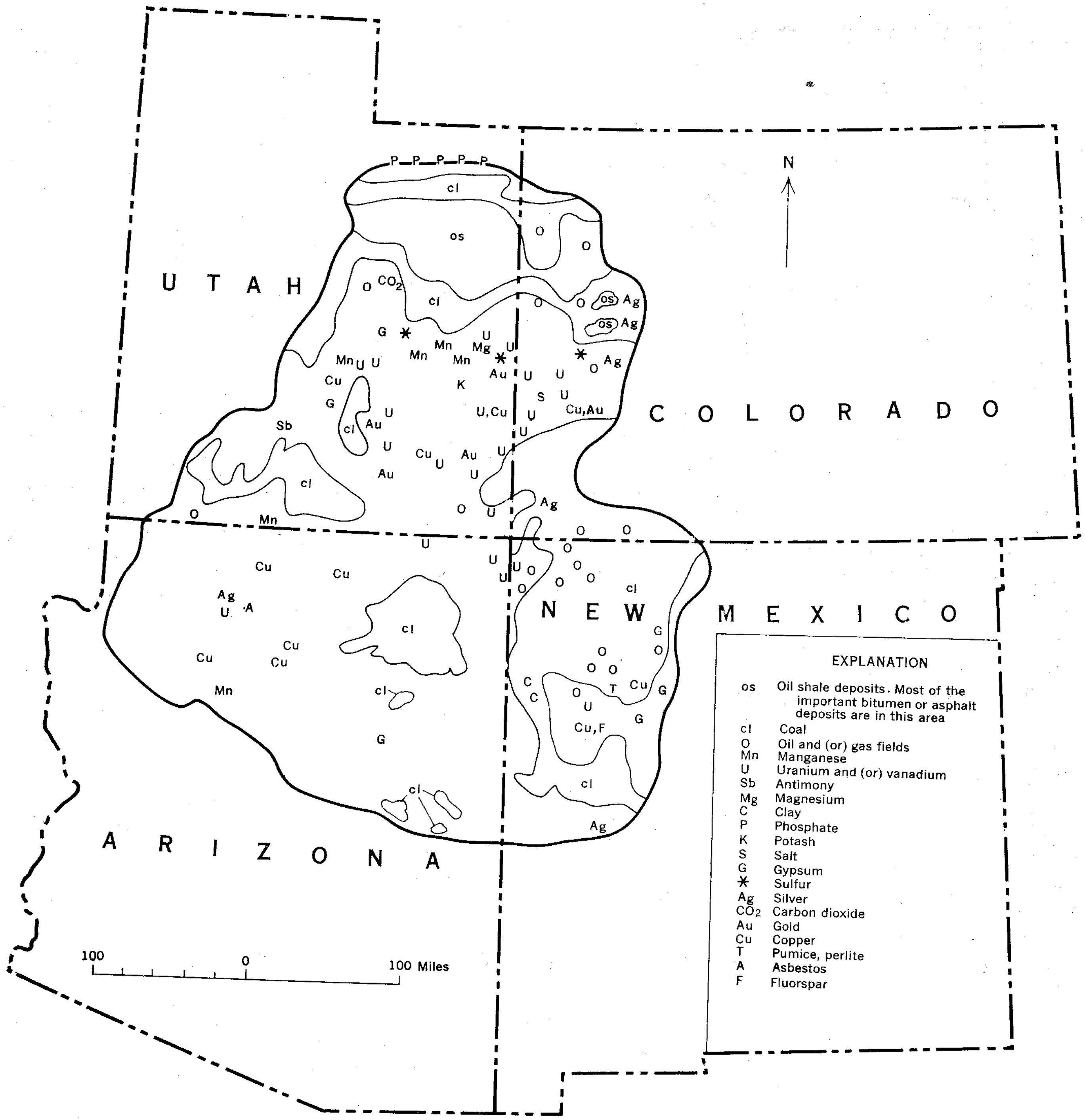


Figure 7.—Mineral deposits on the Colorado Plateau.

an extensive area of chestnut soils that are developed largely on Pleistocene loessial and alluvial upland deposits.

The Colorado Plateau has considerable mineral resources, and the Cenozoic history of the Plateau has considerable bearing on their occurrence. The most developed resource is coal; Gallup, New Mexico and Price, Utah are two major coal-producing centers. Some of the mineral resources are unusual and have posed perplexing problems as to their origin and mode of occurrence. Among these are: the sandstone deposits of uranium and vanadium, manganese, and copper-lead; the gases helium and carbon dioxide; and the hydrocarbon gilsonite. Oil shale resources are tremendous. Other deposits include oil, potash, salt, gypsum, pumice, semiprecious stones, and placer and lode gold (fig. 7).

PRE-CAMBRIAN BASEMENT ROCKS

The structure of the pre-Cambrian basement rocks undoubtedly has been a major factor affecting the Cenozoic history of the Colorado Plateau, but data about the pre-Cambrian rocks are few. Pre-Cambrian rocks crop out extensively south, east, and north of the Plateau, but within the Plateau they are exposed only in the Uncompahgre Plateau, Grand Canyon, Zuni Mountains, and at one small locality on the Defiance uplift.

Generally, in these areas the pre-Cambrian consist of one or more very thick series of metasedimentary and metavolcanic rocks and a series of large and extensive intrusions. The troughs in which the metasediments and metavolcanics were deposited were deep, but data are not available to determine their trends or whether they were narrow or broad. Nor is the trend of the foliation in the pre-Cambrian rocks known at enough places to cast light on the grain of the basement rocks beneath the Colorado Plateau.

At this stage in our knowledge the principal interest in the pre-Cambrian rocks, so far as Cenozoic history is concerned, is the fact that the pre-Cambrian igneous rocks, like the Cenozoic ones, are dominantly subalkalic although they include some alkalic types. Also, amphibolite, a common inclusion in Cenozoic intrusions, is abundant in the pre-Cambrian rocks.

Principal references to studies of pre-Cambrian rocks on the Colorado Plateau are as follows: Grand Canyon area, Noble and Hunter (1917), Campbell and Maxson (1938); Defiance upwarp, Gregory (1917, p. 17); Zuni Mountains, Lindgren, Graton, and Gordon (1910, p. 136); Uncompahgre Plateau, Dane (1935). Some references to studies of the pre-Cambrian rocks around the Plateau are: Hunter (1925); Cross and Larson (1935); Anderson (1951); and Calkins and Butler (1943).

SUMMARY OF PALEOZOIC AND MESOZOIC STRATIGRAPHY

During most of Paleozoic and Mesozoic time the Colorado Plateau was a shelf area and was without deep geosynclinal basins except during Pennsylvanian time (figs. 8, 10). Pre-Tertiary rocks on the Plateau are very much thinner than they are to the east, north, and west of the Plateau. This pre-Tertiary history of comparative stability no doubt was an important factor controlling the events during Cenozoic time, which resulted in the Colorado Plateau becoming a distinctive province.

Cambrian to Devonian sedimentary rocks are thin or absent on the Plateau. They are absent on the Uncompahgre, Zuni, and Defiance upwarps. They are a few hundred feet thick and thicken westward in the Grand Canyon, along the southwest rim of the Plateau, and along the north edge of the Uinta Basin. A moderate thickness of lower Paleozoic rocks may underlie some of the basins on the Plateau.

By contrast, in the Basin and Range province, immediately west of the Plateau, the lower Paleozoic rocks are 10,000 to 20,000 feet thick. The lower Paleozoic deposits also thicken southward across southern Arizona and southern New Mexico. To the east, in the Rocky Mountain Province, the lower Paleozoic rocks are mostly thin, but in central Colorado there was a basin in which 1,000 feet of lower Paleozoic sediments was deposited (Lovering, 1932, pl. 2). Therefore, during Cambrian to Devonian time the Plateau seems to have been a stable shelf area bordered on at least three sides by deep troughs.

Mississippian to Permian rocks on the Plateau also are thin by comparison with those to the west, but in the north-central part of the Plateau a deep trough developed during Pennsylvanian time. This trough, which is known as the Paradox Basin and which apparently is elongated northwestward, lay southwest of the Uncompahgre Plateau. The plateau was an unstable area which was uplifted intermittently during the late Paleozoic and early Mesozoic time, as well as later. At least 7,000 feet of Pennsylvanian marine shale and interbedded salt or other evaporites were deposited in the Paradox Basin. These salt deposits in the Paradox Basin have resulted in salt plugs and salt anticlines (fig. 40). Northeast of the Colorado Plateau, in Colorado, there seem to have been other Pennsylvanian troughs similar to the Paradox Basin. All of these troughs are continuations of the Pennsylvanian troughs that extended in a northwesterly

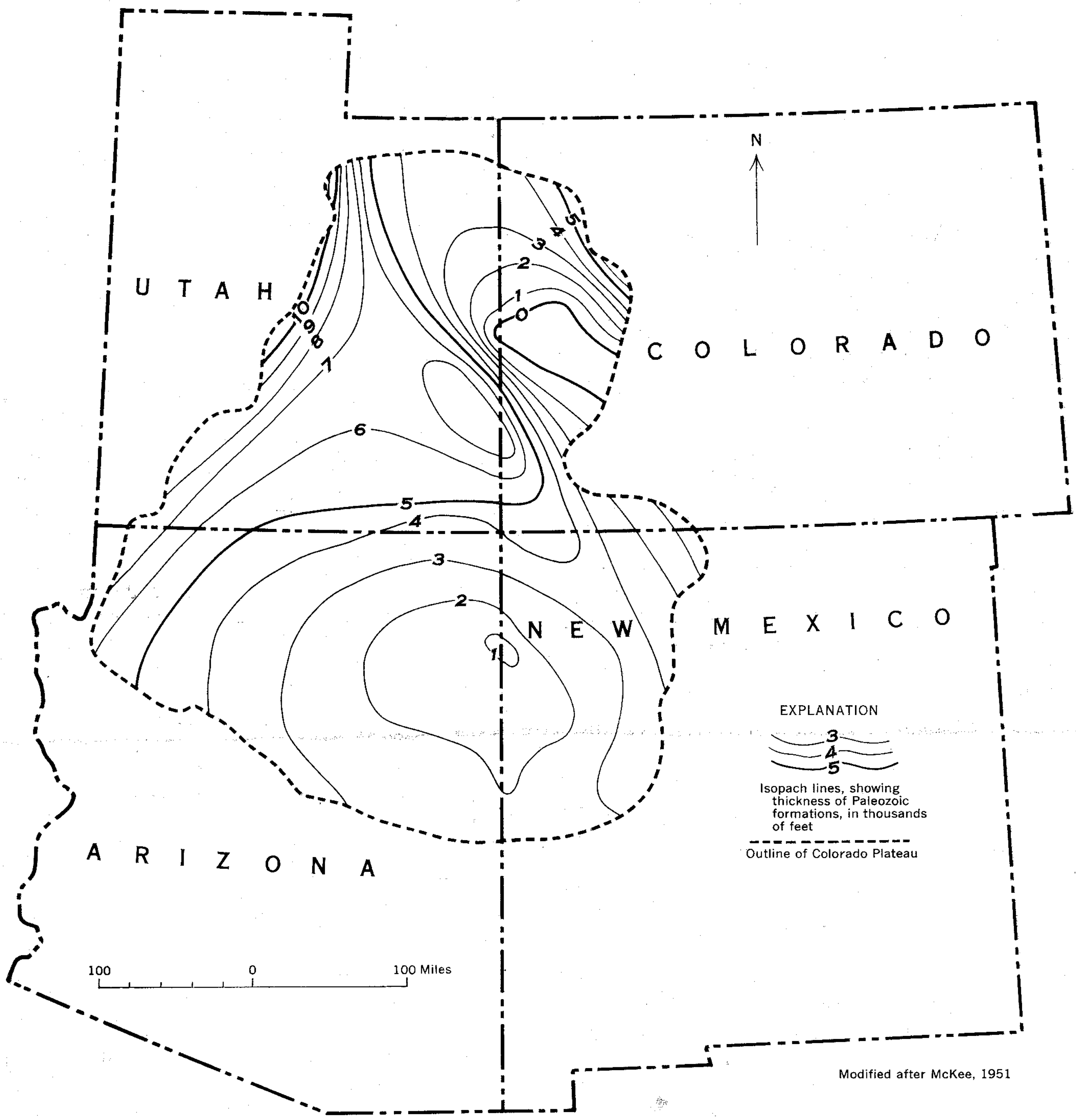


FIGURE 8.—Isopach map showing thickness of Paleozoic formations on the Colorado Plateau.

direction across the Rocky Mountain System. With the exception of the Paradox Basin, the Mississippian to Permian rocks on the Plateau do not exceed 2,500 feet in thickness.

The upper Paleozoic rocks thicken tremendously westward in the Basin and Range province. They are more than 20,000 feet thick in northwestern Utah (Gilluly, 1932, p. 7) and become much thicker eastward. In the central Colorado Basin they are 5,000 feet thick (Lovering, 1932, pl. 2), and in the Sangre de Cristo Range they are 12,000 feet thick (Johnson, 1929, p. 5).

During late Paleozoic time, therefore, most of the Colorado Plateau seems to have been a stable shelf area between deep troughs that lay to the east and to the west. In Pennsylvanian time the east-central part of

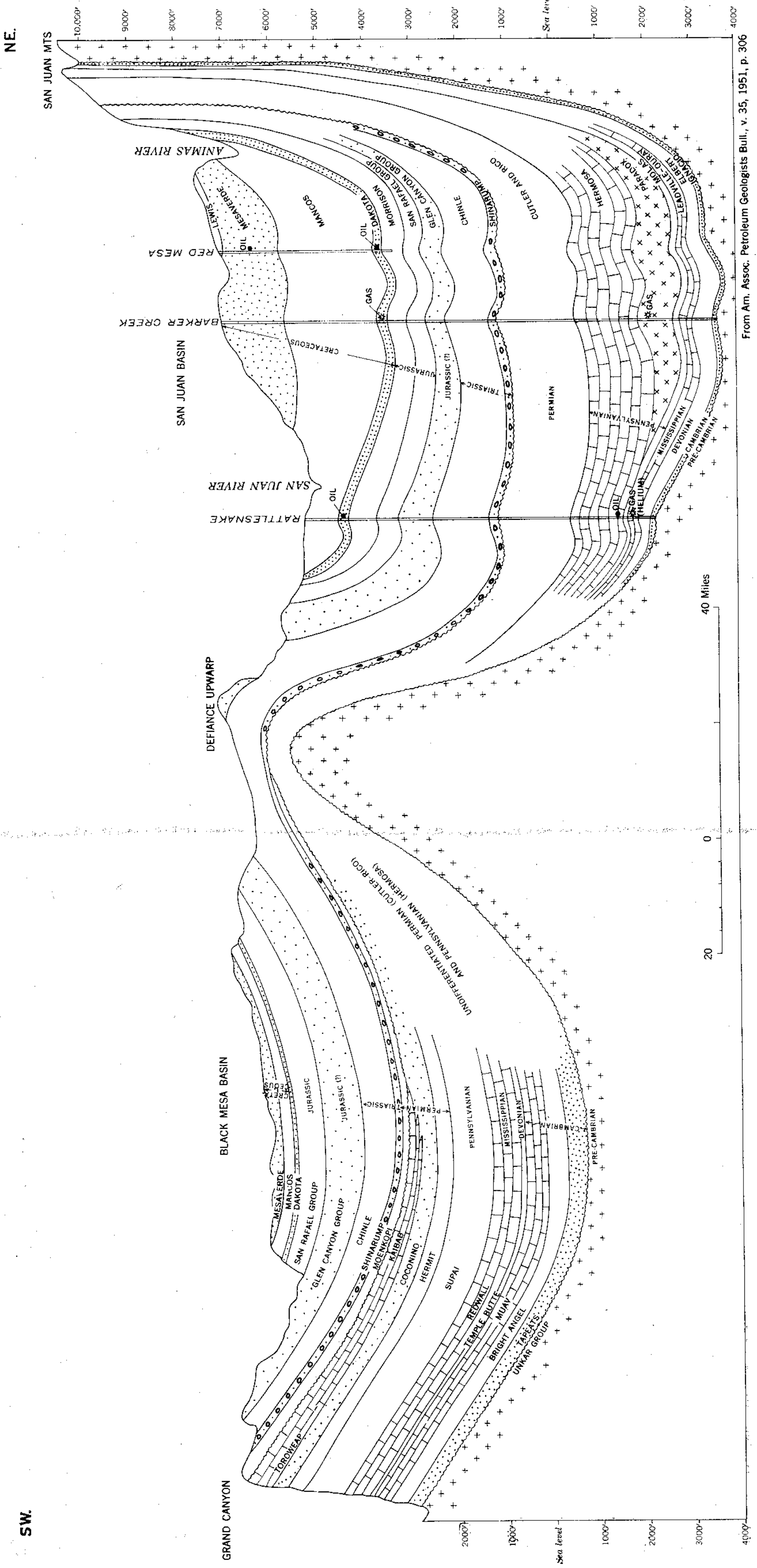


FIGURE 9.—Cross section of basin under Black Mesa and of San Juan Basin.

the Plateau was downfolded in a northwestward-trending trough. In addition, there seems to have been an arch trending northwestward across the south-central part of the Plateau, because in the Zuni Mountains and in the Defiance upwarp Permian strata rest directly on the pre-Cambrian rocks (figs. 9, 38).

Variations in total thickness of the Paleozoic formations on the Colorado Plateau are illustrated in figure 8.

The Colorado Plateau continued to be a stable area during most of the Mesozoic (fig. 10). The Triassic formations throughout the Plateau are redbeds, and at most places they aggregate about 1,000 feet in thickness. Neither the lithology nor the thickness vary markedly within the Plateau, but westward in the Basin and Range province they thicken to more than 3,000 feet.

The Jurassic formations thicken westward across the Plateau from less than 1,000 feet near the Rocky Moun-

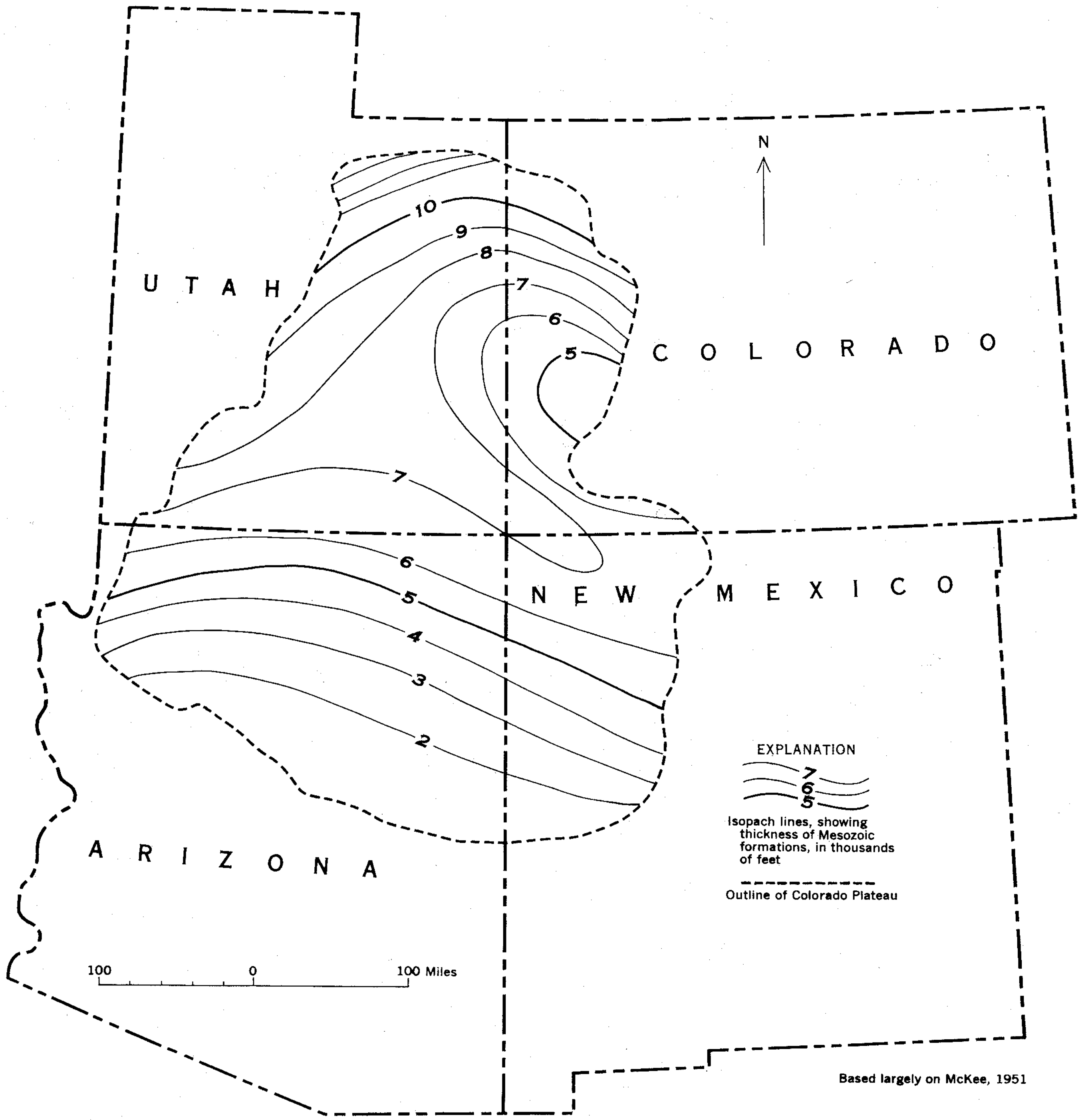


FIGURE 10.—Isopach map showing thickness of Mesozoic formation on the Colorado Plateau.

tains to more than 3,000 feet along the west edge of the Plateau (Baker, Dane, and Reeside, 1936, pl. 10), and immediately west of the Plateau they are at least 11,000 feet thick (Spieker, 1946). An angular unconformity at the base of the Carmel formation along parts of the Defiance upwarp records folding in that area during Jurassic time (Wright and Becker, 1951, p. 609, fig. 2). Prior to Late Cretaceous time the part of the Colorado Plateau southwest of the Little Colorado River was tilted northeastward with the result that the Upper Cretaceous formations overlap southwestward across the older Mesozoic and later Paleozoic formations (fig. 11).

tions that have been recognized on, or adjacent to, the Colorado Plateau.

LOWER TERTIARY DEPOSITS (PALEOCENE AND EOCENE)

Lower Tertiary deposits in the Uinta Basin and High Plateaus include a large proportion of lacustrine sediments in addition to fluviatile sediments. These deposits record a downwarping to accommodate the lakes, a filling of these lakes with sediments derived from adjoining highlands, and a building-up of the surface by deposition of fluviatile sediments. Furthermore, they record many stages of deformation during

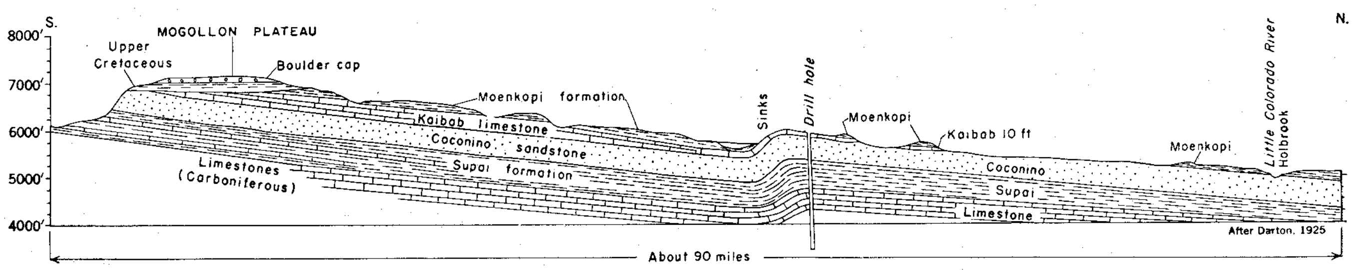


FIGURE 11.—Cross section of Mogollon Rim, illustrating overlap of Upper Cretaceous formations southward onto Permian formations.

Upper Cretaceous strata in the southeastern and northwestern parts of the Colorado Plateau aggregate 6,000 to 7,000 feet in thickness. They appear to thin somewhat southwestward, and they thicken considerably at the northeast corner of the Plateau. On the whole, however, the Plateau seems to have been submerged as a unit block under the marine waters of the Late Cretaceous sea. There may have been a slight tilt northeastward. In general, the thickness of the Upper Cretaceous rocks is fairly constant, and the types of offshore, nearshore, and continental deposits are alike in different parts of the Plateau. However, the mountains that furnished the Upper Cretaceous sediments that were deposited across the area of the Plateau were developing immediately to the west and south.

CENOZOIC DEPOSITS

Early Cenozoic and late Cenozoic deposits are well represented on, or adjacent to, the Colorado Plateau but middle Cenozoic deposits are scarce. As a result, the early Cenozoic and late Cenozoic history of the Plateau can be reconstructed fairly satisfactorily but there are large gaps in the record for middle Cenozoic time. The accompanying chart (fig. 12) shows the probable correlation of the principal Cenozoic forma-

early Cenozoic time—a continuation and extension eastward of the deformation that, along the west edge of the Plateau, had begun in Cretaceous time. The lithology and paleontology of the deposits indicate that the northern and western parts of the Plateau continued at, or near, sea-level until the end of Eocene time.

In the early reports on the Uinta Basin and High Plateaus the oldest deposits were classed as Wasatch formation, and this name still is applied to the deposits in the southern High Plateaus and in the Uinta Basin east of the Green River. West of the Green River and in the Wasatch Plateau the term "Wasatch" has been replaced by other names. Spieker (1946, p. 137) has reviewed the difficulties in connection with the use of the term "Wasatch" for the earliest Eocene deposits in central Utah.

The lower Tertiary formations now recognized in this part of the Colorado Plateau are the fluviatile North Horn formation of Late Cretaceous and Paleocene age, the lacustrine Flagstaff limestone of Paleocene (?) age, the fluviatile Colton formation, the lacustrine Green River formation, the fluviatile Bridger and Uinta formations of Eocene age, and the fluviatile Duchesne River formation of Eocene or Oligocene age (figs. 13, 16).

Epoch	Provincial age (Wood and others 1941)	Faunal zone	Eastern Utah	Western Colorado	Northwest New Mexico	Northeast Arizona
Recent		Bison bison	Historic alluvium Pre-pottery alluvium Dune sand	Historic alluvium Pre-pottery alluvium	Historic alluvium Pre-pottery alluvium	Naha alluvium Tsegi alluvium Dune sand
Pleistocene		Equus	Moraines	Moraines Cerro stage till	Alluvium and other deposits	Jeddito alluvium
Pliocene	Blancan	Plesippus	? Sevier River formation; ? conglomerate in Castle Valley; and ? Parunuweap formation		Santa Fe formation	Hualpai limestone (of Longwell)
	Hemphillian	Dipoides		? Hinsdale formation		Bidahochi fm. Chuska ss. 3/
	Clarendonian	Eucastor				? Muddy Creek formation
Miocene	Barstovian	Monosaulax	? Brian Head formation	? Browns Park fm. ? Bishop cong.		
	Hemingfordian	Merychippus		? Creede formation ? Potosi volcanic series ? Silverton volcanic series ? San Juan tuff ? Lake Fork quartz latite ? Telluride conglomerate and Blanco Basin formation	? Datil formation 2/ ? Abiqui (of Smith) and Picuris (of Cabot) tuffs ? Popotosa formation ? El Rito formation (of Smith) ? Chicoma volcanic formation (of Smith) ? Espinosa volcanics (of Stearns)	
	Arikareean	Diceratherium				
Oligocene	Whitneyan Orellan Chadronian	Protoceras Oreodon Brontotherium				
Eocene	Duchesnean	Teleodus	Duchesne River formation 1/		Galisteo sandstone	
	Uintan	Amynodon	Uinta formation			
	Bridgerian	Orohippus	Bridger formation Green River formation			
	Wasatchian	Hyracotherium	Wasatch and Colton formations	Debeque formation (of Wood and others) Wasatch fm. or San Jose fm. (of Simpson)	Wasatch formation Canyon Largo group (of Wood and others)	
Paleocene	Clarkforkian	Plesiadapis	Flagstaff limestone	? Ohio Creek conglomerate	So-called Tiffany beds	
	Tiffanian		? Tuscher formation			
	Torrejonian	Pantolambda	North Horn formation		Torrejon faunal zone of Nacimiento formation	
	Dragonian	Dracolaenus	Dragon local fauna (of Wood and others)			? Gravel on Mogollon Rim
	Puercan	Taeniolabis		? Ridgeway till	Puerco faunal zone of Nacimiento formation	
Upper Cretaceous		Triceratops		Hunter Canyon formation	Animas formation Ojo Alamo sandstone	? Tohachi shale
		Ceratopsia				

1 Duchesne River formation is considered to be either Eocene or Oligocene.
2 The age of the Datil formation is in doubt. It has been considered Miocene(?) by some authors.
3 Chuska sandstone which crops out on the east side of the Defiance upwarp may correlate with part of the Bidahochi formation on the west side of the upwarp. Allen (1953) designated the age as Pliocene(?).

Provincial ages, faunal zones, and many of the correlations are after Wood and others, 1941. The stratigraphic position and correlation of queried formations are highly uncertain. Major gaps in the section are indicated by shading

FIGURE 12.—Correlation chart of Cenozoic formations on, and adjacent to, the Colorado Plateau.

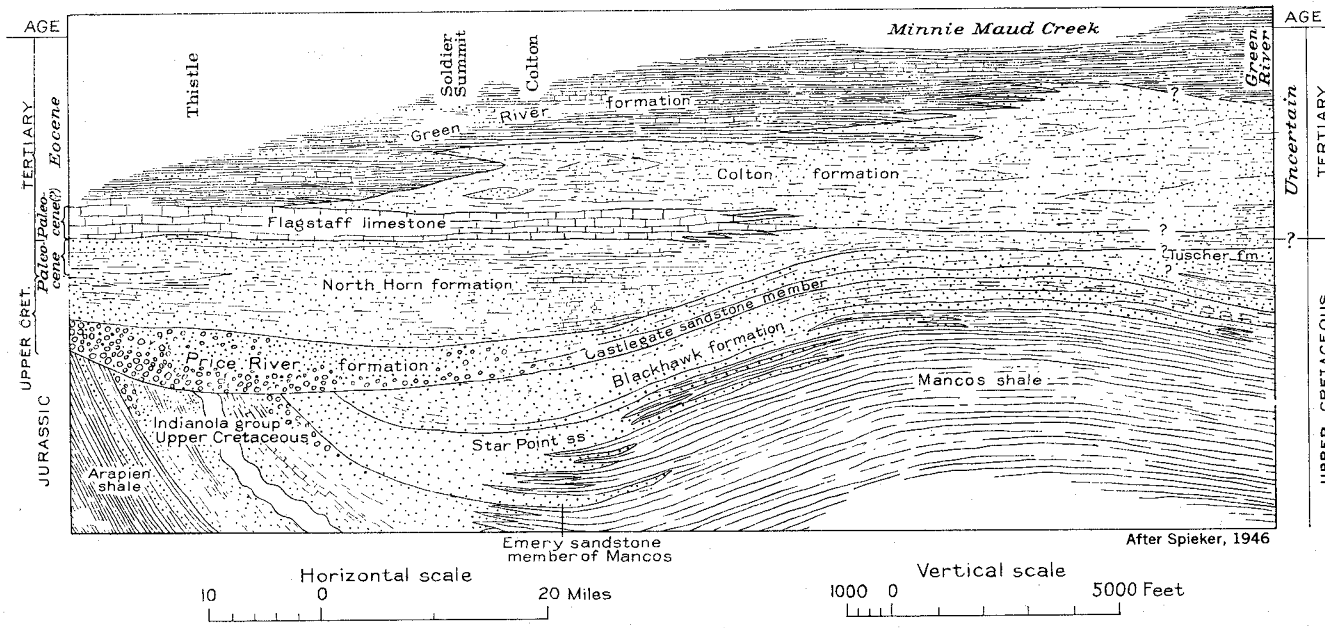


FIGURE 13.—Diagrammatic section of formations exposed in the western part of the Wasatch Plateau, and their relations eastward to Green River.

UINTA BASIN AND HIGH PLATEAUS

NORTH HORN FORMATION

The North Horn formation includes an assortment of lithologic types—variegated shale, sandstone, conglomerate, and fresh-water limestone. In general, the formation records rapidly shifting flood-plain and lacustrine conditions. It thins southwestward from about 2,500 feet (between Castlegate and Soldier Summit) to about 500 feet (Salina Creek). See figure 13. In the eastern part of the Wasatch Plateau, fresh-water limestone and other lacustrine beds are irregularly scattered throughout the formation, and in places it is impossible to define a contact with the overlying Flagstaff limestone. A few thin beds of poor coal are also present. (Spieker, 1946, p. 133, 140.)

The North Horn formation grades downward into the conglomerate or sandstone of the Price River formation, with no evidence of break, at all places where the two formations are known. Also, it passes transitionally upward into the Flagstaff limestone in most of central Utah. On the western margin of the Wasatch Plateau, however, the formation was tilted and truncated by erosion before the deposition of the Flagstaff. The disturbance that produced this angular unconformity was apparently confined to a narrow zone that is now roughly coincident with Sanpete Valley. Throughout the western piedmont of the Wasatch Plateau the Flagstaff overlies all older rocks in angular contact. Locally, the basal Flagstaff overlies steeply folded Jurassic and Cretaceous rocks in angular unconformity. Thus, despite the regional appearance of transition in the passage from North Horn to Flagstaff east of the Wasatch Plateau, in the western districts the two formations were unmistakably separated by a physical disturbance. (Spieker, 1946, p. 134).

Variegated lower Cenozoic deposits similar to the North Horn formation are extensive in the Rocky Mountain region and may record deep weathering under the influence of a warm, humid climate, erosion of the resultant soils, and their redeposition as lacustrine or fluviatile sediments (Van Houten, 1948). If this interpretation is correct, we may assume that the effects of climate controlled the kind of sediments that were deposited during the early Cenozoic, and we may further assume that the structural deformation controlled the continuity of the sedimentation.

The North Horn formation contains fresh-water mollusks and vertebrates. The latter, found in the lower and upper part of the formation, include dinosaurian, chelonian, and crocodilian remains. (Spieker, 1946, p. 134). The dinosaurian remains come from the lower 500 feet of the formation. The middle part has yielded no vertebrate fossile diagnostic of age, but the upper part contains mammalian bones of unquestionable Paleocene age. (Gazin, 1938.)

The North Horn formation thus embodies strata of latest Cretaceous and earliest Tertiary ages, probably to be correlated in some part with the Lance and Fort Union formations of the northern plains, and with the Ojo Alamo, Puerco, and Torrejon formations of the San Juan Basin. It is of especial interest and significance that the passage from Cretaceous to Paleocene is recorded by an apparently transitional succession of strata. No physical basis for regional subdivision of the strata grouped in the North Horn formation has been recognized, and in the present state of knowledge a boundary between Cretaceous and Paleocene cannot be mapped. The record is apparently even more complete than in Montana and Wyoming, where distinction between Lance and Fort Union has been the subject of much discussion. (Spieker, 1946, p. 1353.)

FLAGSTAFF LIMESTONE AND WASATCH FORMATION IN HIGH PLATEAUS

The Flagstaff limestone, a lacustrine deposit, is present throughout the Wasatch Plateau and has been traced about 30 miles to the east. Its extent northward and westward from the Wasatch Plateau is not known, but probably the limy lacustrine deposits that have been classed as Wasatch formation of the Wasatch Plateau are correlative with the Flagstaff.

In the Wasatch Plateau, the Flagstaff limestone consists chiefly of fresh-water limestone of many kinds, with interbedded shale and minor amounts of sandstone, gypsum, oil shale, and volcanic ash. In the western part of the Wasatch Plateau it contains some coal. The limestone in part is dense, homogeneous, exceedingly fine grained, and in part is cellular, like a compacted limy spring deposit. Some beds contain abundant ostracod or other fresh-water shells. The formation ranges from 200 to 1,500 feet in thickness and thickens westward and southwestward. (Spieker and Reeside, 1925; Spieker, 1931, 1946).

East of the Wasatch Plateau the Flagstaff limestone intertongues with the lower part of the Colton formation and grades into the variegated beds of that formation (fig. 13).

In the southern part of the High Plateaus, beds of early Tertiary age, 1,000 feet thick, have been referred to the Wasatch formation (Gregory and Moore, 1931, p. 114). These beds lithologically resemble the Flagstaff limestone and may be a southward extension of it. At their base, locally, is a conglomerate a few feet thick consisting of unusually well-rounded and smoothed pebbles of white and red quartzite, black chert, rhyolite, porphyry, and many kinds of dense igneous rocks. About 50 percent of the pebbles exceed 4 inches in diameter, which suggests that they have not been transported great distance—however, their source is not known. (Gregory and Moore, 1931, p. 114–115).

Overlying the conglomerate is a few hundred to more than a thousand feet of highly lenticular, limy beds. They include dense limestone, brecciated limestone, shaly limestone, and calcareous shale or sandstone. The unweathered rock is white or light pink, but the weathered surfaces are deep pink or red. Fossils contained in the dense and brecciated limestone include *Physa pleuromatis*, probably *P. bridgerensis*, and a small discoid shell that may be a *Valvata* or *Planorbis*. The surfaces of some of the calcareous sandstone beds are covered with plant impressions. (Gregory and Moore, 1931, p. 114–116).

The Flagstaff limestone, and the beds correlative with it, rest with angular unconformity on the older rocks along the west side of the Wasatch Plateau. At places in the southern part of the High Plateaus the Flagstaff limestone or Wasatch formation overlap all of the Cretaceous and many of the Jurassic formations where they have been sharply folded. (Spieker, 1946, p. 137). In the central and eastern parts of the Wasatch Plateau, and along the south and east rims of the Uinta Basin, the beds above and below the unconformity are parallel and apparently gradational (fig. 14).

These lacustrine deposits record Paleocene deformation at the extreme western edge of the Colorado Plateau and downwarping of the northwestern part of the Plateau. The limestone may be in part the product of spring or fumerole activity associated with the early Tertiary volcanism (p. 42), or it may be the result of erosion of Paleozoic limestone in the area immediately west of the Colorado Plateau.

TUSCHER, OHIO CREEK, AND DEBEQUE FORMATIONS

Along the southeastern rim of the Uinta Basin is a set of beds, mostly sandstone, overlying undoubted Upper Cretaceous formations and underlying undoubted Eocene formations. In the southeastern part

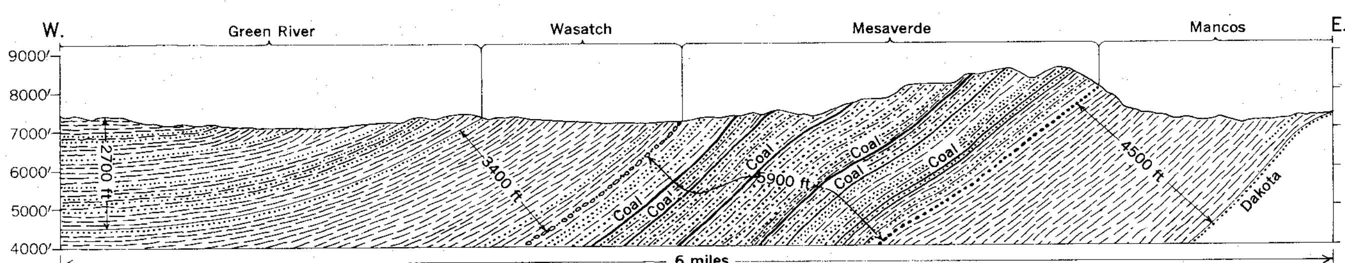


FIGURE 14.—Cross section of Grand Hogback, near Meeker, Colo. The beds shown as Wasatch probably include strata of Paleocene age.

of the Uinta Basin these sandstone deposits have been described as the Tuscher formation (Fisher, 1936, p. 20). Farther east in the Uinta Basin they have been mapped but not named (Erdmann, 1934, p. 53); still farther east, in west-central Colorado, is the Ohio Creek conglomerate (Eldridge, 1894), which may be equivalent to these early Tertiary(?) sandstones. These formations probably are early Tertiary in age and may correlate with Wood's DeBeque formation (Wood and others, 1941) of Paleocene and early Eocene age in western Colorado.

The thicknesses reported for the Tuscher and Ohio Creek formations range from 130 to 600 feet. Their base is commonly conglomeratic sandstone containing well-rounded pebbles of black, gray, or brightly colored chert and quartz. Limestone pebbles are scarce. The sizes range from ¼ to 2 inches in diameter; a few cobbles 6 inches in diameter are quartzite. (Erdmann, 1934, p. 54).

The beds above the conglomerate are mostly lenticular and crossbedded sandstone but they include some shale. Generally, there is an unconformity at the base of these beds, and it may mark a considerable hiatus, perhaps the first half of Paleocene time, but the contact with the overlying Wasatch formation seems to be gradational. Nevertheless, the beds above and below the unconformity are essentially concordant structurally; presumably therefore, there was little or no local folding here in earliest Tertiary or latest Cretaceous time.

COLTON AND WASATCH FORMATIONS IN UINTA BASIN

The Colton formation, a fluviatile deposit in the northern part of the Wasatch Plateau and southwestern part of the Uinta Basin, consists of lenticular sandstone, siltstone, and shale with little or no limestone and no coal. The colors are variegated—brown, yellow, and deep red. The formation has a maximum thickness of about 2,000 feet along Green River, but westward it thins by intertonguing with, and grading into, the shale of the Green River formation and the limy beds of the Flagstaff limestone (fig. 13). Eastward, the upper part of the Colton intertongues with, and grades laterally into, the Green River formation. The beds that are referred to as Wasatch in the eastern and northern parts of the Uinta Basin are, in part at least, correlative with the Colton formation. Along Green River, the formation rests unconformably, but concordantly, on the Paleocene North Horn formation and is overlain conformably by the Green River formation. (Spieker and Reeside, 1925; Spieker, 1931, 1946).

Early Tertiary fluviatile deposits in the eastern part of the Uinta Basin have been referred to as the Wasatch formation. The Wasatch rests conformably on the Upper Cretaceous formations. At the Grand Hogback along the east side of the Uinta Basin the beds that have been mapped as Wasatch, probably including some beds of Paleocene age, are turned up steeply and concordantly with the Upper Cretaceous formations (Hancock and Eby, 1930). See figure 14. The Wasatch formation in the northwestern part of the Colorado Plateau presumably is equivalent in part to the Colton, but it may include some strata of Paleocene age. The formation thins eastward in the Uinta Basin and comprises only 400 feet of drab mudstone with thin bands of red where it crosses the arch separating the Uinta Basin and Piceance Creek Basin (fig. 37). It thickens again eastward to more than 3,000 feet in the Piceance Creek Basin, where it consists chiefly of variegated mudstone with a subordinate amount of friable, medium-grained sandstone and some conglomerate. (Bradley, 1931, p. 8, 9).

The lower part of the Wasatch formation is very conglomeratic in the eastern part of the Piceance Creek Basin and south of Grand Mesa, but it becomes less conglomeratic westward and passes from conglomerate to sandstone and variegated mudstone. Pebbles in the conglomerate include acidic and basic igneous rocks, flint, vein quartz, and red and light-colored quartzite. Conglomerate is scarce at the western edge of the Piceance Creek Basin, but occasional lenses of pebbles include some limestone that may have been derived from the Flagstaff limestone to the west (Lee, 1912; Hancock and Eby, 1930, p. 209; Erdmann, 1934, p. 56); but probably most of the Wasatch formation in the Piceance Creek Basin was derived from the east.

The extensive conglomerate in the lower Cenozoic formations on the Colorado Plateau generally has been interpreted as the result of vigorous dissection, presumably fluviatile dissection, of newly uplifted tectonic blocks. Without doubt, some of the deposits are essentially tectonic in origin, although the evidence points to repeated small movements rather than to one of catastrophic dimensions. On the other hand, it seems quite possible that the gravels represent outwash resulting from glacial or periglacial activity in the mountains. There is evidence of early Tertiary glaciation in the San Juan Mountains (p. 26). Furthermore, alpine glacial or periglacial activity is a common source for gravel whereas tectonic breccias rarely are extensive. Lastly, it is doubtful that large volumes of rocks and rock fragments would be supplied to streams in the absence of frost action.

GREEN RIVER FORMATION

Conformably overlying the Wasatch and Colton formations, and grading laterally into them, is the lacus-

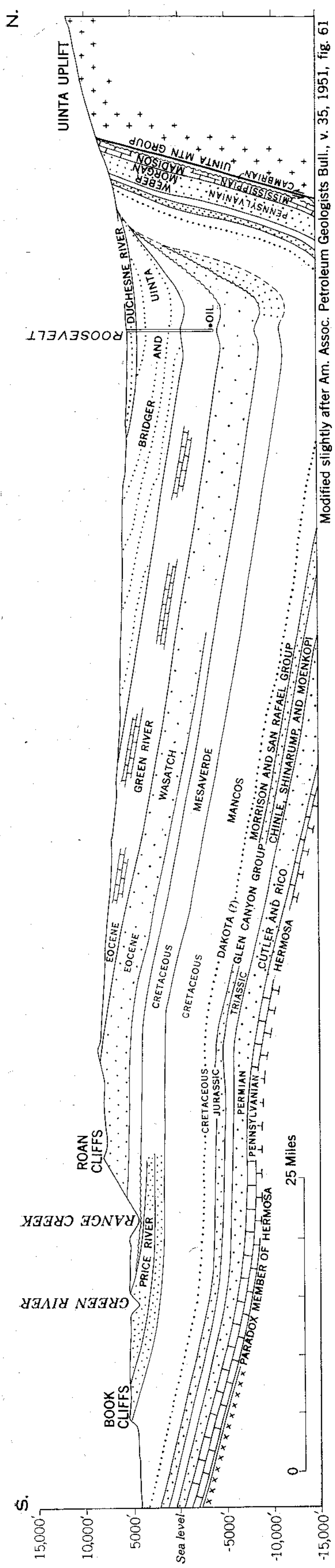


FIGURE 15.—Diagrammatic cross section of the Uinta Basin north from Green River, Utah.

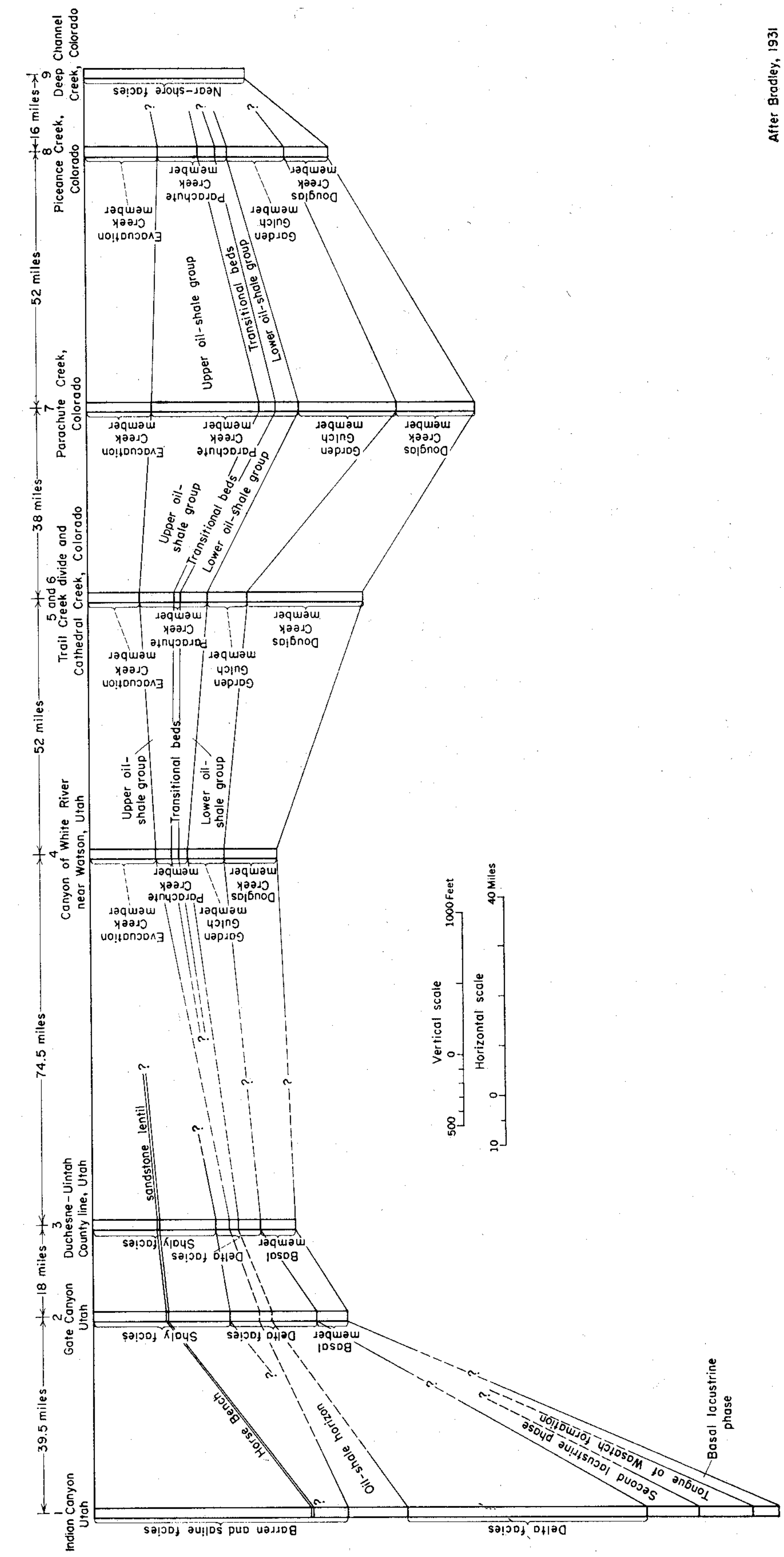


FIGURE 16.—Stratigraphic relations of the subdivisions of the Green River formation in Colorado and Utah.

trine Green River formation of middle Eocene age. It underlies the Uinta Basin (fig. 15) and extends northward into the Wyoming Basin.

The Green River formation can be divided into four members (fig. 16). At the base is the Douglas Creek member, which is composed of 200 to 800 feet of buff or yellow-brown shale containing considerable sandstone, marlstone, algae reefs, and oolite. Overlying this is the Garden Gulch member, which is composed of 200 to 700 feet of marlstone or organic-rich shale in paper-thin laminae and some fine-grained sandstone and siltstone. Next higher is the Parachute Creek member, which is 1,000 feet thick and which contains most of the oil-shale beds in the formation. The Evacuation Creek member, at the top of the Green River formation, is 2,000 feet thick in the western part of the Uinta Basin, but thins eastward to 500 feet. It consists chiefly of barren shale and marlstone. (Bradley, 1931, p. 9–14.)

In the northeastern part of Uinta Basin, a shore and delta facies of the Green River formation, 1,100 to 1,200 feet thick, consists of sandstone and shale that grade southward into finer-grained offshore facies. Other deltaic deposits in the central and western parts of the Uinta Basin, where the formation is at least 4,000 feet thick, intertongue with the Colton or Wasatch formations (fig. 17). (Bradley, 1931, p. 14–19.)

The change from nearshore to offshore lake beds southward in the Uinta and Piceance Creek Basins shows that the Uinta Mountains were a source of the Green River formation. Considerable upwarp of the Uinta Mountains preceded deposition of the Green River formation but there also was a later upwarp (p. 57). An interpretation of the climatic conditions that prevailed while the Green River formation was being deposited is given on page 64.

It is not possible to accurately determine the southern limit of the Green River lake. Southeastern Utah, during Green River time, was at the northern end of an epeirogenic platform that included most of the Colorado Plateau south of the Uinta Basin (p. 64). Southward, the lake probably ended against the north flank of this platform (fig. 56). It probably extended southward in great bays located in structural basins similar to the Henry Mountains basin. The Uncompahgre Plateau is assumed to have been a peninsula dividing the bay in Piceance Creek basin from shallower bays in southeastern Utah. Uplifts, such as the San Rafael Swell and Monument upwarp, may have stood above

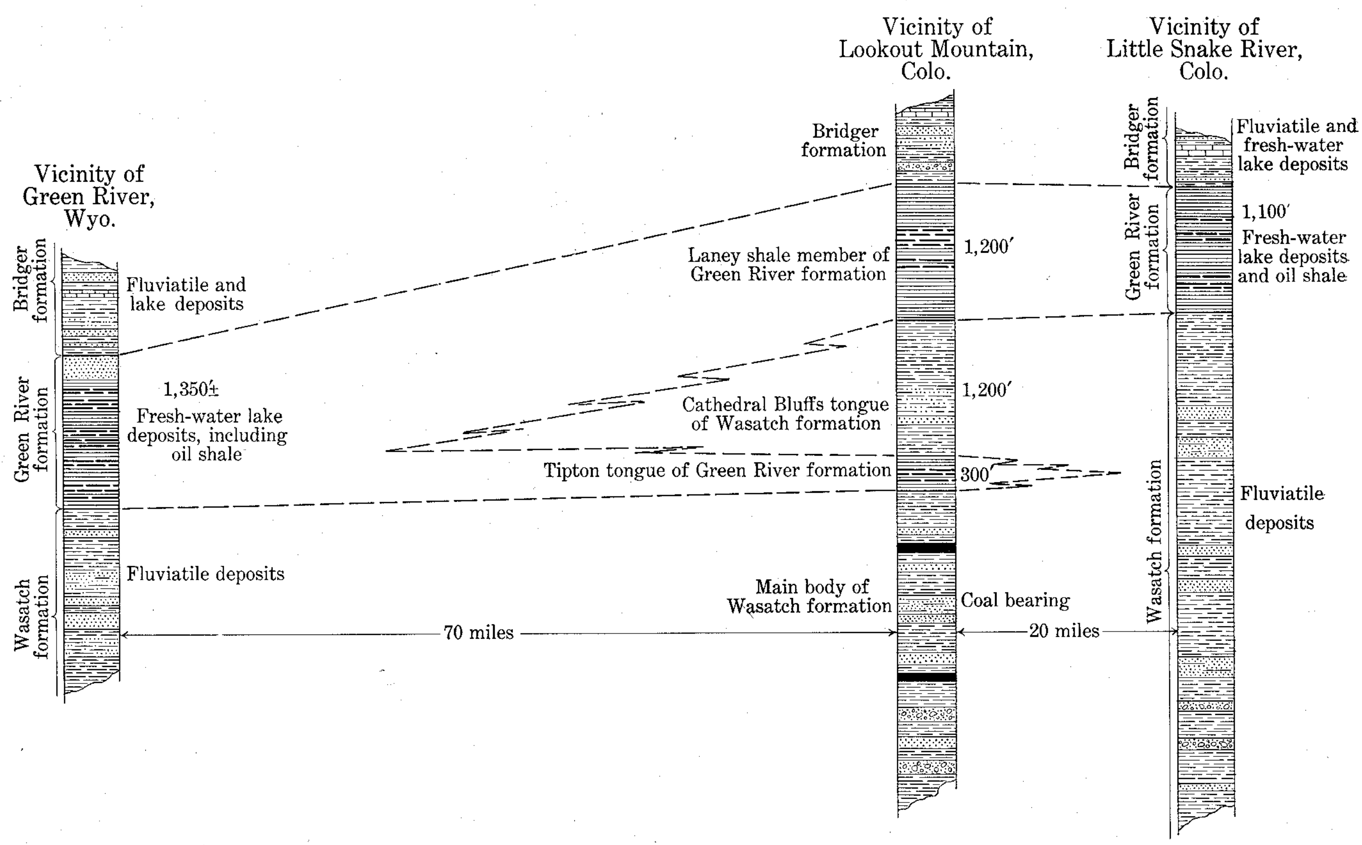


FIGURE 17.—Sections from northwest to southeast in the Green River Basin, Wyo. and Colo., showing intertonguing of the Wasatch and Green River formations.

water level. There is no reason to suppose that the Arizona or New Mexico segments of the Colorado Plateau were more than slightly higher than the lake.

BRIDGER FORMATION

Overlying the lacustrine Green River formation is the fluviatile Bridger formation, which consists of about 1,000 feet of sandstone and subordinate amounts of shale and conglomerate. Beds of sandstone are thick, brown, massive or crossbedded, and medium- to coarse-grained. The shale is greenish-gray sandy mudstone.

In most places, the Bridger rests with apparent conformity on the Green River formation. Locally, however, the contact is very irregular with a relief of 50 feet, but this irregularity is attributed to differential compaction rather than to an erosional unconformity (Bradley, 1931, p. 20).

Although there is no angular discordance between the Bridger and Green River formations along the southern edge of the Uinta Basin, an angular unconformity at the base of the Bridger is inferred along the northern edge of the basin where the contact is concealed by the northward overlap of the Uinta formation. The overlap of the Uinta formation onto Green River and older formations along the northern edge of the basin establishes the existence of an angular unconformity, and it seems probable that this unconformity is between the Bridger and Green River rather than between the Uinta and Bridger, because the Bridger and Uinta formations are very similar lithologically whereas they are very different from the Green River formation. Moreover, on the northern side of the Uinta Mountains there is an angular unconformity at the base of the Bridger. (Sears and Bradley, 1924, p. 96; Bradley, 1931, p. 22.)

It is probable that the Bridger and younger Eocene fluviatile deposits extended southward at least as far as the southern limit of the Green River formation. Playa, or perhaps lake, conditions may have existed in the Henry Mountains basin while the fluviatile formations were being deposited in the Uinta Basin (fig. 57). This late Eocene drainage probably had no outlet, because at this time the Colorado Plateau area was low, and, except for the San Juan Basin, all the basins were surrounded by mountains or other highlands, at least until the end of Eocene time.

UINTA FORMATION

The Uinta formation, also a fluviatile deposit, is about 1,000 feet thick and is lithologically similar to the Bridger and separable from it only on the basis of vertebrate fossils. Along the southern edge of the Uinta Basin the Uinta formation conformably overlies the Bridger, but along the northern side of the basin it overlaps onto the Mesaverde formation of Late Cretaceous age. As pointed out in the preceding section, however, an angular unconformity between the Uinta and Bridger formations seems unlikely, but the Bridger might be expected to rest with angular discordance on the Green River formation.

In the northwestern part of the Uinta Basin, the lower Tertiary deposits, which are several thousand feet thick, unconformably overlie folded and faulted Mesozoic rocks including the Currant Creek formation, which probably is of Late Cretaceous or Paleocene age (Bissell, 1952, p. 614) but possibly Eocene age (Williams, 1950, p. 106). The definitely Tertiary deposits, however, have not been traced laterally into the other Tertiary formations in the Uinta Basin and have been mapped as Uinta(?) formation (Kay, 1934, p. 357–372; Walton, 1944, p. 122 and pl. 2). It seems likely that these deposits include nearshore lacustrine or fluvial facies, or both, of the Green River formation and equivalents of the Bridger formation.

The original extent of the Uinta formation probably was similar to that of the Bridger.

DUCHESNE RIVER FORMATION

The fluviatile Duchesne River formation consists of about 1,300 feet of cliff-forming, reddish-brown sandstone. Along the southern side of the Uinta Basin the sandstone conformably overlies the soft clays of the Uinta formation, but northward it is unconformable on the older formations.

Opinions differ as to whether the Duchesne River formation should be classed as latest Eocene or earliest Oligocene, but in any case the Duchesne River fauna generally is regarded as transitional between the Uintan and the Chadronian (Wood and others, 1941).

The limits of the Duchesne River formation are not well known. It may be more extensive than has been supposed and may be represented in the deposits that elsewhere have been mapped as the Uinta formation.

The lower part of the Duchesne River formation consists of 500 feet of variegated clay alternating with brown and gray sandstone (Randlett Horizon of Kay, 1934). Overlying this is 500 feet of conglomerate, sandstone, and shale (Halfway horizon of Kay, 1934). Above this is 300 feet of conglomeratic sandstone, sandy clay, and coarse conglomerate (Lapoint horizon of Kay, 1934).

The original extent of the Duchesne River formation probably was similar to that of the Bridger. However, the fact that strata younger than Duchesne River do not occur in the Uinta Basin suggests that a major change in drainage conditions occurred at about this time. Either the supply of sediments became cut off, or the streams hereafter transported most of their loads past the areas that had been aggraded during Eocene time. It is very likely that both happened. The Uinta and other mountains that were eroded during Eocene time must have become greatly reduced by Oligocene time; and it seems probable that the Colorado Plateau began to be raised during Oligocene time (p. 64).

SAN JUAN BASIN

Deposits of early Tertiary age in the San Juan Basin include the upper part of the Animas formation, the Puerco and Torrejon formations, and the Wasatch formation (including the so-called Tiffany beds). Unlike the lower Tertiary deposits in the Uinta Basin, all these deposits are of fluviatile origin. Their aggregate thickness in the northern part of the basin, near the San Juan Mountains which was a source area, is nearly 5,000 feet, but in the southern part of the basin they are only about 1,000 feet thick (fig. 18).

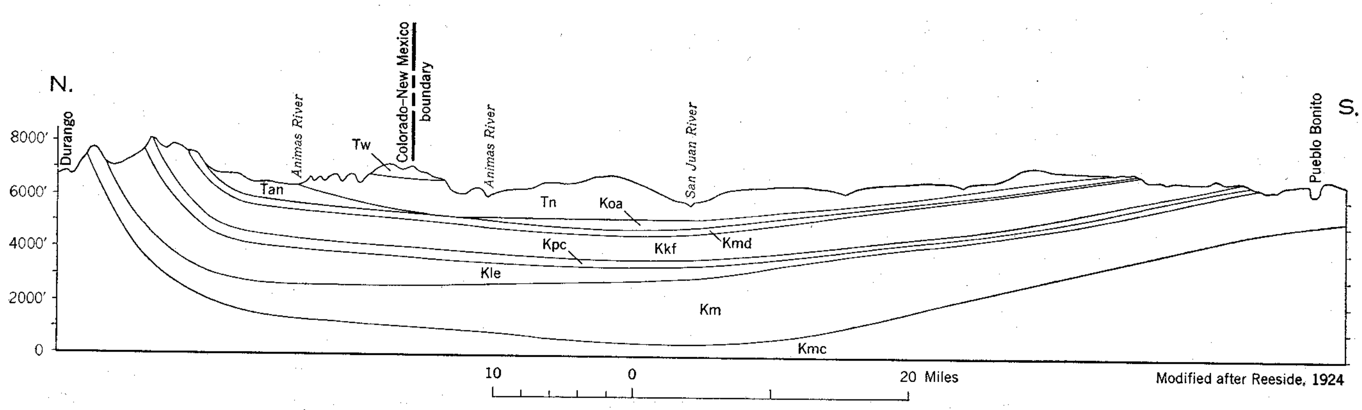
The youngest Upper Cretaceous deposits under these lower Tertiary formations, the Ojo Alamo sandstone and lower part of the Animas formation, are believed to be correlative with the lower part of the North Horn formation of the High Plateaus. The upper part of the Animas, the Puerco and Torrejon formations, and part of the Wasatch formation, including the so-called Tiffany beds, are equivalent to the Paleocene formations represented in the Uinta Basin. The vertebrate fauna of the Wasatch formation in the Uinta Basin is correlative with the fauna of the Wasatch formation in the San Juan Basin. However, deposits of Bridgerian, Uintan and Duchesnean age (terminology of Wood and others, 1941) are not represented in the San Juan Basin.

The Wasatch formation is upturned against the San Juan and Nacimiento Mountains, thus indicating post-Wasatch uplift of these mountain areas. In addition, an angular unconformity at the base and top of the Animas formation in the northern part of the basin indicates two earlier stages of upwarp in the San Juan Mountains. The northward dip of these formations in the southern flank of the San Juan Basin indicates that it too was raised in post-Wasatch time.

ANIMAS FORMATION

The fluviatile Animas formation is restricted to the northern end of the San Juan Basin where it attains a maximum thickness of about 2,700 feet. The lower part is coarse conglomerate; the upper part is mostly shale and sandstone but contains numerous thin layers of conglomerate. A high proportion of the pebbles are andesitic. Vegetable debris is common, and locally it is sufficiently abundant to form thin coal beds, especially eastward across the northern end of the San Juan Basin (Reeside, 1924, p. 32–34).

In the northwestern part of the San Juan Basin the Animas formation is unconformable on the McDermott formation, which is of Late Cretaceous age and which also is composed very largely of andesitic debris. Locally, the unconformity between the two formations is an angular unconformity, as along the Animas River. Eastward, the Animas formation overlaps successively onto the McDermott formation, Kirtland shale, and part of the Fruitland formation. The top of the Animas formation in the northwestern part of the basin also is an unconformity, and it is overlapped by the Torrejon formation and by the Wasatch formation. (Reeside, 1924, p. 32–34; Silver, 1951, p. 118). On the other hand, in the northeastern part of the basin the Animas apparently intertongues with Upper Cretaceous formations as old as the Lewis shale (Dane, 1946). See figure 19. Thus, the lower part of the Animas is regarded as Late Cretaceous age, and the upper part is Paleocene.



Tw, Wasatch formation; Tn, Nacimiento formation (Puerco and Torrejon faunal zones): Tan, Animas formation; Koa; Ojo Alamo sandstone; Kmd, McDermott formation; Kkf, Fruitland formation and Kirtland shale; Kpc, Pictured Cliffs sandstone; Kle, Lewis shale; Km, Mesaverde group; Kmc, Mancos shale

FIGURE 18.—Diagrammatic section across the San Juan Basin from Durango, Colo., to Pueblo Bonito, N. Mex.

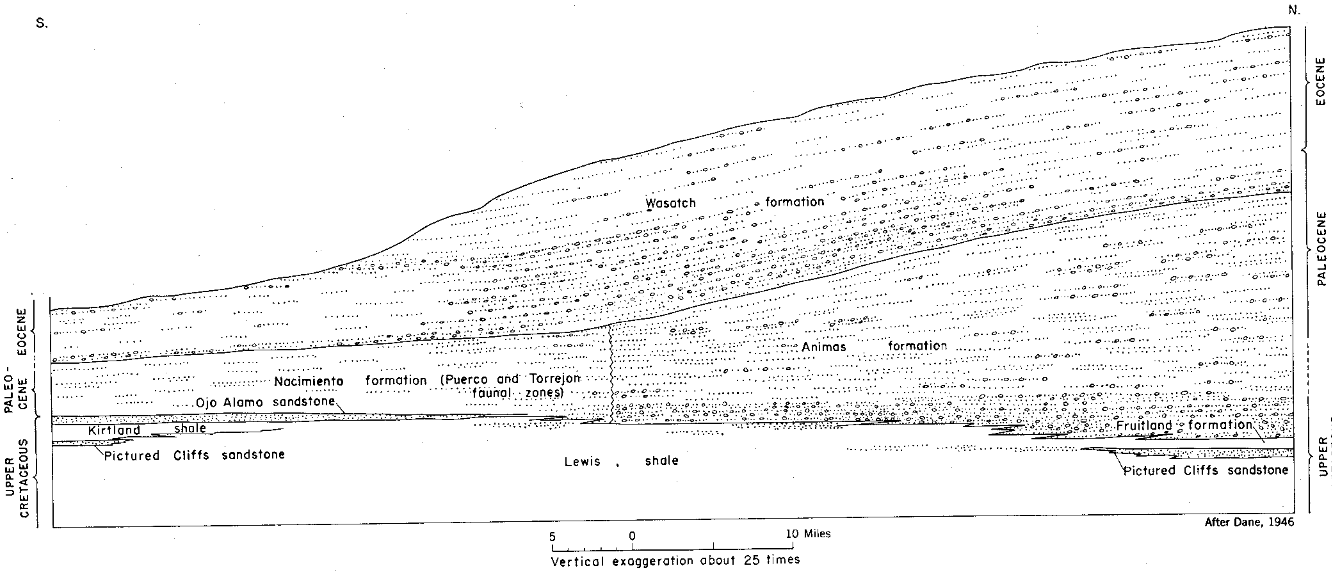


FIGURE 19.—Diagram showing inferred stratigraphic relations of Paleocene and Eocene formations on east side of San Juan Basin.

The andesitic debris in the Animas formation apparently was deposited by streams flowing southward from the San Juan Mountains. Some of the siliceous material in the formation, however, is similar to that in the Ojo Alamo sandstone (an Upper Cretaceous formation that does not extend to the northern part of the San Juan Basin) and to that in the McDermott formation, which unconformably underlies the Animas. These siliceous materials are unlike any that are known in the San Juan Mountains and must have been derived from some other source.

NACIMIENTO FORMATION (PUERCO AND TORREJON FAUNAL ZONES)

The Puerco and Torrejon faunal zones, which have previously been described as formations, have been referred to (jointly) as the Nacimiento formation. They are quite alike in lithology, but their faunas are sufficiently different that vertebrate paleontologists believe they are separated by an important hiatus although the stratigraphic position of the hiatus has not yet been discovered. (Reeside, 1924, p. 35–44; Dane, 1936, p. 122–124).

In the northern part of the San Juan Basin the Nacimiento formation consists of brown conglomeratic sandstone interbedded with red and gray shale. In the southern part of the basin it consists largely of banded and sandy clays of dull colors with some interbedded sandstone. The formation is about 1,500 feet thick along the western side of the basin, about 400 feet thick along parts of the north rim, and about 800 feet thick in the southeastern part of the basin. Presumably, the thinning is due, in part at least, to unconformities at the base, top, or within the formation. (Reeside, 1924, p. 35–44; Dane, 1936, p. 122–124.)

The mammalian faunas of the Puerco and Torrejon faunal zones are marked by the abundance of primitive mammals, turtles, and crocodiles and by the absence of dinosaurs. Although there is no discernable stratigraphic break between the two zones, the two faunas do not have a single species in common, and only three or four genera are in common. The younger fauna has been judged to be a lineal descendant of the older, and, because of the physical geology gives no basis for attributing the faunal difference to facies change of migration, a hiatus is inferred. (Reeside, 1924, p. 35–44.) The Puerco fauna is regarded as earliest Paleocene.

Both the physical geology and the paleontology indicate that the Nacimiento formation represents deposits that accumulated on the surface of floodplains or on broad, gently sloping, coalesced alluvial fans. The mammal bones generally are not articulated and occur with the remains of fish, crocodiles, and turtles, thus leading to the belief that the bones had been washed into streams. A heavy growth of vegetation along the streams and in the interstream areas is indicated by the abundant remains of leaves of figs, plane trees, poplars, relatives of the breadfruit, and various shrubs. The invertebrate fauna includes both terrestrial and fresh-water shells. (Sinclair and Granger, 1914, p. 309, 313.) The drab beds may have been deposited in forest swamps and heavily wooded areas of a savanna environment, while the redbeds were accumulating in the more open country (Van Houten, 1948, p. 2084). The absence of gravel attributable to sources in the San

Juan Mountains suggests that those mountains had become reduced in height and presumably were below the level of much frost action. Perhaps a part of the Nacimiento formation was derived from the west as a result of erosion of Upper Cretaceous and other formations uplifted in the Defiance upwarp.

WASATCH (SAN JOSE OF SIMPSON) FORMATION (AND SO-CALLED TIFFANY BEDS)

The Wasatch formation in the San Juan Basin is at least 2,000 feet thick and probably exceeds 2,500 feet. In the northern part of the basin it is composed chiefly of variegated shale with beds of coarse arkose containing abundant pink feldspar. In the western and southern parts of the basin, at the base, is a massive and persistent gray to brown conglomeratic sandstone, 150 to 300 feet thick, locally containing some interbedded shale. Above, is mostly variegated red shale. Because the upper part of the formation has been eroded, the original variations in thickness in different parts of the basin are not known. (Reeside, 1924, p. 44–48; Dane, 1936, p. 125; 1946.)

The Wasatch formation seems to be conformable on the Torrejon faunal zone, but locally along the contact there are irregularities, such as channeling; however, in general, the lithologies of the two formations are gradational. The upper part of the formation in the San Juan Basin contains the fauna that includes *Eohippus* (now called *Hyracotherium*) and its associated forms, and in general it is similar to the Wasatch and Colton formations in the Uinta Basin (Reeside, 1924; Dane, 1936).

In the northeastern part of the San Juan Basin the lower part of the Wasatch formation contains the so-called Tiffany fauna, which is intermediate between that of the Torrejon and that of the higher Wasatch beds—intermediate in the sense that it includes genera found in the typical Torrejon but not in the typical Wasatch, and genera found in the typical Wasatch but not in the typical Torrejon (Simpson, 1935, p. 3–8). The beds containing the so-called Tiffany fauna have been mapped as part of the Wasatch and may occur as much as 1,000 feet above the base of the formation. The Wasatch formation, therefore, as mapped in the San Juan Basin, includes an undetermined thickness of Paleocene strata. (Dane, 1946.) Because of the uncertain range in age of the Wasatch formation in the San Juan Basin and because of the difficulty of correlating it with the type Wasatch, Simpson (1948) proposed that its name be changed to San Jose formation.

The Wasatch formation in the San Juan Basin seems to have been derived from the San Juan Mountains. The occurrence of conglomerate at the base of the Wasatch suggests that the San Juan Mountains may have become raised above frost line at the beginning of Wasatch time. The occurrence of variegated beds in the upper part of the Wasatch suggests restoration of the conditions that prevailed during Nacimiento time. The fact that the Wasatch rises northward towards the San Juan Mountains indicates that those mountains were further uplifted in post-Wasatch time. The Nacimiento Mountains and the south flank of the San Juan Basin also were uplifted after the Wasatch formation had been deposited, although they may have started to rise earlier than this. In any case, the Wasatch formation seems to have been deposited by streams that drained southward or southeastward across the San Juan Basin, and they seem to have discharged in the general area of what later became the Rio Grande depression. Sometime after the Wasatch formation had been deposited, aggradation ended in the San Juan Basin, and thereafter the streams transported their loads beyond the limits of the basin. It is possible that the early Eocene aggradation of the San Juan Basin, coupled with post-Wasatch uplift of the east and south flanks of the basin, turned the drainage westward across the top, or around the ends, of the Defiance upwarp and thus into the basin under the Black Mesa of Arizona. We know that the drainage ultimately took a westward course, but we have no basis for guessing when it first did so.

MOGOLLON RIM

On the Mogollon Rim, in Arizona, at the very south edge of the Colorado Plateau are some bouldery gravel deposits that may be of early Tertiary age. The gravel, exposed west of Show Low, Ariz., where it overlies Cretaceous formations (fig. 11), evidently was derived from pre-Cambrian rocks and must have been transported northward from lofty mountains that lay south of the Plateau. The age of the gravel is not known. It may be of Late Cretaceous age and analogous to some of the conglomerate in central Utah that had been regarded as Tertiary until Spieker (1946) demonstrated the age as Late Cretaceous. The deposits on the Mogollon Rim may be of early Tertiary age. If they were derived from the south it seems unlikely that they are much, if any, younger than Eocene because there does not appear to be any suitable source for the pre-Cambrian debris after early Tertiary time. Moreover, these deposits are not known to contain much, if any, volcanic debris, and in this respect they differ markedly from the later Tertiary deposits on the Plateau, such as the Datil (p. 29) or Bidahochi formations (p. 29).

DEPOSITS IN ADJOINING AREAS

SAN JUAN MOUNTAINS

Till, believed to be of Paleocene or Eocene age, underlies Oligocene deposits at several localities in the San Juan Mountains. The deposit, as much as 100 feet thick, contains fragments derived from the pre-Cambrian and Paleozoic formations and from volcanic tuff and porphyries.

The presence of abundant fragments of volcanic rocks in the till wherever it has been found shows that the glaciation took place before the Cretaceous and early Tertiary volcanic pile had been completely removed by erosion. The fact that the post-Animas beds of the San Juan Basin lack volcanic material indicates that the volcanic pile had been largely or completely removed before the deposits of the Puerco faunal zone were laid down. (Atwood, 1915, 1917; Atwood and Atwood, 1926; Cross and Larsen, 1935, p. 47).

The later Tertiary formations in the San Juan Mountains are described on pages 31–32.

RIO GRANDE VALLEY

Deposits of early Tertiary age in the Rio Grande depression along the east side of the southern part of the Colorado Plateau include the Galisteo sandstone, the upper part of which has been correlated with the Duchesne River formation. The Galisteo sandstone consists of from 900 to at least 4,000 feet of variegated sandstone and clay with minor amounts of conglomerate, fresh-water limestone, and water-laid tuff. Pebbles in the conglomerate were derived from the Paleozoic and pre-Cambrian rocks that must have formed highlands adjoining the basin of deposition. (Stearns, 1943, p. 301–319).

The Galisteo sandstone, known only on the east side of the Rio Grande depression, is older than, and cut by, the intrusions at the Cerrilos Hills. Its composition indicates that it was derived from ancestral highlands, presumably in the southern Rocky Mountains and at the east edge of the Colorado Plateau. But the Galisteo, although much faulted and folded, is largely concordant, although unconformable, on the Upper Cretaceous formations on the flanks of the folds at the northeast end of Sandia Mountain; therefore it may predate the block faulting and tilting there. (Stearns, 1943, p. 301–319).

SOUTHERN ARIZONA

Tertiary formations south of the Colorado Plateau, in the Basin and Range province in Arizona, are illustrated by exposures in the vicinity of the Artillery Mountains, Arizona. These exposures include the Artillery formation of early Eocene(?) age, volcanic rocks of Miocene(?) age, the Chapin Wash formation and overlying Cobwebb basalt of early Pliocene(?) age, and the Sandtrap conglomerate of late Pliocene(?) age. (Lasky and Weber, 1949.) Although the dating of these formations involves many uncertainties they record a sequence of structural movements that bear on the history of the Colorado Plateau. They record early Tertiary (but post-Artillery formation) thrust faulting, middle Tertiary vulcanism and block faulting of the Basin and Range type, and late Tertiary (late Pliocene?) folding and later block faulting.

UPPER TERTIARY DEPOSITS (MIOCENE AND PLIOCENE)

Upper Tertiary deposits are abundant around the periphery of the Colorado Plateau but they are scarce and not at all well dated within the Plateau. In the southern part of the High Plateaus are the Brian Head, Sevier River, and Parunuweap formations. In the basin under Black Mesa, Ariz., is the Bidahochi formation. Elsewhere within the Colorado Plateau, deposits believed to be of late Tertiary age consist of scattered gravel deposits on erosion surfaces, similar to deposits south of the Defiance upwarp, the Datil formation, and in the salt anticlines.

North of the Plateau, in the Wyoming Basin, are the Bishop conglomerate and Browns Park formation. To the east, in the San Juan Mountains, is a thick volcanic sequence of late Tertiary age. East of Mount Taylor, N. Mex., is the Santa Fe formation. Along the southwest edge of the Plateau are the Muddy Creek formation and Hualpai limestone (of Longwell). In central Utah, west of the High Plateaus, is the Sevier River formation. Much of the late Tertiary history of the Colorado Plateau must be inferred from the record of the deposits around it; the deposits within the Plateau are not complete enough for satisfactory reconstruction of the history.

None of these deposits has been dated with certainty. All of them lie with angular unconformity on the older rocks, including the lower Tertiary deposits where they are present, and intraformational unconformities are common. The upper Tertiary deposits are mostly fluviatile but include some sediments that were deposited in ephemeral lakes or ponds; most of them are associated with vulcanism or other igneous activity.

HIGH PLATEAUS

BRIAN HEAD FORMATION

Generally, along the western edge of the Aquarius, Sevier, and Markagunt Plateaus, the pink, compact limestones of the Wasatch formation are overlain unconformably by white, regularly stratified calcareous and siliceous beds, and they in turn are overlain by gray conglomerate and agglomerate, which in places extend upward to sheets of lava capping the plateaus. On the southern part of the Aquarius, Paunsaugunt, and Markagunt Plateaus the white beds are essentially limestone that include varying amounts of quartz, chalcedony, and decomposed lavas. On the northern Aquarius, southern Sevier, and central Markagunt Plateaus, beds in the same stratigraphic position consist chiefly of pyroclastics and highly siliceous limestone. Thus, the quartzose and volcanic debris increase from south to north, but the change from dominant limestone to dominant tuff and ash is not regularly progressive. These deposits, which are 500 to 1,000 feet thick, have been named the Brian Head formation. (Gregory, 1945, p. 105–110.)

The sources of materials in the Brian Head formation have not been identified. Some of the loosely compacted, regularly stratified, and dominantly calcareous beds may represent the reworking of the underlying Wasatch formation, but their chalcedony and tuffaceous conglomerate are out of place in the normal Wasatch formation. The pyroclastic beds are not local in origin. They are water-laid sediments derived from the disintegration of lavas that are not exposed in southern Utah. (Gregory, 1945, p. 109.)

The Brian Head formation is tentatively considered to be of Miocene age, but the evidence for this assignment is far from satisfactory. The rare fossil snails and fragmental turtle bones belong to genera that range throughout the Tertiary, and few have been identified specifically. On the Markagunt Plateau, the Brian Head overlies rocks of Eocene—possibly middle or even late Eocene—age and underlies Tertiary volcanic rocks, which in turn underlie Quaternary basalt and glacial deposits. It is older than the Sevier River formation, which contains fossils of Pliocene(?) age. The formation predates the late Tertiary and Quaternary movements along the Hurricane, Sevier, and Paunsaugunt faults. (Gregory, 1945, p. 110.)

SEVIER RIVER AND PARUNUWEAP FORMATION

The Sevier River formation is exposed along the Sevier River and is extensive in the valleys of the Basin and Range province west of the High Plateaus. Diatoms and gastropods obtained from the formation north of Marysville, Utah, establish its age as late Pliocene(?) or early Pleistocene(?). (Callaghan, 1938).

The formation is fanglomerate composed of poorly sorted pebbles, cobbles, and boulders, which range in diameter from ½ inch to 4 feet and which are cemented with reddish sand, silt, and clay, and some calcareous material. Most of the debris is angular or subangular andesite, basalt, and quartzite. (Gregory, 1945, p. 115; 1949, p. 987).

In the southern High Plateaus, in the valleys at heights of 10 to more than 200 feet above the surface of the late Pleistocene and Recent alluvial fills, are consolidated or partly consolidated masses of boulders, gravel, and stratified sand, which are classed as part of the Parunuweap formation and believed to be correlative with the Sevier River formation. These deposits lie midway up, or at the top of, the walls of some of the canyons; they completely fill some short, shallow valleys, and they extend onto some low interstream divides. (Gregory, 1945, p. 110–111).

The Parunuweap formation includes conglomerate and alluvial or lacustrine silt; the composition varies widely from place to place. In the valleys farthest west, the conglomeratic facies consists chiefly of angular slabs of gray sandstone, 1 to 4 feet long; partly worn pebbles of limestone; elongated iron concretions, 1 to 12 inches in diameter; and rounded pebbles of quartz, quartzite, and chert, generally less than 3 inches in diameter. North of Kanab, the conglomerate includes chunks of basalt and many mud balls. In Coal Creek valley are slabs of pink and red limestone, gray sandstone, and rhyolite 1 to 3 feet in diameter; angular and rounded pebbles of quartzite and chips of chalcedony. Everywhere, the cement of the conglomerate is calcareous and includes enough iron oxides to produce in places a tint of brown or yellow. The lacustrine facies, apparently restricted in extent, consists of thin layers of fine-grained sand interlaminated with calcareous and gypsiferous silt. (Gregory, 1945, p. 111–114).

The Sevier River formation is unconformably overlain by basaltic lavas, believed to be of Quaternary age, and unconformably rests on the deeply eroded surface of the Brian Head formation. Farther to the west, along the west foot of the Pavant Range, the Sevier River formation is much faulted and is tilted southeastward as steeply as 35°. The Parunuweap formation also is older than the Quaternary basalt flows and fossiliferous Pleistocene sediments and is older than some of the faulting and uplift in the southern High Plateaus. It is younger than the widespread rhyolite, andesite, and latite of probable Miocene age and predates much of the canyon cutting. (Gregory, 1945, p. 114; 1949, p. 987; Maxey, 1946, p. 341.) The stratigraphic position and regional relations of both the Sevier River and Parunuweap formations are comparable to those of the Pliocene Bidahochi formation in the basin under Black Mesa.

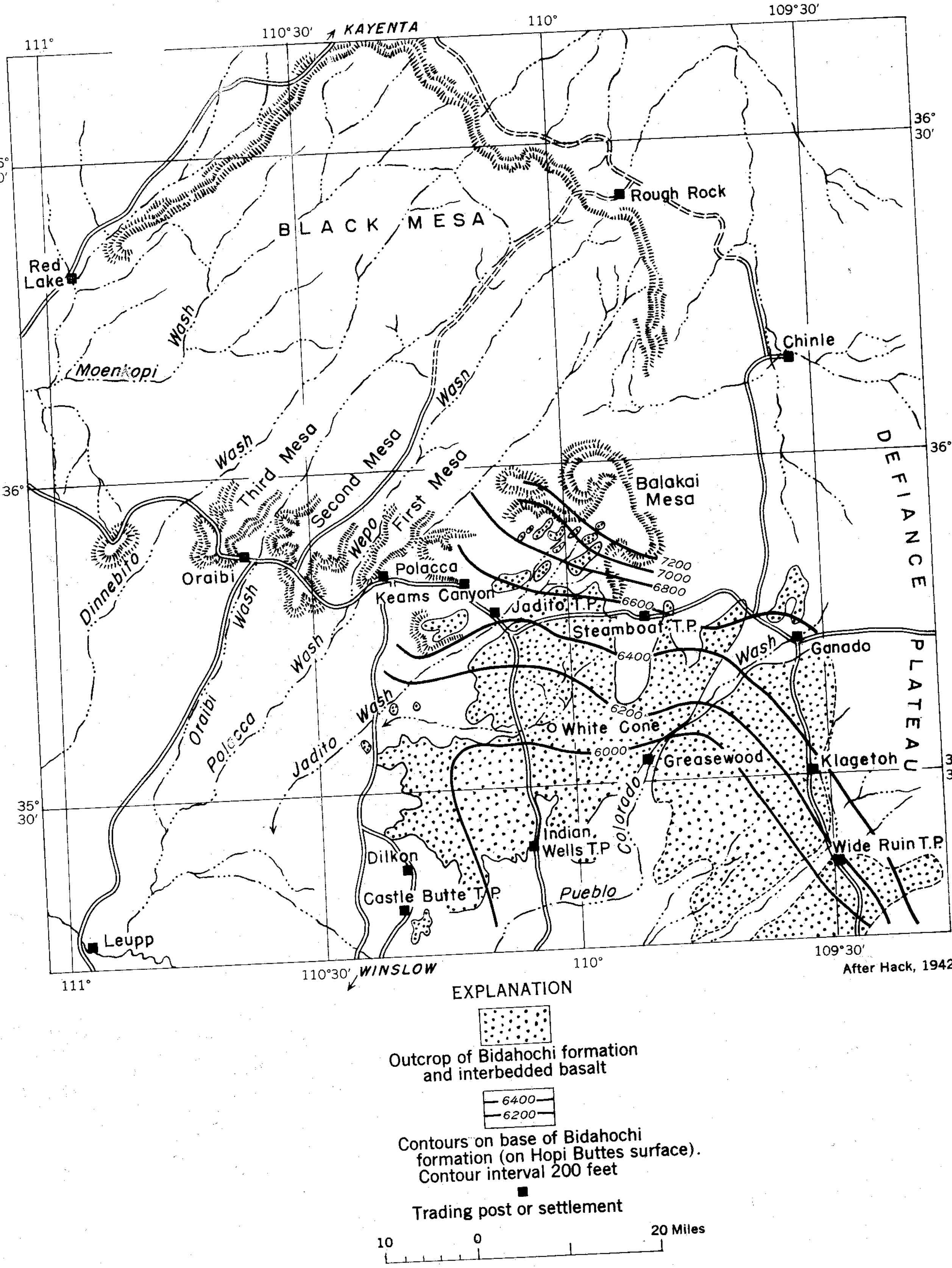


FIGURE 20.—Map showing outcrop of Bidahochi formation.

SOUTHERN PART OF THE COLORADO PLATEAU

BIDAHOCHI FORMATION

In the basin under Black Mesa, Ariz., are Pliocene deposits, known as the Bidahochi formation, which consist of interbedded calcareous sand, clay, marl, tuff and other pyroclastic material and which are interbedded with lavas. (Fig. 20.) The deposits extend from the Hopi Buttes eastward to the west flank of the Defiance upwarp and southeastward to the Zuni area, N. Mex.; a maximum thickness of about 400 feet has been reported. (Hack, 1942b, p. 336–340.)

The lithology varies considerably in short distances. In the vicinity of the Hopi Buttes, pyroclastic rocks that range from fine ash to coarse agglomerate locally make up the entire Bidahochi formation. North of the Buttes, on Black Mesa, the formation contains material derived from the Mesaverde group and is chiefly calcareous sand. Eastward and southeastward, the beds contain considerable sandy conglomerate or gravel. Locally, there are beds of ripple-marked and mud-cracked sand and clay. In general, the formation thickens and becomes coarser to the north and northeast and seems to have been deposited by streams flowing from that direction. (Hack, 1942b, p. 340–244.)

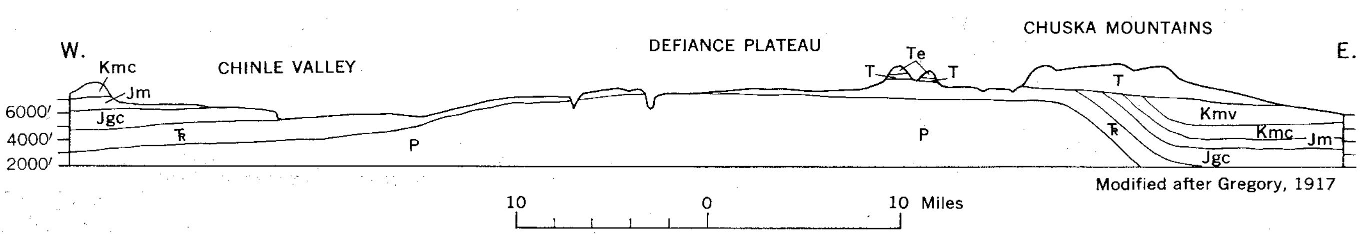
Fresh-water shells obtained from some of the finer beds have been identified as *Unio*, *Planorbis trivolis* Say, and *Limnaea stagnalis appressa* Say, and these have been interpreted to indicate an age no older than Pleistocene (Reagan, 1932, p. 258). Vertebrate remains, however, indicate the age to be middle or late Pliocene, probably middle Pliocene. These remains include fish vertebrae, pieces of bird and amphibian bones, the broken jaw of a new species of beaver, and a huge species of camel (Williams, 1936, p. 130).

The formation is interpreted as having been deposited by southwestward flowing streams on a low, wet, swampy floodplain. The vegetation was lush, and the climate must have been warm and moist at least part of the year. Since deposition, there seems to have been southward tilting of about 10 feet per mile (Hack, 1942b, p. 344–345).

The Gallup-Zuni basin also contains Tertiary deposits very similar to, and probably correlative with, the Bidahochi formation. These sediments consist of nonfossiliferous, tuffaceous, loosely consolidated alluvial and lacustrine beds of white sandstone, light-gray clay shale, gravel, limestone, marl, bentonite, and tuff having a maximum thickness of about 350 feet. The pebbles that are found in the gravel are largely derived from the Zuni Mountains to the east, and the deposits evidently were deposited by streams draining westward from those mountains. The deposits overlie an erosion surface that slopes westward from the Zuni Mountains. Figure 39 illustrates the general structural setting but does not show these deposits. Since deposition, the beds seem to have been tilted westward as a result of roughly 700 feet of additional uplift at the Zuni Mountains (McCann, 1938). South of Zuni, N. Mex., similar beds extend beneath lavas of the Mogollon volcanic field.

CHUSKA SANDSTONE

The Chuska sandstone outcrops at the east edge of the Defiance upwarp and may correlate with the Bidahochi formation. It rests on Tohachi shale, which is thought to be of Late Cretaceous age (Allen, 1953; Allen and Balk, 1954). The Chuska sandstone, about 700 feet thick, is well-bedded, medium-grained sandstone containing some volcanic ash. Locally, the base is conglomeratic (Gregory, 1917, p. 80–81). The Chuska sandstone unconformably overlaps the tilted Mesozoic rocks along the east side of the Defiance upwarp (fig. 21).



Te, late Tertiary lavas; T, Chuska sandstone; Kmv, Mesaverde group; Kmc, Mancos shale; Jm, Morrison formation and San Rafael group; Jgc, Glen Canyon group; Ꞧ, Triassic formations; P, Permian formations

FIGURE 21.—Cross section of the Defiance uplift.

DATIL FORMATION

In the Datil section, New Mexico, along the southeastern part of the Colorado Plateau is the Datil formation, which consists of highly lenticular, well-indurated tuff, rhyolite, crossbedded sandstone, and conglomerate. The formation is 2,000 feet thick and is probably of late Tertiary age, although no fossils have been found to support this interpretation. (Win-

on which the formation rests slopes northward from a maximum altitude of 13,000 feet in the Uinta Mountains to an altitude of 7,300 feet in the Wyoming Basin. (Bradley, 1936, p. 169, 172).

The erosion surface beneath the Bishop conglomerate has been interpreted as a pediment; the change in stream regimen, represented by the change from planation to deposition of the thick conglomerate, is attributed to a slight change in climate towards greater aridity rather than to a renewal of mountain uplift or other structural movements. (Bradley, 1936, p. 178–179; Rich, 1910, p. 619–620; Sears, 1924). On the other hand, the erosion surface may be a series of closely spaced pediments that were cut and aggraded in the manner of those along the foot of the Book Cliffs and around the foot of the Henry Mountains (fig. 24). (Rich, 1935; Hunt, 1953b).

The Bishop conglomerate is younger than the main uplift of the Uinta Mountains, although it predates the collapse at the eastern end of the mountains. No fossils have been obtained from the conglomerate, but probably it is Miocene in age. It is older than the Browns Park formation, which is regarded as late Miocene or early Pliocene in age.

Browns Park formation.—The Browns Park formation, of late Miocene or early Pliocene age, outcrops in a belt 6 to 10 miles wide extending from the Green River at the north foot of the Uinta Mountains nearly to Craig, Colo., a distance of about 100 miles. This is in the Wyoming Basin rather than in the Colorado Plateau, but the history of this formation bears on the history of the Plateau.

The formation, at least 1,200 feet thick and probably originally thicker, rests with angular unconformity on rocks that range in age from pre-Cambrian to Bridger. The formation is composed principally of white, well-bedded quartz sandstone having a calcareous cement. Locally, there is an angular unconformity within the formation (Sears, 1924, p. 295).

The base of the formation is a conglomerate that ranges in thickness from a few inches to 300 feet, but it has very different characteristics in the eastern and western half of the outcrop area. In the east, the pebbles rarely exceed 2 inches in diameter and consist of metamorphic and igneous rock, quartzite, chert, and vein quartz. In the west, conglomerate consists predominantly of red quartzite pebbles and boulders, which reach a maximum diameter of several feet, and which were derived from the pre-Cambrian core of the Uinta Mountains anticline. (Sears, 1924, p. 295).

The Browns Park formation contains a considerable amount of volcanic material including some interbedded basalt (Hancock, 1915, p. 187). The sandstone is tuffaceous, and there are numerous beds of tuff. The formation is regarded in part as an eolian deposit that was transported not far from its source (Bradley, 1936, p. 182–184).

Mammalian fossils collected near Greystone, Colo., indicate that the formation is of late Miocene or early Pliocene age. (Peterson, 1924, 1928).

The Browns Park formation overlaps an extensive erosion surface on the northern side of the Uinta Mountains. Aridity, at the time that the Browns Park formation was deposited, is suggested by the occurrence of halite crystal molds in part of the formation and by the occurrence of wind-blown sand, including some wind-faceted cobbles in other parts of the formation. The formation was involved in the graben faulting at the north foot of the Uinta Mountains; father east, it was tilted. (Bradley, 1936, p. 184).

SAN JUAN MOUNTAINS

Unconformably overlying the early Tertiary till in the San Juan Mountains is the Telluride conglomerate of probable Oligocene age. It ranges from a thin, coarse conglomerate in the eastern part of the San Juan Mountains to a sandstone, shale, and fine conglomerate 1,000 feet thick in the western part of the San Juan Mountains. Volcanic rocks are lacking. No fossils have been found in the Telluride conglomerate, but Oligocene(?) age is indicated by its apparently conformable relation to the overlying San Juan tuff, which is probably Miocene. (Cross and Larsen, 1935).

Along the southern side of the San Juan Mountains is the Blanco Basin formation, which consists of several hundred feet of arkosic sandstone, conglomerate, and other sediments. The Blanco Basin formation, like the Telluride conglomerate, lacks volcanic materials. It unconformably overlies folded Cretaceous formations and the Animas formation and is apparently conformable beneath the Miocene volcanic sequence. It is thought to be of Oligocene age, but it could be late Eocene, Oligocene, or early Miocene. (Cross and Larsen, 1935, p. 48–50).

The conglomeratic deposits in these formations suggest that their source area in the San Juan Mountains was high enough to be in a zone of vigorous frost action, and perhaps it was high enough to be in a zone of periglacial or glacial action.

The younger Tertiary deposits in the San Juan Mountains comprise a thick and extensive series of volcanic rocks. This volcanic activity began in the Miocene and continued, with interruptions, into Pleistocene or Recent time. It built a volcanic dome more than 100 miles wide and probably several miles high. This dome has been faulted, tilted to the east and north, folded, and deeply incised by erosion to form the present San Juan Mountains. (Cross and Larsen, 1935, p. 50).

The earliest of the eruptive formations, the Lake Fork andesite,[1] built a volcanic mountain about 15 miles wide and 4,000 feet high on the north flank of the San Juan Mountains. The Lake Fork andesite is composed mostly of andesitic breccia with some basalt and quartz latite. (Cross and Larsen, 1935, p. 50).

Before the Lake Fork volcano had been greatly modified by erosion it was in large part buried by much more widespread andesitic tuff-breccia, the San Juan tuff. This tuff, made up almost entirely of bedded clastic material, was deposited by water and probably was derived from explosive vents located west of the Lake Fork volcano, although that volcano contributed very little of the material. The San Juan tuff still is preserved in an area nearly 100 miles wide from southwest to northeast; its thickness commonly exceeds 1,000 feet. (Cross and Larsen, 1935, p. 51).

After some erosion, the San Juan tuff was partly buried by the Silverton volcanic series, which consists of quartz latite, rhyolite, and pyroxene andesite lavas and pyroclastics. These, in turn, were followed by local, water-laid tuff. Well-preserved plant remains in some of the tuff beds are of Miocene age. The Silverton eruptives built a dome 40 miles wide and 3,000 feet high. (Cross and Larsen, 1935, p. 51).

Following eruption of the Silverton volcanic series, there seems to have been a period when erosion cut deep canyons in the volcanic mountains and in the bedrock formations on which the volcanics rest. Towards the end of this period of erosion, a volcano northeast of the Silverton area erupted a considerable volume of rhyolite. (Cross and Larsen, 1935, p. 51–52).

This period of erosion was followed by a long series of great eruptions that filled the canyons and finally buried all of the mountains. The resulting low, broad dome of the Potosi volcanic series makes up the main part of the volcanic rocks of the region. It was 150 miles across, and over a very large area it was a mile thick. The eruptions alternated between andesitic and rhyolitic materials. Three periods of erosion that interrupted the accumulation of volcanic rocks were sufficiently long to allow the development of canyons comparable in depth to the present canyons. (Cross and Larsen, 1935, p. 52).

Erosion continued after the Potosi eruptions ceased. During this period, the Creede formation, which is a thick deposit of fine rhyolitic tuff containing plant remains of Miocene age, was deposited in a lake in one of the canyons. After further erosion, the Fisher latite-andesite was erupted, and this was followed by a long period of erosion during which an erosion surface developed throughout most of the region—the San Juan peneplain of Atwood and Mather (1932, p. 21–26). (Cross and Larsen, 1935, p. 53).

Overlying the San Juan peneplain is the Hinsdale formation, which probably is of late Pliocene age. The basal part of the Hinsdale is sand and gravel with local flows of latite-andesite. This is overlain by rhyolite, and the rhyolite in turn is overlain by andesite and basalt. The resulting basaltic plateau was then tilted to the east, faulted, and folded at about the end of the Pliocene. (Cross and Larsen, 1935, p. 54, 95, 100).

During Pleistocene time, minor eruptions of basalts flowed into some of the canyons. (Cross and Larsen, 1935, p. 54).

Associated with these eruptives are intrusives that fall into two groups—the laccoliths and stocks that intrude chiefly the sedimentary rocks in the western part of the mountains, and the stocks and associated dikes that intrude the earliest Potosi rocks in the eastern part of the mountains. (Cross and Larsen, 1935, p. 101).

RIO GRANDE VALLEY

Post-Galisteo and pre-Santa Fe deposits.—At many places in the Rio Grande Valley there have been recognized deposits, which underlie the Santa Fe formation but which are younger, or apparently younger, than the Galisteo sandstone. These deposits include a high proportion of volcanic rocks in the form of water-laid breccia, conglomerate, agglomerate, tuff, and lava flows. Numerous local names have been given to them.

The Galisteo sandstone is conformably overlain by 1,000 feet of water-laid breccia, conglomerate, and tuff, with massive flows and pyroclastic material in subordinate amount. These have been referred to by Stearns (1943, p. 309) as the Espinaso volcanics. Northeast of the Nacimiento Mountains, the earliest Tertiary formations consist of several thousand feet of andesite and latite flows, with some basalt, rhyolite, and volcanic breccia that have been referred to as the Chicoma volcanic formation of Smith (1938). Younger than these is a unit consisting of 200 feet of sandstone, conglomerate, and breccia that has been referred to as Smith's El Rito formation. Unconformably on his El Rito formation is the Abiquiu tuff of Smith, which consists of 1,200 feet of stream-laid tuff and volcanic conglomerate with a few small interbedded lava flows and which apparently was derived from the north. On the east side of the Rio Grande depression and at the west foot of the Sangre de Cristo Range, 1,200 feet of beds similar to Smith's Abiquiu tuff have been referred to

[1] In a more recent publication, in press, Cross and Larsen call this formation the Lake Fork quartz latite.

by Cabot (1938, p. 91) as Picuris tuff. At the east edge of the Mount Taylor district, tuffaceous fan deposits unconformably underlie the Santa Fe formation (Bryan and McCann, 1937, p. 817–818). Farther south, on the east side of Sierra Ladron, between 3,500 and 5,000 feet of tuffaceous sandstone, conglomerate, and tuff overlie the Miocene(?) volcanic rocks and, in turn, are overlain with angular unconformity by the Santa Fe formation. These tuffaceous sediments have been referred to as the Popotosa formation (Denny, 1940a). Pebbles of granite, schist, quartzite, and sandstone in these beds indicate that there were highlands in the Sierra Ladron while these beds were being deposited.

Santa Fe formation.—The most extensive of the Tertiary formations in the Rio Grande Valley is the Santa Fe formation, which extends across New Mexico from Colorado to Texas. Along the valley the formation consists of a few thousand feet of sand, silt, and gravel, which were deposited by the ancestral Rio Grande between broad alluvial fans which, in turn, were deposited by tributaries from the east and from the west. Locally, there are discontinuous thin beds of tuff. Southeast of the San Juan Basin the gravels include some pre-Cambrian rocks, apparently derived from the Nacimiento or Zuni uplifts; andesite and other volcanic rocks are also common. (Bryan and McCann, 1938; Wright, 1946).

Vertebrate fossils obtained from the Santa Fe formation north of Santa Fe indicate that these beds are late Miocene or early Pliocene in age, and possibly younger. Fossils obtained from deposits in the San Acacia area indicate a middle or late Pliocene age. (Denny, 1940a, p. 93–94).

Immediately east of the Colorado Plateau, and east of Mount Taylor, the Santa Fe formation overlies the much faulted and tilted Upper Cretaceous formations (fig. 43) with strong angular unconformity. This edge of the Colorado Plateau was faulted before the Santa Fe formation was deposited, but the formation itself is broken by many faults, which parallel the edge of the Plateau and which, in part at least, represent renewed movement along the faults of pre-Santa Fe age (Hunt, 1938, p. 56, 57, 77, 78). Pre-Santa Fe uplift of the Sierra Ladron portion of the Plateau is indicated by the gravels in Denny's Popotosa formation, which unconformably underlies the Santa Fe (Denny, 1940a, p. 77–84). It seems probable that the Santa Fe formation will be found to contain numerous angular unconformities as do the other upper Tertiary deposits in the basins of the Basin and Range province. Apparently, downfaulting of the basins was synchronous with deposition.

GRAND WASH TROUGH

Upper Tertiary deposits in the Grand Wash trough and other basins immediately west of the Grand Wash Cliffs lie across the course of the Colorado River. These deposits include one or more thick series of clastic fluviatile sediments, referred to as the Muddy Creek formation, and a thick series of lacustrine limestone, referred to as the Hualpai limestone of Longwell (1936, p. 1429). See figure 22. The deposits are assumed to be of late Miocene and Pliocene age.

The oldest exposed deposits include a coarse breccia that rests with erosional unconformity, but concordantly (locally at least), on highly tilted Kaibab limestone. The breccia, about 350 feet thick, contains angular blocks of Kaibab limestone as much as 10 feet long (Longwell, 1936, p. 1,414–1,415). The occurrence of such breccia suggests that it was being deposited while the faulting progressed along the western edge of the Colorado Plateau.

Unconformably overlying the breccia is fanglomerate and siltstone, which locally have been faulted and folded and which in places have been turned up as steeply as 70°. In most of the basin the fanglomerate consists almost entirely of granitic and gneissic debris from the Virgin Mountains. Some blocks of granite, which must have been moved 12 to 15 miles, are 15 to 20 feet long. Fanglomerate, containing limestone and sandstone derived from Paleozoic formations on the Colorado Plateau, occurs at the mouth of Grand Canyon and overlaps eastward onto the pre-Cambrian and Cambrian formations in the Grand Wash Cliffs (fig. 22). (Longwell, 1936, p. 1434–1436).

In the middle of the basin, the fanglomerate grades upward into several hundred feet of playa deposits, consisting mostly of siltstone and clay with a few thin beds of volcanic ash. These, in turn, are overlain conformably by Longwell's Hualpai limestone (Longwell, 1936, p. 1435). See figure 23.

Presumably, the scarcity of Paleozoic debris in the fanglomerate derived from the Virgin Mountains indicates an earlier uplift of those mountains to allow removal of the Paleozoic strata that must have extended across them. The Virgin Mountains may have been a source for some of the Upper Cretaceous sediments on the Colorado Plateau. Therefore, at least three stages of deformation are recorded—one or more antedating the fanglomerate, one that caused the fanglomerate to be deposited, and one that caused the post-fanglomerate faulting and folding.

The Hualpai limestone of Longwell, which is more than 1,000 feet thick, overlaps the edges of the fanglomerate and extends onto the pre-Cambrian rocks along the east and west sides of the trough. Not only is the

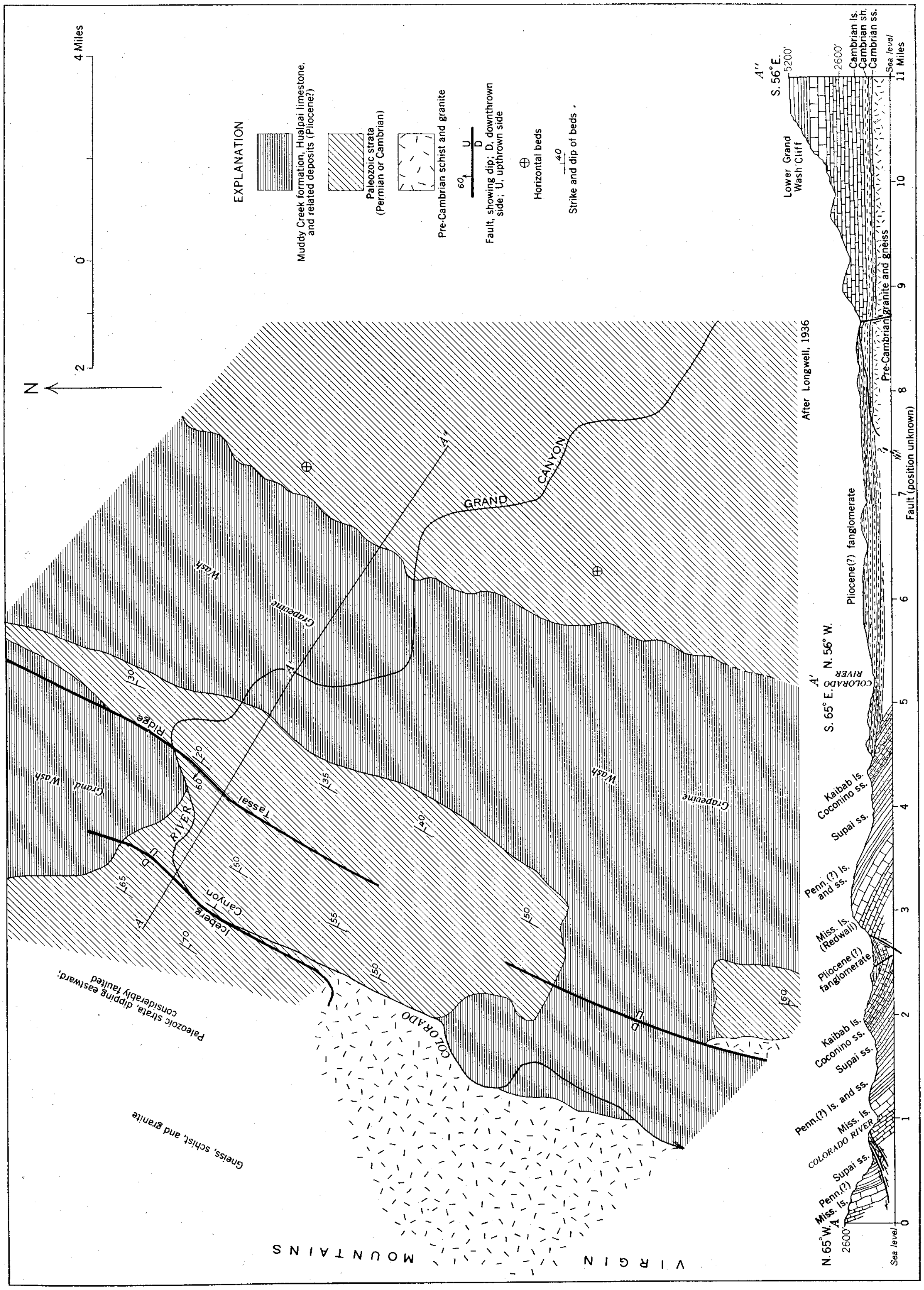


FIGURE 22.—Geologic map and cross section of part of Grand Wash trough. (After Longwell.)

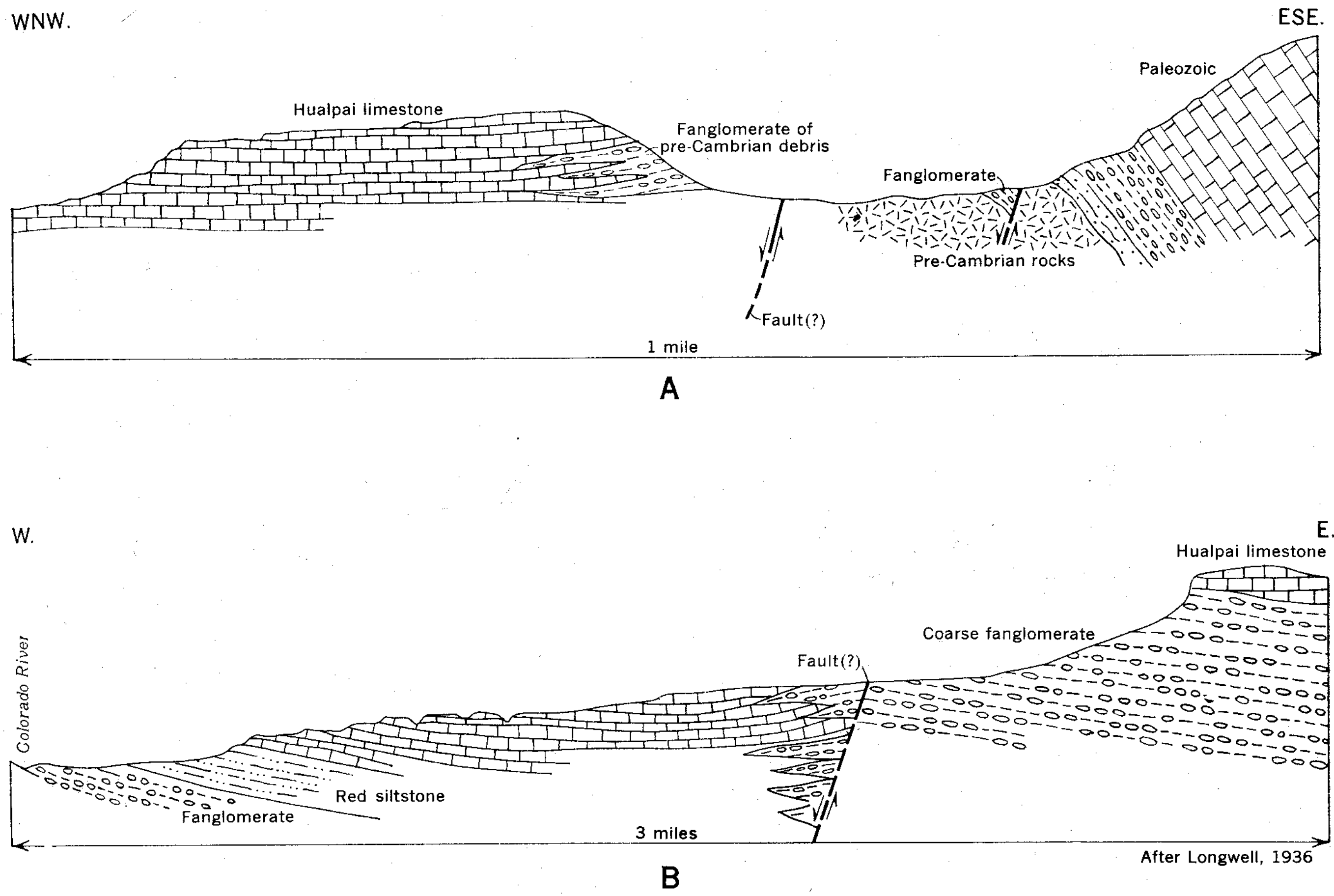


FIGURE 23.—Cross sections of valley fill in vicinity of Grand Wash trough. (A) Fanglomerate of pre-Cambrian debris intertongues with Hualpai limestone and indicates a steep scarp directly to the east while the limestone was accumulating. (B) Faulted fanglomerate and red siltstone of Muddy Creek formation and Hualpai limestone.

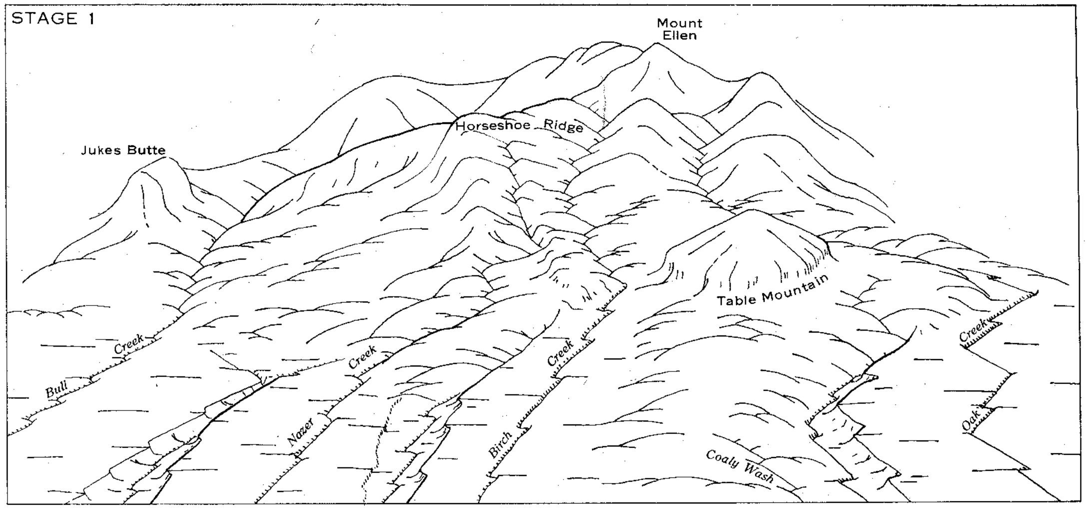
limestone thick and widely distributed, it is regularly stratified and a large part contains remarkably little impurity even where it lies against the Grand Wash Cliffs or similar steep slopes. It appears to have been deposited in a lake, or perhaps in several connected lakes. Locally, where the limestone has been faulted against pre-Cambrian rocks, it includes fragments of them, therefore it is probable that the faulting in the Grand Wash trough continued while the limestone was being deposited. (Longwell, 1936, p. 1432–1434, 1438–1439).

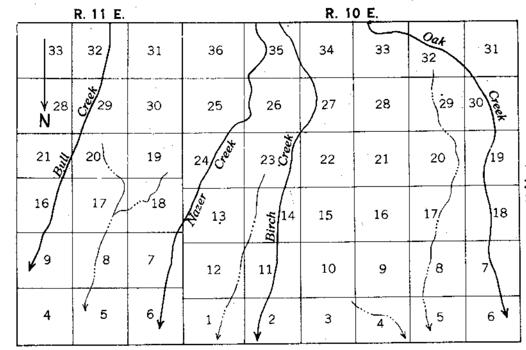
QUATERNARY DEPOSITS

Quaternary deposits on the Colorado Plateau include glacial and periglacial deposits of various kinds on and near the higher mountains, fanglomerate on pediments and in alluvial fans, gravel or alluvium both on cut terraces and in fill terraces along streams, colluvial and talus deposits on the valley walls, and eolian deposits and residual soils on uplands. Although fossils are scarce, several different ages of deposits generally can be distinguished by supplementing the scanty paleontologic data with information about the physical sequence, interbedded soils, and archeological remains. Generally, it is possible to distinguish pre-Wisconsin from the Wisconsin deposits, and these deposits of Pleistocene age usually are distinguishable from Recent ones.

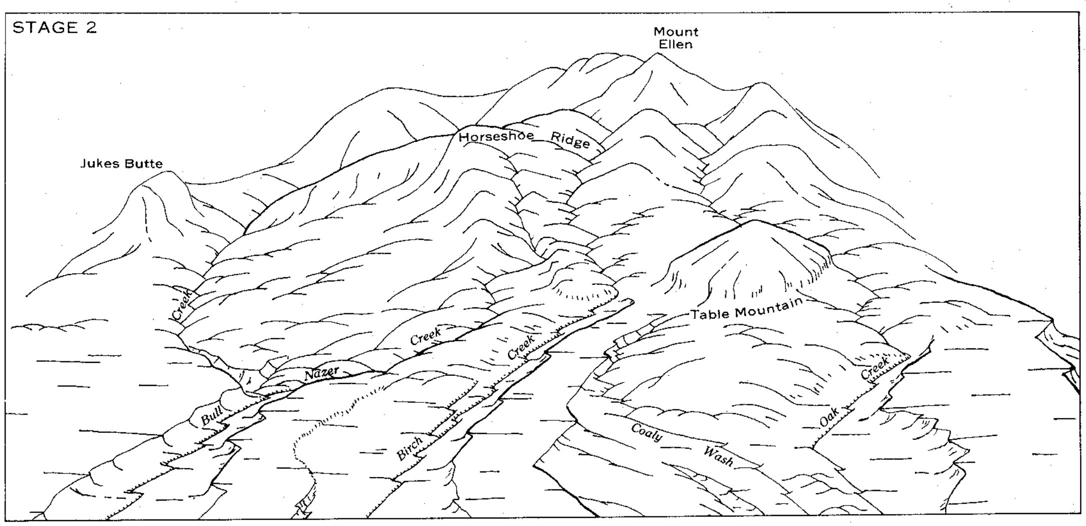
PRE-WISCONSIN DEPOSITS

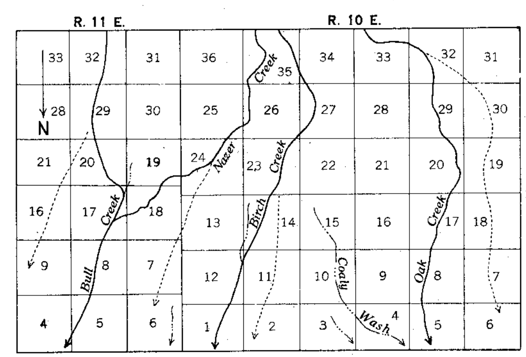
Pre-Wisconsin glacial deposits have been recognized in the mountains along the north and east sides of the Colorado Plateau and in the southern part of the Plateau, but curiously they are lacking to the west in the High Plateaus. In the Uinta, San Juan, and La Sal Mountains pre-Wisconsin glacial deposits extend to altitudes as low as 7,000 feet (Atwood, 1909; Atwood and Mather, 1932; Richmond, in preparation). No pre-Wisconsin glacial deposits have been recognized in the Abajo Mountains, but probably snow or ice fields were there and on some of the nearby ridges whose altitude is about 8,500 feet. On the San Francisco Mountain, pre-Wisconsin glacial deposits extend downward to an altitude of 8,000 feet (Sharp, 1942, fig. 1). On the High Plateaus, similar deposits are scarce, although





Bull Creek, Nazer Creek, Birch Creek, and Oak Creek are independent streams. The topography necessarily has been generalized and probably was as intricate as the present topography. The streams are on gravel-covered pediments and their channels are in the gravel. Tributary streams are cutting headward between the main streams, and along the lower part of some of these tributaries gravel-free pediments have developed.

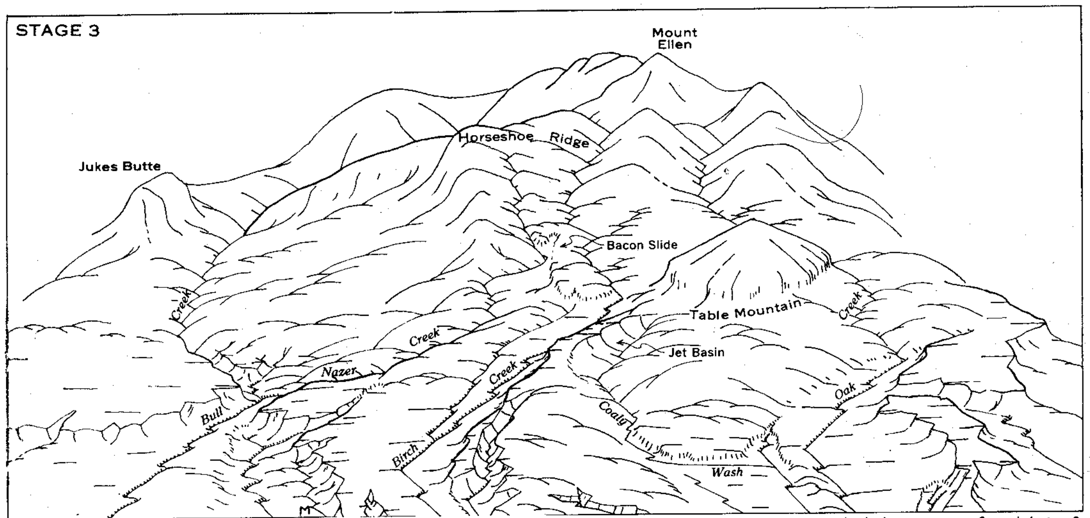


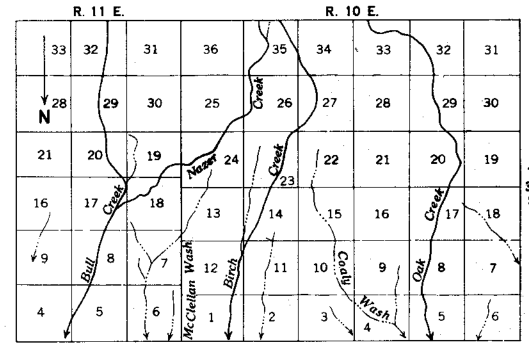


After Hunt, 1954

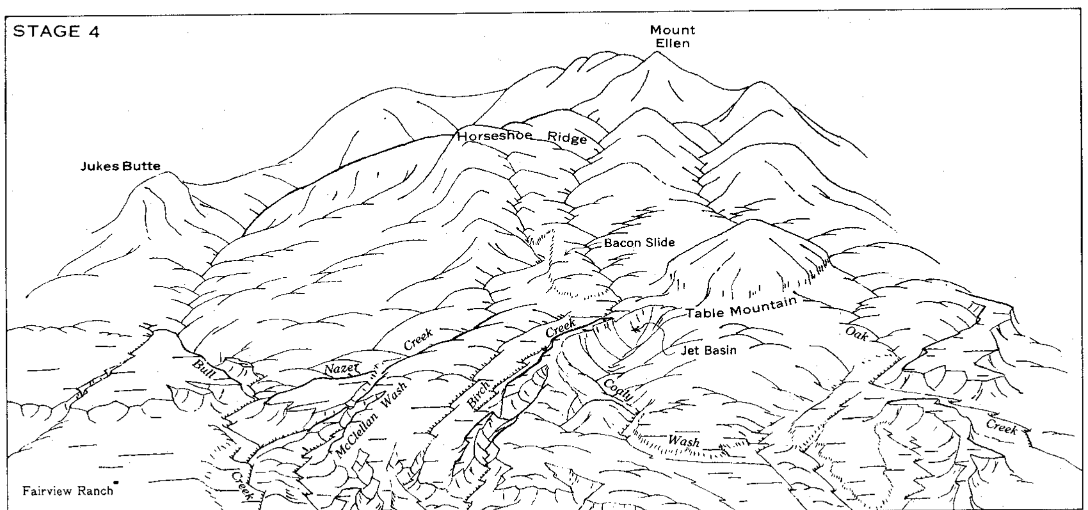
Both Bull Creek and Nazer Creek have been captured by the stream that eroded headward between them during Stage 1. They are in youthful valleys above the stream junction but flow onto a pediment below. The pediment is being aggraded with fanglomerate.
The wash that eroded headward east of Birch Creek during Stage 1 developed a pediment all the way to the foot of the mountain and there captured Birch Creek. The abandoned course of Birch Creek is left as a gravel-capped ridge dividing the new course from Coaly Wash.
A stream that cut headward between Coaly Wash and Oak Creek during Stage 1 has captured Oak Creek at the west side of Table Mountain.

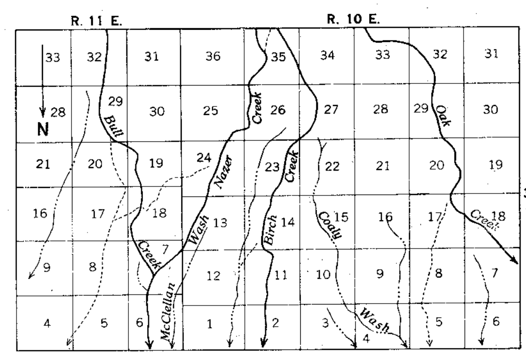
FIGURE 24.—Diagrams illustrating four stages in the development of pediments in the Colorado Plateau.





The courses of Bull Creek and Nazer Creek are not changed. The gravel-covered surfaces on which these streams flowed during Stage 1 have been greatly reduced. A stream, eroding headward along the east edge of the surface on which Nazer Creek flowed during Stage 1, threatens to capture Bull Creek. McClellan Wash is a youthful valley west of this pediment.
Birch Creek and Coaly Wash have maintained their courses but their tributaries have greatly reduced the gravel-covered Stage 1 surface of Birch Creek.
Oak Creek has maintained its course. Its abandoned surface (Stage 1) has been eroded further and is cut through by a stream from the west.





After Hunt, 1954

Bull Creek has been diverted westward onto the pediment that developed during Stage 3 and is aggrading that pediment. Another minor diversion occurred above the junction with Nazer Creek and was caused by a tributary cutting headward along the foot of the mountain isolating a small remnant of the surface on which Bull Creek flowed during Stage 1.
The lower end of Nazer Creek was diverted into a tributary of the pediment now being aggraded by Bull Creek.
Bull Creek is about to be diverted onto a pediment along McClellan Wash. The two drainages are separated by a 10-foot divide and the pediment is considerably lower. A youthful valley at the head of the wash has nearly captured Nazer Creek at a place where the west bank of Nazer Creek is 5½ feet high and the wash is 55 feet lower.
The lower part of Birch Creek has been diverted into a youthful valley which is now being aggraded.
A broad pediment has developed along the lower part of Coaly Wash and a deep valley, known as Jet Basin, extends headward close to where Birch Creek emerges from the mountain. The head of this valley is several hundred feet lower than Birch Creek and the divide between them is only 20 feet high.
Oak Creek has been diverted to the west. A new gravel-free pediment is developing between the new and the abandoned courses of Oak Creek.

FIGURE 24.—Continued.

some of the catchment basins are between 10,000 and 11,000 feet in altitude, and there are extensive areas higher than 9,000 feet (Spieker and Billings, 1940, p. 1193–1196).

This distribution of the pre-Wisconsin glacial deposits is anomalous. It is unlikely that pre-Wisconsin glaciation was less extensive at high altitudes in the High Plateaus than at similar altitudes in the other mountains, one of which lies 300 miles farther south. In addition, it is unlikely that erosion completely destroyed the stratigraphic and physiographic record in and around the High Plateaus but so clearly preserved it in the other highlands. The anomaly could be attributed to Pleistocene upwarp of the High Plateaus. (p. 61).

Deeply weathered pre-Wisconsin fluvial and loessial deposits several feet thick are extensive on the plateau surfaces east of the Abajo Mountains and at the northwest foot of the San Juan Mountains. The pre-Wisconsin soils on these deposits are classed as chestnut soils (fig. 6) and are productive for farming.

The only assuredly pre-Wisconsin fill terrace that has been found along the Colorado River is located in a cut-off meander of the river east of Hite. The alluvial fill is at least 130 feet thick. Its base is at least 300 feet higher than the present river. Overlying the fill is fanglomerate believed to be of late Pleistocene age.

Some of the higher pediments and the fanglomerate lying on them around the foot of the Henry Mountains and along the foot of the Book Cliffs also appear to be of pre-Wisconsin age. The pediments around the foot of the Henry Mountains extend into, and therefore are younger than, the canyons tributary to the Dirty Devil and Colorado River Canyons east of the Henry Mountains. Figure 24 illustrates a common process of pediment development on the Colorado Plateau. The extensive gravel deposits on the pediments probably were derived from glacial or periglacial debris in the mountains.

Remnants of a soil that is wholly unlike that on any of the Wisconsin, or younger, deposits occur on the pre-Wisconsin deposits (Hunt and Sokoloff, 1950). This soil consists of a reddish clayey upper layer, a few feet thick, over several feet of a strongly lime-enriched layer of weathered parent material. At higher altitudes the limy layer is missing and the soil is acid. Wherever it occurs this soil is associated with subdued land forms that are in striking contrast to the rugged, youthful land forms that are developing under the Recent climatic environment.

WISCONSIN DEPOSITS

Wisconsin glacial deposits are extensive on the mountains and plateaus on all sides of the Colorado Plateau, including the High Plateaus. Two sets of Wisconsin glacial deposits, representing an early and a late stage of Wisconsin glaciation, have been recognized. (Spieker and Billings, 1940; Gould, 1939; Atwood, 1909; Atwood and Mather, 1932; Sharp, 1942; Richmond, in preparation; Flint and Denny, in preparation.) In the Henry Mountains, Abajo Mountains, and Mount Taylor no moraines have been recognized, but periglacial deposits, mostly in the form of boulder fields, are extensive.

Talus cones and colluvial aprons of periglacial origin, judged to be of Wisconsin age, are extensive along canyon walls in southeastern Utah. Along the canyons east of Hite are some spectacular debris avalanches that certainly are no younger than Wisconsin and may be older. All these canyon-wall deposits now are deeply dissected, but they record a time when the climate was more moist than now and when the canyon country developed smooth contours.

Fluvial deposits of Wisconsin age include glacial outwash near the mountains and alluvial fill in valleys remote from the mountains. Along the Colorado River, for example, about a mile upstream from Hite, alluvial gravel, believed to be of early Wisconsin age, comprises a fill more than 100 feet thick. Interbedded with the fill are thick spring deposits of calcium carbonate. The deposits reveal that Glen Canyon was about as deep then as it is now, that there was considerable spring activity apparently reflecting a high groundwater table, and that since the deposits were formed the history of this canyon consisted alternately of deposition of fill and of erosion of the fill without major changes in the depth and shape of the canyon. Nearer the mountains other canyons probably became deepened and extended headward during Wisconsin time.

The alluvial deposits of late Wisconsin age resemble the Recent deposits, except that they tend to be thicker, more extensive, more clayey and more compact. The regimen of the late Wisconsin streams seems to have been somewhat different from that of the Recent streams (p. 39). Also, the late Wisconsin alluvium contains the remains of mammoth or of extinct longhorn bison. (Hunt, 1953a).

RECENT DEPOSITS

The earliest Recent deposits on the Colorado Plateau are represented by dune sand. Overlapping the dune sand is alluvium that was deposited before pottery was introduced among the prehistoric inhabitants of the region. This pre-pottery alluvium in northeastern Arizona has been referred to by Hack (1942a, p. 51) as the Tsegi alluvium. Much of the pre-pottery alluvium apparently was deposited during the first and second millennia B. C. Towards the close of the 13th century A. D. this alluvium was cut by deep arroyos, and these in turn were partly filled by younger alluvium that apparently was deposited during the 16th and 17th centuries. The present-day arroyo cutting began in the period 1880–1895. Figure 25 illustrates some typical sequences of late Pleistocene and Recent alluvial deposits in the Colorado Plateau.

The early Recent dunes became stabilized during the comparatively moist period or periods when the pre-pottery alluvium was deposited. The old dune sand is moderately firm and stained with iron oxide. Locally, the area sustained vegetation that today characterizes somewhat higher areas. Most of the dune sand that was active later during the Recent, as well as the sand that is active today on the Colorado Plateau, is derived from the early Recent stabilized dunes (Hack, 1941, p. 261), but the volume of sand being moved today is small compared to that of the early Recent.

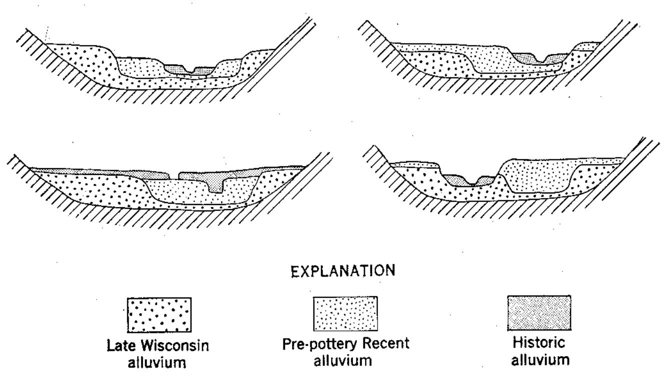


FIGURE 25.—Diagrammatic sections illustrating some common stratigraphic relationships in the alluvial deposits on the Colorado Plateau.

The pre-pottery, Recent alluvium generally occurs as fill in arroyos cut in the Wisconsin alluvium, but in some valleys the pre-pottery alluvium overtops the older deposits. The pre-pottery alluvium represents coalescing alluvial fans built in the main valleys at the mouths of the tributaries. Thus, the surface of this alluvium is broadly rolling, and the texture and composition of the alluvium vary according to the kind of material brought into the valley by the tributaries. The Wisconsin alluvium, on the other hand, generally represents a smooth floodplain built by the main stream itself; not only is its surface smooth, but the composition and texture of the alluvium commonly vary only slightly from the mouth of one tributary to another. Evidently, the regimen of the streams that deposited the pre-pottery, Recent alluvium was different from the regimen of the streams that deposited the Wisconsin alluvium. Generally, this difference in regimen also is reflected in differences in the molluscan fauna in the two alluvial deposits. The total list of species in the two faunas may be alike, but the proportion of different species, and the number and size of the individuals, generally are very different when comparisons are made between deposits in nearby localities.

Mammalian remains in the pre-pottery alluvium are those of modern forms. The associated artifacts are those of pre-pottery lithic cultures. Hearths and charcoal are abundant at many places in the alluvium and help to distinguish it from the older and younger deposits. Building foundations, irrigation systems, and other structures constructed by the pottery-making Anasazai and related prehistoric cultures are found on and in the uppermost part of the alluvium. Dendrochronologic and radiocarbon data indicate that this Anasazai occupation began early in the Christian era and ended towards the close of the 13th century, when deep arroyos were cut in the alluvium.

In these younger arroyos was deposited still younger alluvium that, in the Navajo country, has been referred to by Hack (1942a, p. 53) as the Naha alluvium. Presumably, deposition occurred during the period of Spanish occupation in the southwest. The present-day arroyo cutting began during the 1880's (Bryan, 1925).

CENOZOIC IGNEOUS ROCKS

GENERAL FEATURES

Cenozoic intrusive rocks in the Colorado Plateau occur as stocks, laccoliths, and bysmaliths in the dozen or so laccolithic mountains. Eruptive rocks occur at the large, central-type volcanoes at Mount Taylor and the San Francisco Mountain, and as extensive sheets of basaltic lavas and pyroclastic rocks (fig. 26). Laccolithic types of intrusions and large, simply constructed, central-type volcanoes generally are lacking in the structurally more complex provinces surrounding the Colorado Plateau; the development of these igneous forms on the Plateau was favored by the simplicity of its regional structure.

The volume of the basaltic lavas and associated pyroclastic rocks, including the alkalic basalts, greatly exceeds the volume of other igneous rocks. Roughly 15,000 square miles of the Plateau are covered by these eruptives; if they average about 75 feet in thickness, their volume amounts to about 200 cubic miles. The San Francisco Mountain and Mount Taylor together aggregate about 50 cubic miles of eruptive rocks, and there is about 50 cubic miles of intrusive rocks in the laccolithic mountains. These volumes are considerable, but they are very small as compared with the volumes of eruptives in the San Juan Mountains and in the adjoining parts of the Basin and Range province.

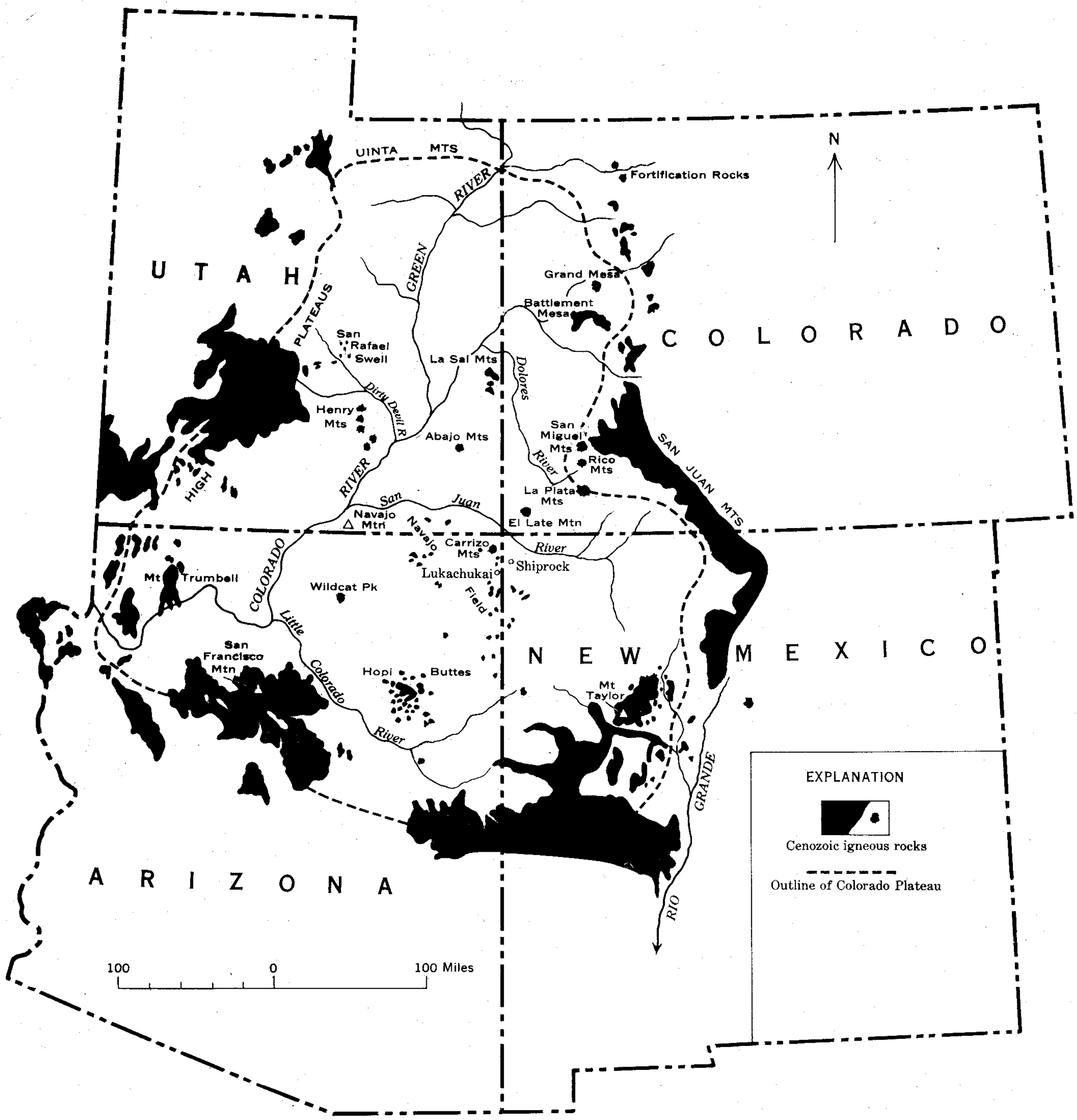
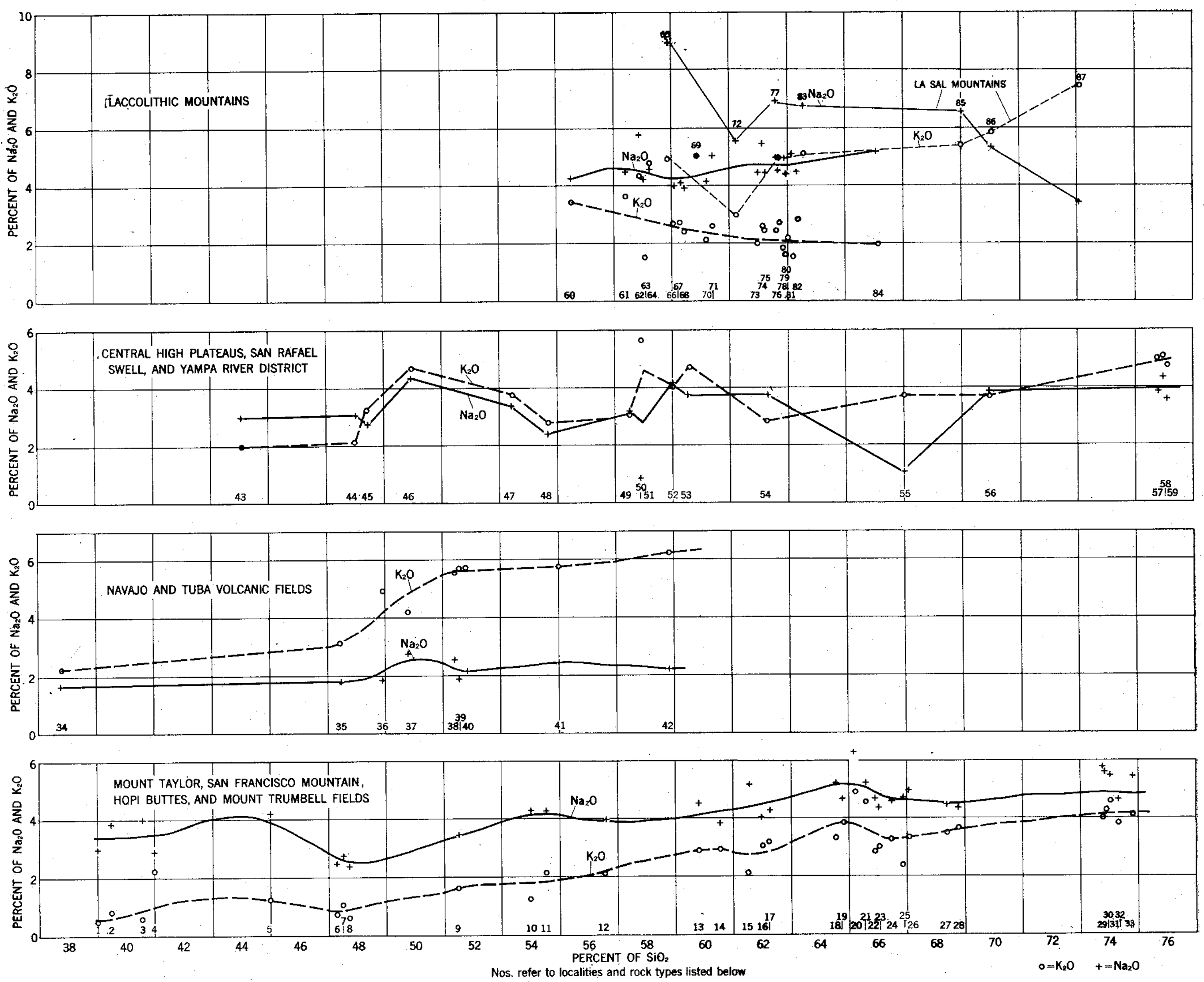


FIGURE 26.—Sketch map illustrating distribution of Cenozoic igneous rocks on the Colorado Plateau. The laccolithic mountains are mostly in the central part of the Colorado Plateau; the volcanic centers are mostly around the edges.

The laccolithic mountains are clustered in the central and east-central part of the Colorado Plateau. The volcanic centers are mostly around the edges of the Plateau, and especially around the southern edges.

The Colorado Plateau is a petrographic province high in alkalis and alumina and low in zirconium. In common with the Great Basin, the content of BaO is high. It is of interest to note that the pre-Cambrian rocks in adjoining areas, especially in the San Juan Mountains, also include considerable bodies of alkalic rocks. The igneous rocks of the Plateau can be grouped into four subprovinces based on the proportions between the alkalis (fig. 27). In the interior of the Plateau, in the laccolithic mountains, soda greatly exceeds potash. In



1. Monchiquite, Hopi Buttes
2. Analcite basalt, Hopi Buttes
3. Apatite-rich monchiquite, Hopi Buttes
4. Limburgite, Hopi Buttes
5. Basaltic (?) lava, near Mt. Trumbell
6. Augite basalt, Kendrick Peak, San Francisco field
7. Basalt, near Grants, N. M., Mt. Taylor field
8. Augite basalt, Cedar Ranch Mesa, San Francisco field
9. Augite andesite basalt, Bill Williams Mtn., San Francisco field
10. Hornblende soda andesite basalt inclusion in hornblende soda dacite, Bill Williams Mtn., San Francisco field
11. Augite andesite, San Francisco Mtn
12. Augite andesite, Kendrick Peak, San Francisco field
13. Pyroxene-hornblende latite, San Francisco Mtn
14. Hypersthene dacite, Kendrick Peak, San Francisco field
15. Pyroxene latite, Mormon Peak, San Francisco field
16. Pyroxene dacite, Kendrick Peak, San Francisco field
17. Hornblende dacite, O'Leary Peak, San Francisco field
18. Hypersthene soda dacite, San Francisco Mtn
19. Cerro Colorado, Mt. Taylor field
20. Andesite, Mt. Taylor
21. Quartz latite, Mt. Taylor
22. Hornblende soda dacite, Bill Williams Mtı ın Francisco field
23. Hypersthene-hornblende soda dacite, Elden Mtn., San Francisco field
24. Biotite-hornblende dacite, San Francisco Mtn
25. Hornblende soda dacite, Mormon Mtn., San Francisco field
26. Biotite dacite, O'Leary Peak, San Francisco field
27. Mount Taylor
28. Biotite dacite, Kendrick Peak, San Francisco field
29. Riebeckite soda granite porphyry, San Francisco Mtn
30. Riebeckite soda rhyolite, San Francisco Mtn
31. Biotite rhyolite, Sugarloaf Hill, San Francisco field
32. Biotite soda granite porphyry, Marble Hill, San Francisco field
33. Biotite soda rhyolite, San Francisco Mtn
34. Nepheline monchiquite, Wildcat Pk., Tuba field
35. Olivine leucitite, Todilto Park, Navajo field
36. Minette, Black Rock, Navajo field
37. Minette, Chaistla Butte, Navajo field
38. Minette, Shiprock, Navajo field
39. Trachy basalt, Washington Pass, Navajo field
40. Minette, dike at Shiprock, Navajo field
41. Trachy basalt, Palisades, Navajo field
42. Pale minette, Mitten Rock, Navajo field
43. Analcite diabase, San Rafael Swell
44. Analcite basalt, Craig, Colorado
45. Alkalic olivine basalt, Marysvale, Utah
46. Analcite syenite, San Rafael Swell
47. Dike rock, Fortification Rocks, Craig, Colorado
48. Intrusive calcic latite, Marysvale, Utah
49. Calcic latite flow, Marysvale, Utah
50. Andesite breccia, Marysvale, Utah
51. Quartz monzonite, intrusive, Marysvale, Utah
52. Latite, Marysvale, Utah
53. Latite, Marysvale, Utah
54. Quartz latite, Marysvale, Utah
55. Rhyolite tuff, Marysvale, Utah
56. Rhyolite glass or pitchstone, Marysvale, Utah
57. Banded gray rhyolite, Marysvale, Utah
58. Granular gray rhyolite, Marysvale, Utah
59. Tuffaceous red rhyolite, Marysvale, Utah
60. La Plata Mts
61. Monzonite, Babcock Peak, La Plata Mts
62. Monzonite porphyry, Mt. Pennell stock, Henry Mts
63. Diorite porphyry, Mt. Hillers, Henry Mts
64. Monzonite porphyry, sill on Mt. Pennell, Henry Mts
65. Noselite syenite porphyry, La Sal Mts
66. Porphyritic augite-diorite, Lone Cone, San Miguel Mts, Colorado
67. Hornblende porphyrite, Ute Peak, El Late Mts
68. Diorite porphyry, Black Mesa bysmalith, Henry Mts
69. Monzonite porphyry, La Plata Mts
70. Diorite porphyry, sill, Mt. Pennell, Henry Mts
71. Diorite porphyry, Deadwood Gulch, La Plata Mts
72. Diorite porphyry, Tukuhnikiwatz laccolith, La Sal Mts
73. Diorite porphyry, sill on Mt. Holmes, Henry Mts
74. Diorite porphyry, Mt. Ellen stock, Henry Mts
75. Diorite porphyry, Mt. Pennell stock, Henry Mts
76. Diorite porphyry, Mt. Ellsworth stock, Henry Mts
77. Soda syenite porphyry, La Sal Mts
78. Diorite porphyry, South Creek Laccolith, Henry Mts
79. Diorite porphyry, interior of Table Mtn. bysmalith, Henry Mts
80. Quartz diorite, Mt. Ellen stock, Henry Mts
81. Diorite porphyry, dike on Mt. Hillers, Henry Mts
82. Hornblende porphyrite, Carrizo Mts
83. Soda syenite porphyry, La Sal Mts
84. Diorite porphyry, roof of Table Mtn. bysmalith, Henry Mts
85. Soda rhyolite dike, La Sal Mts
86. Soda rhyolite dike, La Sal Mts
87. Aegirine granite, La Sal Mts

FIGURE 27.—Variation diagrams showing proportions of alkalis and silica in the igneous rocks in four parts of the Colorado Plateau.

the High Plateaus, soda and potash are about equal. In the Navajo volcanic fields, potash exceeds soda. In the volcanic fields along the southern edge of the Colorado Plateau, soda exceeds potash.

Probably the igneous rocks on the Plateau are closely related genetically despite very different modes of occurrence and regional variations in composition. The rocks at the laccolithic mountains and large central-type volcanoes are similar porphyries. The chemical average of these basalt and alkalic basalt series is less basic than would appear at first, because considerable quantities of rhyolitic ash are associated with these eruptive rocks. Assuming that the rhyolitic tuffs were derived from vents on the Plateau, it is possible that the original average composition of these eruptive rocks approximated that of the porphyries. In any case, there remains the question of whether the differences in rock types are the cause or the effect of their different modes of irruption. That both the composition of the rocks and their mode of irruption are dependent variables is suggested by a striking reversal in proportion of soda and potash at the North La Sal Mountain where the intrusions breached the surface and erupted. The aegirine-granite (no. 87 in fig. 27) contains more potash than soda and became emplaced during or just after the eruptive stage (p. 43).

EARLY TERTIARY IGNEOUS ROCKS

Igneous activity during the early Tertiary on, or around, the Colorado Plateau is recorded by the tuff beds and other volcanic detritus in the lower Tertiary sedimentary formations. Practically all the lower Tertiary formations are tuffaceous; the Animas formation in the San Juan Basin contains a larger amount of coarse volcanic debris. The igneous centers on the Colorado Plateau are regarded as Miocene, or younger, and the volcanic activity recorded in the lower Tertiary sedimentary formations is attributed to activity in adjoining provinces. There must have been considerable volcanic activity during the early Tertiary in the San Juan Mountains, and there certainly was volcanic activity in the Basin and Range province. These areas probably are the sources of the volcanic materials that occur in the lower Tertiary formations on the Colorado Plateau. Some of the earliest igneous rocks in the central part of the High Plateaus may be of early Tertiary age, but they probably are younger.

LATE TERTIARY IGNEOUS ROCKS

LACCOLITHIC MOUNTAINS

The laccolithic mountains on the Colorado Plateau include the Henry Mountains, Navajo Mountain, the La Sal, Abajo, El Late, and Carrizo Mountains. To the east, on the flank of the San Juan Mountains, are the La Plata, Rico, and San Miguel Mountains, all of which also are laccolithic. The intrusive rocks, intrusive forms, structures, and sequence of intrusive events are much alike at all these centers, and the mountains therefore are regarded as representing one intrusive process, involving one type of magma, intruded into very similar host rocks and pre-existing structures. The differences between the mountains represent differences in the stage reached by the intrusive process.

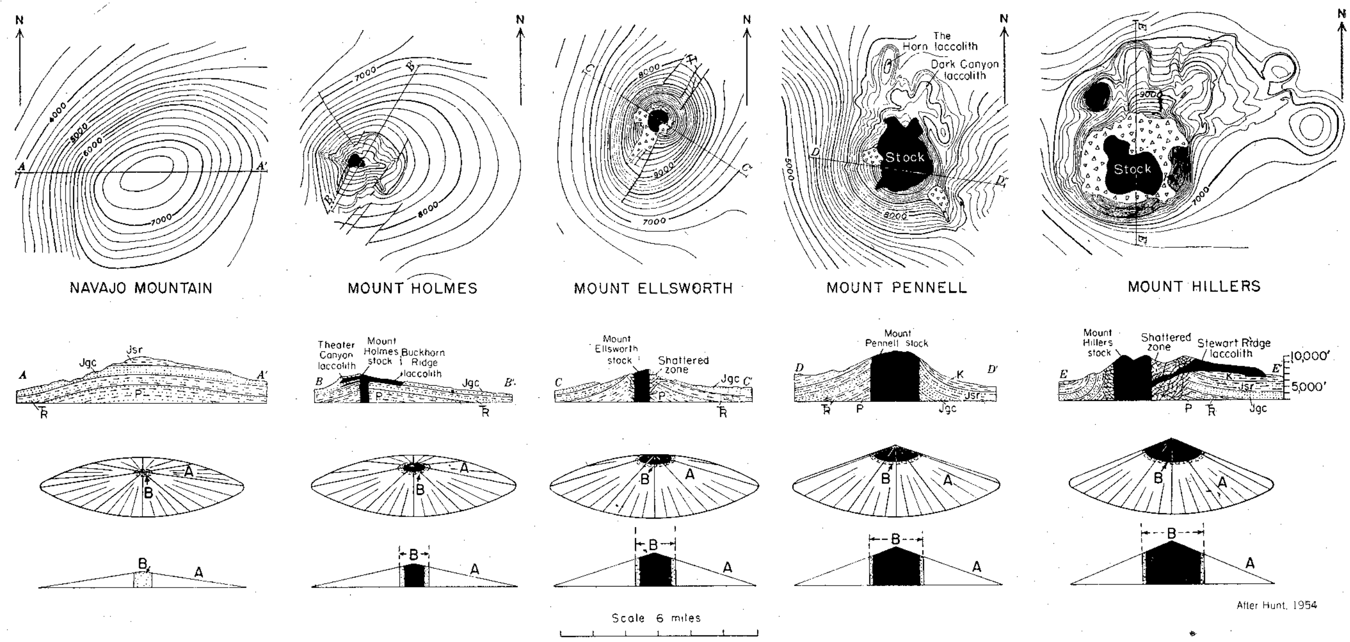
The least-advanced stage in the process is illustrated by Navajo Mountain. No igneous rocks are exposed at Navajo Mountain, but the similarity of this structural dome to the domes at the other laccolithic mountains, and the differences between this dome and the evident orogenic structures, provide almost certain evidence that it is due to intrusion.

The large mountain domes at the laccolithic mountains, including the dome at Navajo Mountain, are attributed to the physical injection of stocks rather than to arching over buried laccoliths (fig. 28). Laccoliths develop around the stocks where the stocks are wide and where the doming around the stocks is higher than at Navajo Mountain.

The next stage in the process is illustrated by Mount Holmes and Mount Ellsworth in the Henry Mountains. The doming there is higher than at Navajo Mountain; stocks are exposed at the centers of the domes, and around them are sills, dikes, and small laccoliths.

The next more advanced stage is illustrated by Mount Hillers. The structural dome there has a relief of 8,000 feet; the stock at the center is a mile or more in diameter, and radiating from it are huge tongue-shaped laccoliths (figs. 29, 30, 31).

The geologic structure at these mountains is such that it is possible to estimate the volume of intrusive rock in them, including intrusions that are not exposed at the surface. As the volume of instrusive rock increases, the deformation is increased, and changes develop in the type of intrusive rock. The earliest intrusions at each of the mountains, and the greatest in volume—as much as 5 or 6 cubic miles—is diorite porphyry. As the intrusive process continues, however, monzonite porphyry becomes intruded, as at Mount Pennell in the Henry Mountains and the southernmost La Sal Mountain. And this porphyry, in turn, is followed by syenite porphyries, as at the North La Sal Mountain and La Plata Mountains. The volume of monzonite porphyry is less than one-half that of the diorite porphyry, and the volume of syenite porphyry is less than one-half that of the monzonite porphyry.



K, Cretaceous rocks. Jsr, rocks of San Rafael group. Jgc, rocks of Glen Canyon group. Ꝧ, Triassic rocks. P, Permian rocks. Structure contours drawn on base of Ferron sandstone member of Mancos shale. Contour interval is 200 feet, datum is sea level

Structure contour maps, cross sections, and diagrams of Navajo Mountain and of Mounts Holmes, Ellsworth, Pennell, and Hillers in the Henry Mountains. The location of the cross sections is shown by lines on the maps. The diagrams are on the same scale as the structure-contour maps and geologic cross sections of the mountains.

Each diagram is set beneath the mountain it portrays. In the oblique diagrams of the conically deformed circular areas the lined area A on the lateral surface of each cone equals the area of the basal circle, and the area B is the amount by which the lateral surface exceeds the circular base.

On the Navajo Mountain cone the stippled area B (0.5 sq mi) represents the extent of stretching of the domed strata. Areas of the same size are represented by stippling on the other cones. On the assumption that this 0.5 sq mi is the limit of stretching of the domed strata, the black areas in the cones of the Henry Mountains represents the theoretical space formed by doming of the strata and available for the intruding stock.

FIGURE 28.—Diagrams illustrating the relationship between the stocks and the domes at the laccolithic mountains on the Colorado Plateau.

The chemical composition of the average rock intruded at the laccolithic mountains is estimated (in percent) as follows:

SiO_2	62.50
Al_2O_3	17.75
Fe_2O_3	2.50
FeO	2.00
MgO	1.50
CaO	5.00
Na_2O	5.00
K_2O	2.50
other	1.25
Total	100.00

The ratio of K_2O to $CaO+Na_2O$ increases eastward. It is smallest in the Henry Mountains; somewhat greater in the La Sal, El Late, and Carrizo Mountains; and greatest in the La Plata Mountains.

Laccoliths and bysmaliths (fig. 31) were formed during the diorite and monzonite porphyry stages, but there are no syenite porphyry laccoliths. Through the monzonite porphyry stage the mode of intrusion was physical injection. The magma evidently was highly viscous, and judging by slight alteration of coal xenoliths, and of organic-rich shale at the contacts, the magma was at low temperatures (Hunt, 1953b). The later syenite porphyry and some nonporphyritic intrusions became emplaced in part by assimilation or replacement of the earlier rocks (fig. 32). These later intrusions were more fluid and apparently were at higher temperature than the earlier ones, perhaps because of endothermic reactions. Whatever the reason, they contain high-temperature quartz (Hunt and Waters, in preparation).

At the La Sal Mountains, the latest intrusions breached the surface and erupted explosively; in the eruptive rocks the potash greatly exceeds soda, whereas in the earlier intrusive rocks the reverse was true. It seems likely that most of the larger stocks in the laccolithic mountains reached the surface and erupted, although probably none of them extruded any great quantity of lava or pyroclastic materials. At least, there is no evidence of low-pressure, oxygen-rich conditions at these stocks.

Hydrothermal activity and mineralization become progressively more extensive and more intensive around the stocks representing the more advanced stages of the intrusive process. The alteration culminates in the mineral deposits associated with the laccolithic mountains on the flanks of the San Juan Mountains.

The intrusive structures at the laccolithic mountains seem to be younger than the orogenic structures. The drainage is superimposed on the orogenic structures, and its pattern is indifferent to them. But the drainage

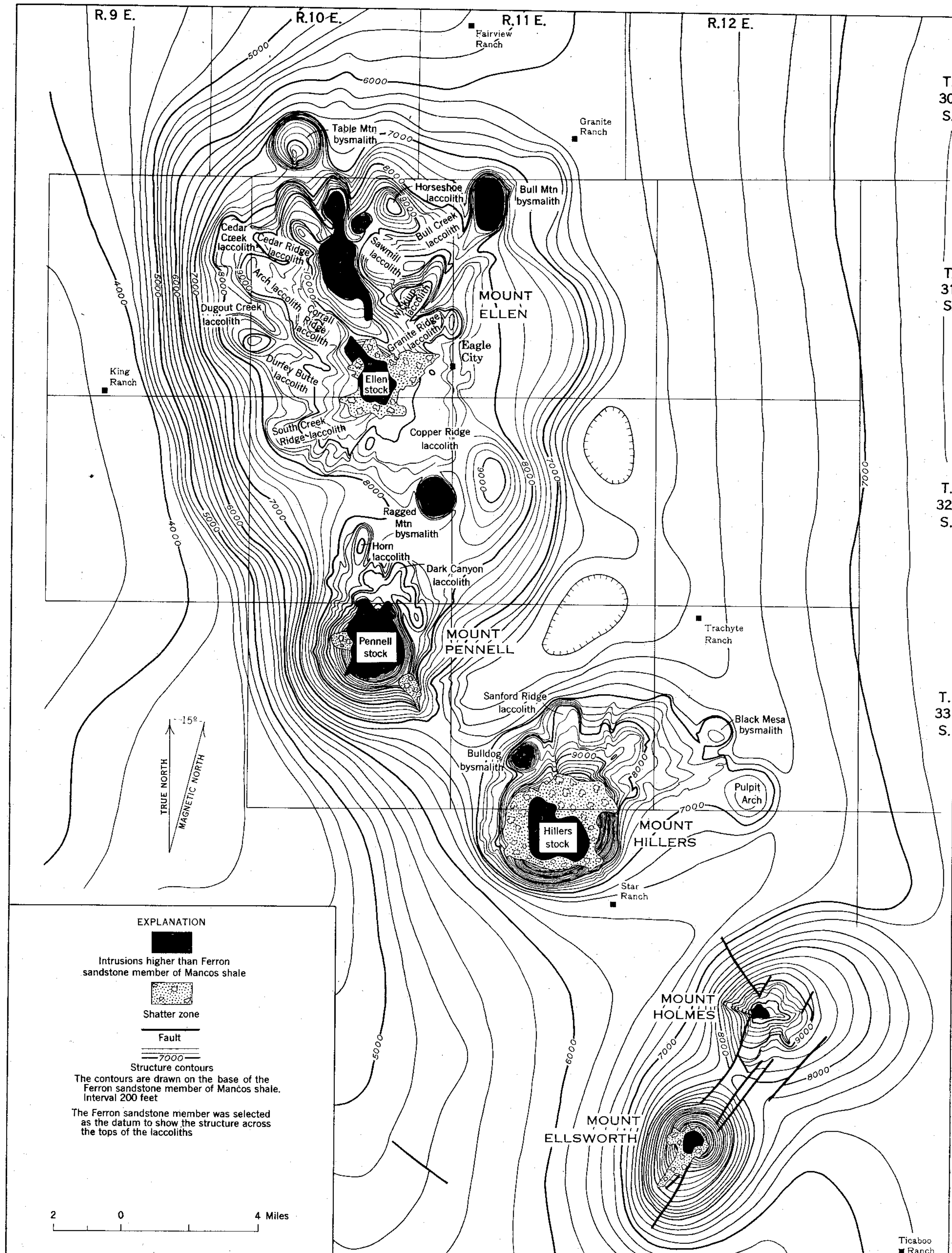


FIGURE 29.—Structure-contour map of the Henry Mountains.

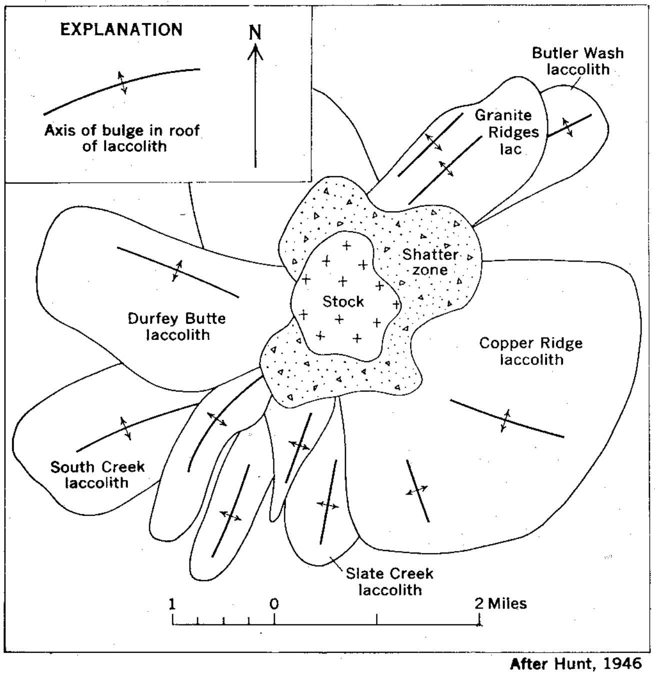


FIGURE 30.—Ground plan of intrusions around the Mount Ellen stock in the Henry Mountains, illustrating radial distribution of the laccoliths.

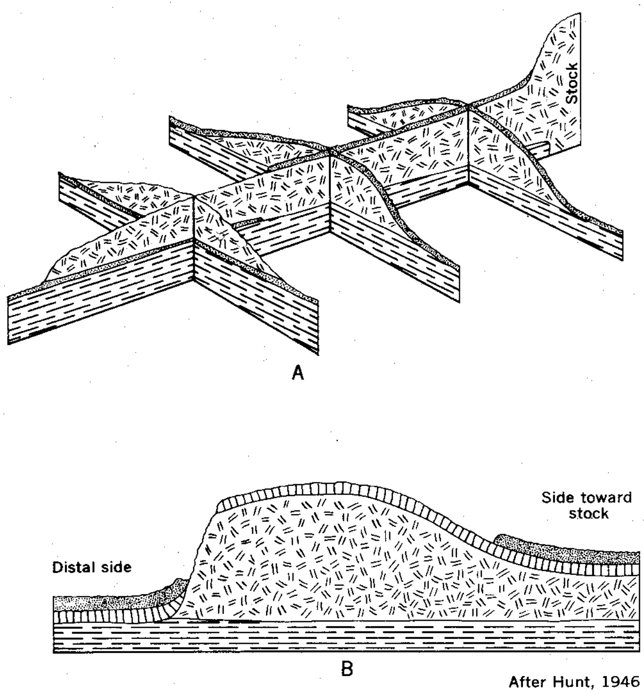


FIGURE 31.—Diagrams illustrating shapes of laccoliths and bysmaliths on the Colorado Plateau. The laccoliths (A) are tongue-shaped and are bulged linearly and radially from the stocks. The distal ends are blunt; the sides are tapering. In general, the strata rise toward the stocks, and the laccoliths cut discordantly to younger beds away from the stocks. The laccoliths commonly are 1 or 2 miles long, ½ to 1 mile wide, and at least 1,000 feet thick along the axial bulge. The bysmaliths (B) have their roofs faulted on the sides away from the stocks. In other respects they resemble the laccoliths.

mostly is consequent, and strikingly so, around the laccolithic mountains, as if it had been monoclinally shifted during the doming. Thus, the Dirty Devil River swings in a wide arc around the Henry Mountains, as does the Dolores around the La Sals. The San Juan River follows the syncline between the El Late and Carrizo Mountains. Possibly, the headward part of the Dolores River once flowed southwestward to join the San Juan River and then was diverted northward by the intrusions at the La Plata and Ute Mountains. On the other hand, the dome at the Rico Mountains is breached by the Dolores River, which seems to be superimposed on the structure.

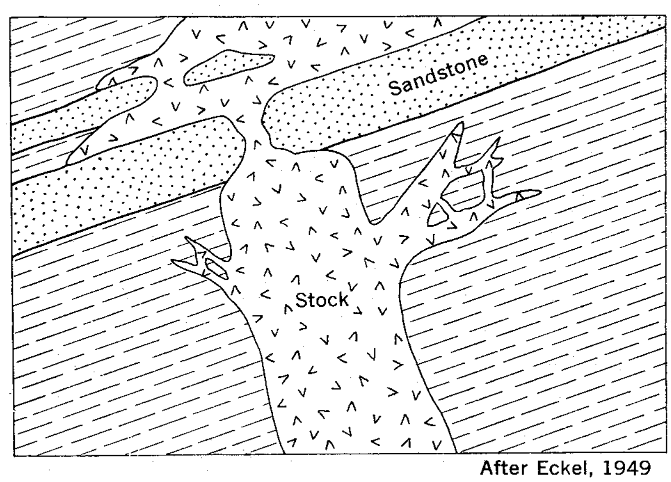


FIGURE 32.—Schematic section through a nonporphyritic stock in the La Plata Mountains. Existing structures are not disturbed, and stock narrows where it passes through a thick bed of sandstone. The bulging part of the stock is 1 mile wide.

Doming at the Rico Mountains is younger than the San Juan peneplain, which is either late Miocene or Pliocene age (Atwood and Mather, 1932, p. 66–67). It is believed that most of the laccolithic mountains are of late Miocene or early Pliocene age. In any case, they antedate the canyons. Gravels derived from the Henry Mountains intrusions occur on the rims of the canyons of the Dirty Devil and Colorado Rivers. Gravels derived from intrusions in the La Sal Mountains occur on the rims of the canyons in that part of the Plateau.

The locations of the intrusions seem to be completely independent of the regional structures on the Colorado Plateau (p. 63), but most of the mountains are located in a vaguely defined belt extending from the San Juan Mountains to the volcanic field in the central part of the High Plateaus. Moreover, the belt coincides with the north edge of the structural platform that breaks off northward into the Uinta Basin (fig. 37).

LARGE CENTRAL-TYPE VOLCANOES

The Mount Taylor volcano erupted subsequent to the major movements of folding and faulting in that district, probably in late Miocene time. The volcano broke out in a syncline. The eruption, which occurred in a fairly well defined compositional sequence, began with rhyolitic tuff. This was followed by relatively quiet eruptions of porphyritic lavas in which two and possibly three series are distinguishable on the basis of their content of potash feldspar. The oldest of these is porphyritic trachyte, but the volume is very small. The next eruption was a large volume of porphyritic latite, interrupted, however, by at least one more flow of porphyritic trachyte. The latite, in turn, was followed by a slightly smaller volume of porphyritic andesite. (Hunt, 1936, p. 63–64.)

The total volume of the tuffs and lavas is about 12.5 cubic miles, of which about 5 cubic miles is rhyolitic tuff, 4 cubic miles is latite, and 3.6 cubic miles is porphyritic andesite. (Hunt, 1938, p. 64.) Following is an estimate of the average composition (in percent) of these eruptives:

SiO	66.50	CaO	1.20
Al_2O_3	17.40	Na_2O	5.40
Fe_2O_3	2.60	K_2O	4.40
FeO	1.50	Other	.55
MgO	.45		
		Total	100.00

The rhyolite and trachyte and most of the latite seem to have been erupted from the central crater, but most of the porphyritic andesite and perhaps the latest latite were erupted by dikes intruded radially around the main pipe. (Hunt, 1938, p. 64.) Part of the rhyolite may have been erupted from other centers (Callaghan, oral communication).

The volcano is a cone 3,000 feet high whose base is more than 10 miles in diameter. It is on a pedestal of sedimentary rocks about 2,000 feet higher than the general level of the surrounding country (fig. 33); erosion has lowered the surrounding country by this amount since the volcano was active. The original volcano probably was about 1,000 feet higher than the present cone. The original crater probably had a diameter of somewhat less than a mile, but it has been greatly enlarged by erosion. (Hunt, 1938, p. 58.)

Except for some local flows of basaltic lava, the earliest eruptions in the district were from Mount Taylor. The erosion surfaces that subsequently were developed around the base of the cone later became flooded with sheets of nonporphyritic basaltic and andesitic lavas erupted from the scores of vents that comprise the volcanic field. A few of the sheets were erupted prior to the latest eruptions on Mount Taylor, but most of them

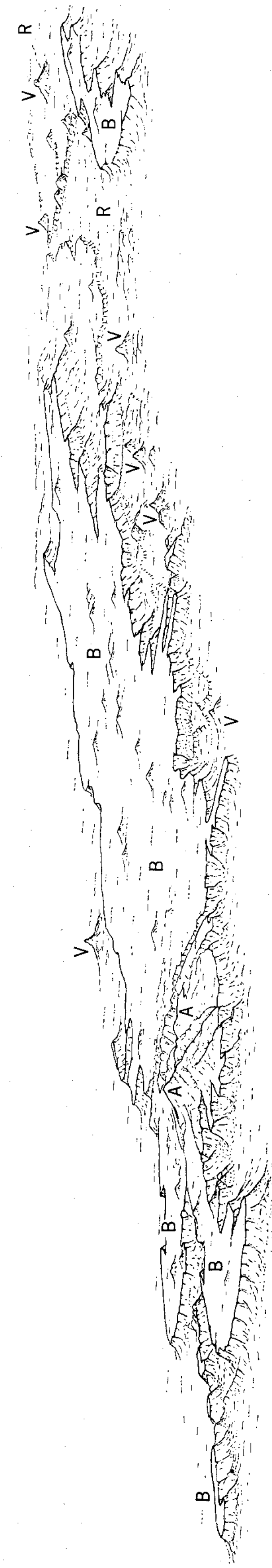


FIGURE 33.—Diagrammatic view of the Mount Taylor volcanic field. Since the eruptions occurred, erosion has lowered the general level of the surrounding country 1,500 to 2,000 feet.

were erupted after Mount Taylor had become quiescent and they overlap the outer edges of the Mount Taylor cone. (Hunt, 1938, p. 58.)

San Francisco Mountain is much larger than Mount Taylor. At the close of its activity its summit stood 8,800 feet above the surface of the surrounding country, the base had a diameter exceeding 10 miles, and the cone had a volume of almost 40 cubic miles. Whereas the Mount Taylor volcano lies in a structural basin, San Francisco Mountain is on a broad dome. Five stages of activity are recognized. The earliest eruptions, aggregating 21 cubic miles of material, consisted of latitic lava, tuff, and breccia. This was followed by 13 cubic miles of pyroxene dacite lava. This was followed, in succession, by eruption of lavas that formed 0.5 cubic mile of hornblende dacite, 0.5 cubic mile of rhyolite, and 3.0 cubic miles of andesite (Robinson, 1913, p. 52). The Mount Taylor volcano stands on a pedestal, and the surrounding country has been lowered considerably since the volcano formed; however, the general level of the country around the San Francisco volcano has been lowered no more than a few hundreds of feet since that volcano was active. The difference probably is not one of age. The Permian formations, on which the San Francisco volcano was built, are more resistant to erosion than the Upper Cretaceous formations that underlie Mount Taylor. Also, basaltic rocks are more extensive around the base of San Francisco Mountain than around the base of Mount Taylor.

The eruptions at San Francisco Mountain were preceded by eruption of about 30 cubic miles of sheet basalt, and were followed by sheet flows of basaltic lavas and pyroclastic materials covering 1,200 square miles—aggregating 20 cubic miles and erupted from about 200 vents (Robinson, 1913, p. 52, 87). See figure 34.

There are several other large, central-type volcanoes clustered near San Francisco Mountain and belonging to the same general period of activity (fig. 35). Kendrick Peak, 11 miles northwest of San Francisco Mountain, built a cone 4,800 feet high covering 40 to 50 square miles, and aggregating more than 6 cubic miles. It began by erupting 5 cubic miles of rhyolite, followed in succession by lesser amounts of pyroxene dacite, hypersthene dacite, and andesite. Bill Williams Mountain, 33 miles south of west San Francisco Mountain, erupted 3 cubic miles of lavas. The earliest eruptions were andesitic; these were followed by a much larger volume of dacite. O'Leary Peak, 9 miles northeast of

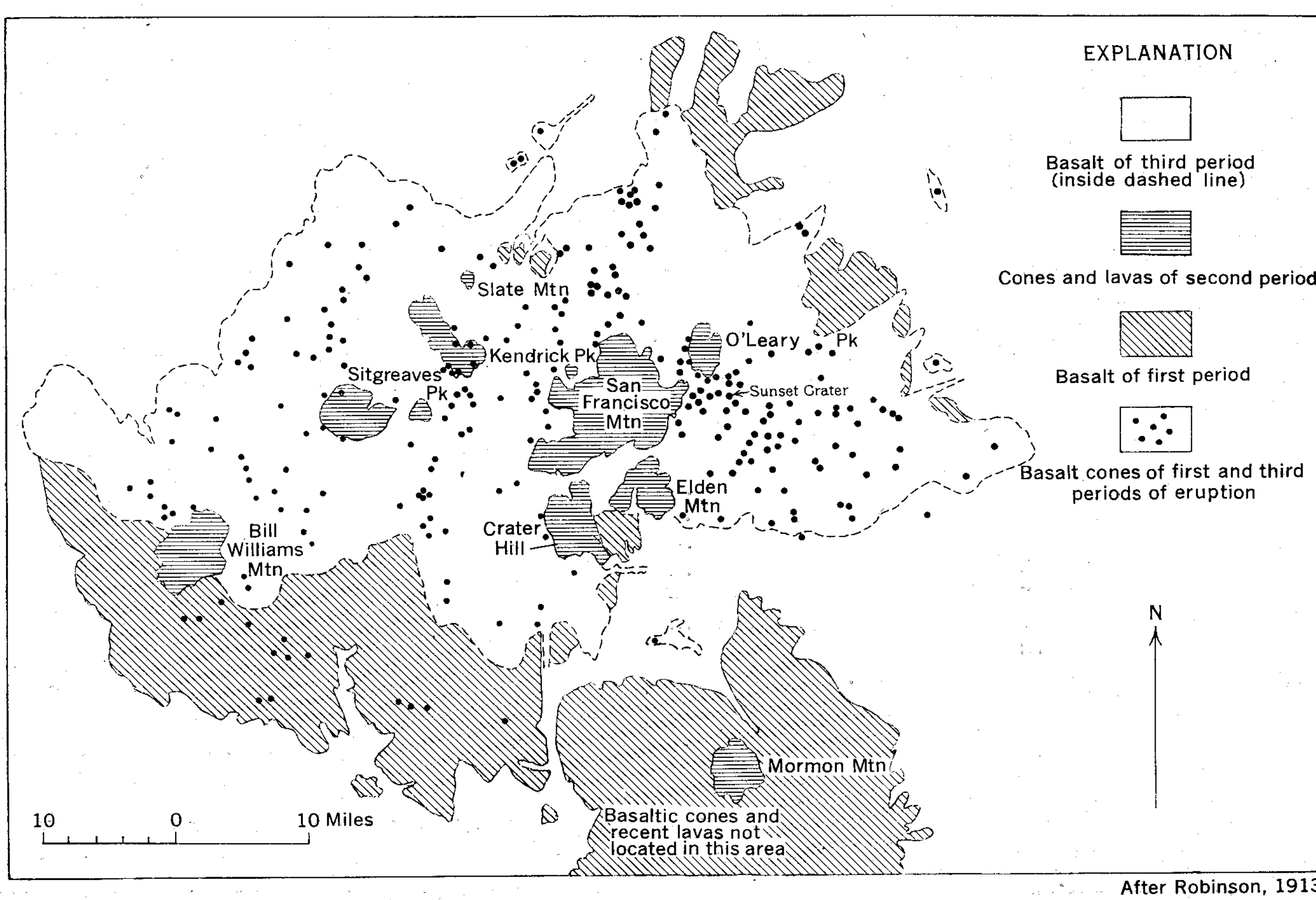
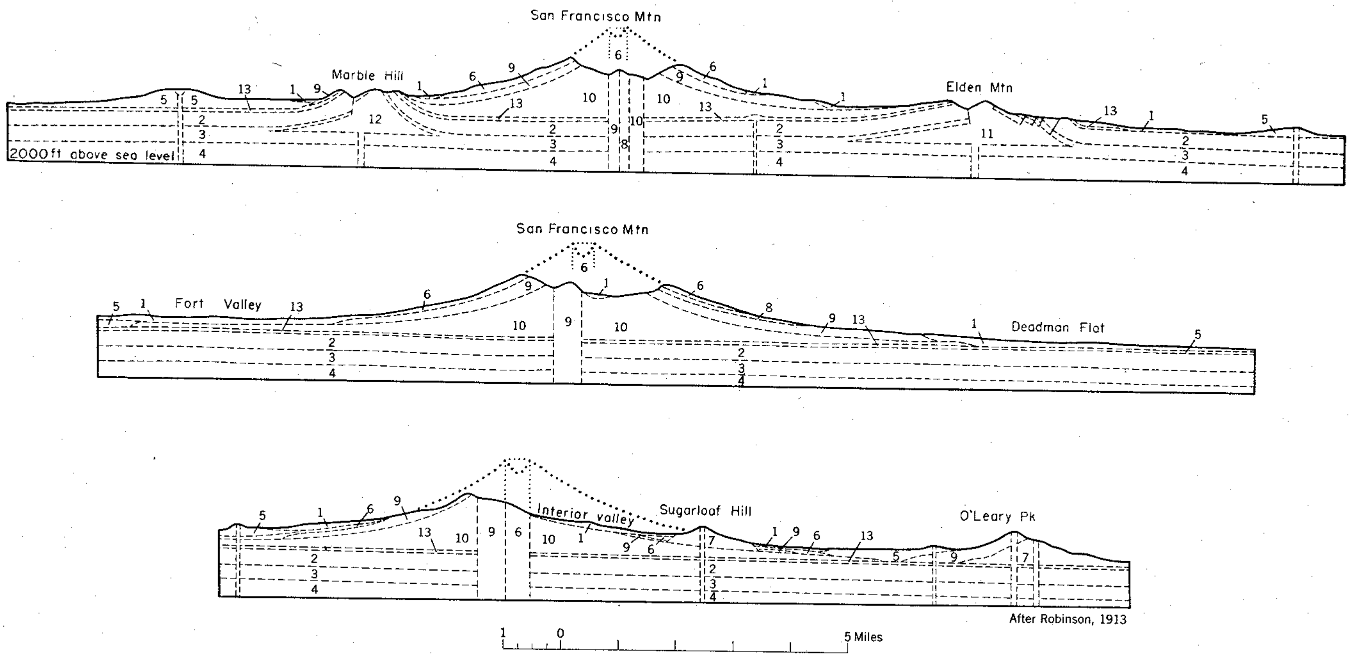


FIGURE 34.—Map of San Francisco volcanic field, showing distribution of cones.



1, Alluvium (Quaternary); 2, Pennsylvanian formations (undivided); 3, Mississippian (including some Pennsylvanian); 4, pre-Mississippian (undivided); 5, basalt (third general period of eruption); 6, andesite (second general period of eruption; 7, rhyolite, (second general period of eruption); 8, hornblende dacite (second general period of eruption); 9, pyroxene dacite (second general period of eruption); 10, latite dacite (second general period of eruption); 11, dacite of Elden Mountain (intrusive portion); 12, granite porphyry of Marble Hill; 13, basalt (first general period of eruption)

FIGURE 35.—Geologic cross sections of San Francisco Mountain and vicinity.

San Francisco Mountain, is a double cone built of lavas during two separate stages of activity. These lavas aggregate 2 cubic miles and are about equally divided between an earlier rhyolite and later dacite. Sitgreaves Peak and Sugarloaf Hill (fig. 35) erupted rhyolite; Mormon Mountain erupted latite and dacite (Robinson, 1913, p. 58, 63, 65, 66–70).

The calculated chemical composition (in percent) of the average lava from these central-type volcanoes in the San Francisco district (Robinson, 1913, p. 159), is as follows:

SiO_2	63.8	H_2+	0.4
Al_2O_3	16.3	H_2O-	.3
Fe_2O_3	2.6	TiO_2	.8
FeO	2.8	P_2O_5	.3
MgO	1.5	BaO	.1
CaO	3.3		
Na_2O	4.7	Total	100.2
K_2O	3.2		

The overall proportion of rock types is rhyolite, 38.5 percent; andesite, 43.5 percent; trachyte, 18.0 percent. (Robinson, 1913, p. 160.)

The average lava from the large cones in the San Francisco district and from Mount Taylor contains less CaO and more K_2O than does the average rock in the laccolithic mountains.

In the laccolithic mountains the differentiation sequence progressed from basic to acid, but at the large central-type volcanoes the sequence generally was reversed and progressed from acid to basic.

VOLCANIC ROCKS AND INTRUSIONS IN THE CENTRAL PART OF THE HIGH PLATEAUS

The igneous rocks in the central part of the High Plateaus are dominantly latite or rhyolite but range from basalt to rhyolite. Volcanic breccias and tuffs make up the greater volume of material. Four stages of igneous activity are distinguished. The earliest is volcanic and formed a group of latitic breccias, tuffs, and flows, at least 5,000 feet thick. The second stage produced intrusive quartz monzonite, in stocks. After deformation and erosion, additional vulcanism occurred, the resulting rocks consisting of rhyolite, quartz latite, latite, and tuff, at least 7,000 feet thick. These volcanic rocks are overlain by the Sevier River formation of late Pliocene or early Pleistocene age. The fourth stage of igneous activity formed scattered thin basalt flows, most of which are associated with the Sevier River formation (Callaghan, 1938, 1939).

The table below gives the estimated average composition (in percent) of each of the igneous series in the central High Plateaus (after Callaghan, 1939, p. 443).

	1 (Early)	2 (Intrusive quartz monzonite)	3 (Volcanics)	4 (Late basalt)
SiO_2	57.00	59.40	71.00	48.65
Al_2O_3	13.75	16.50	13.00	10.40
Fe_2O_3	5.20	3.40	1.60	7.45
FeO	2.50	1.75	.20	6.05
MgO	3.55	2.40	.40	5.55
CaO	5.70	3.90	1.40	8.10
Na_2O	3.70	4.00	3.50	2.77
K_2O	2.75	4.50	4.20	3.40
Other	5.85	4.15	4.70	7.63
Total	100.00	100.00	100.00	100.00

All these are saturated with respect to silica, and they tend to be alkalic. Throughout the group the alkalis are essentially equal and lime content is low. It has been inferred that these rocks, despite the considerable range in their ages, are differentiates of a monzonitic magma, rather than a representative of the basaltic substratum. They differ from average basalt in their high content of potash and low content of alumina. These rocks are much less sodic than those in the laccolithic mountains. (Callaghan, 1938, p. 450–451.)

BASALT AND ALKALIC BASALT SERIES

The upper Tertiary basalt and alkalic basalt series of eruptive rocks on the Colorado Plateau include the extensive flows in the Mount Taylor district and in the Datil section, the equally extensive flows in and south of the San Francisco district, the eruptives at the Hopi Buttes and, in the Navajo field, the flows on the High Plateaus and western part of the Grand Canyon section, the intrusions in the San Rafael Swell, and the eruptives at Grand and Battlement Mesas, Colo.

In the Mount Taylor district some of the sheet lavas preceded the last flows from Mount Taylor, but most of them were poured out after Mount Taylor had become quiescent. Most of the lavas were erupted from central vents, although a few came from fissures. The sheets spread on erosion surfaces developed on Cretaceous formations around the base of the Mount Taylor cone; by the time these eruptions occurred, the Tertiary formations and uppermost Upper Cretaceous formations had already been eroded back to a position north of Mount Taylor. Erosion has lowered the general land surface 1,500 to 2,000 feet since these eruptions occurred (fig. 33). (Hunt, 1936, p. 64.)

Where erosion has removed the lava cap and lowered the country rock the vents are marked by picturesque necks—columns of lava and breccia that solidified in the pipes without reaching the surface. Some of these are 1,800 feet high. There are all gradations from the lava cones, completely surrounded by lava sheets, through cones with the lava removed on one side, thus exposing a natural cross section of the cone and pipe in its center, to necks from which the surrounding lava sheets have been completely removed. There are scores of these eruptive centers, but their distribution seems to be independent of the preexisting structures. (Hunt, 1938, p. 64.)

These basaltic lavas contain very few phenocrysts, mostly olivine. The feldspar is either calcic andesine or sodic labradorite. The ground-mass commonly is glassy. (Hunt, 1938, p. 64.)

Widespread and similar eruptive deposits cover the southern edge of the Colorado Plateau in west-central New Mexico and extend westward into east-central Arizona. They overlap and conceal the boundary between the Colorado Plateau and the Basin and Range province. No satisfactory way of distinguishing between the Tertiary and Quaternary lavas in this area has been found.

In the San Francisco district and to the south are extensive basaltic lava flows that antedate the San Francisco volcano. The lava occurs predominantly as flows; fragmental material is largely restricted to the cinder cones. The scattered lava and cinder cones, in general, do not exceed 700 feet in height, although a few are more than 1,000 feet high. It is estimated that the eruptions were supplied by at least 100 vents distributed in an area covering 3,000 square miles. (Robinson, 1913, p. 39.)

The flows commonly are 25 to 75 feet thick, and none exceeds 200 feet. Their thinness is impressive considering the large area they cover. Few of the flows have scoriaceous surfaces; most of them are dense and jointed in columns. Presumably, the lava had a high degree of fluidity to enable it to spread so widely and so thinly. (Robinson, 1913, p. 39.)

The basalt contains about 10 percent of olivine phenocrysts in an aphanitic groundmass. A partial analysis (in percent) is as follows (Robinson, 1913, p. 39):

SiO_2	47.7	Na_2O	2.5
Al_2O_3	15.3	K_2O	0.6
Fe_2O_3	5.9	CO_2	1.9
FeO	4.8	TiO_2	1.4
MgO	7.3		
CaO	11.8	Total	99.2

Other basaltic eruptions occurred subsequent to the eruptions at San Francisco Mountain. These were provided by about 200 basalt cones; about 20 cubic miles of lava spread over an area of 1,200 square miles. The lava, a normal basalt, is almost identical in chemical composition with the basalts of pre-San Francisco Mountain age. It has a very fine texture, and phenocrysts are rare. Most of it occurs as flows, but cinder deposits are common locally. As compared with the basalt of the earlier period, these lavas tend to form thicker and rougher flows of smaller extent, thus indicating greater viscosity. (Robinson, 1913, p. 87.)

These basalts overlie an erosion surface of very low relief, cut on Permian and Triassic formations. The Jurassic and Cretaceous formations had been stripped from this area, and their outcrop belts had retreated northeastward into Black Mesa basin, by the time these eruptions occurred. Also, the fact that many of the flows spread toward the Little Colorado River indicate that its valley was in existence at that time.

The Navajo-Hopi volcanic districts comprise scores of necks, dikes, and lava-capped mesas (fig. 36). The largest cluster are the Hopi Buttes. The surface on which the eruptions occurred was one of low relief, but it was several hundred and perhaps more than a thousand feet higher than the present surface. The typical Hopi vent was opened by the explosive drilling of a cylindrical pipe, and doubtless a pyroclastic cone or maarlike depression was formed about the orifice. Subsequently, upwelling lava filled the crater and finally spilled over the rim in broad floods. (Williams, 1936, pp. 117–118).

Explosive ejecta from the Hopi vents probably exceed the lava flows in volume. Typically, the ejecta consist of angular and subangular chips of black limburgite and monchiquite in a sedimentary matrix. True bombs and scoriaceous lapilli blown out in a viscous state are uncommon. Great volumes of pulverized sandstone and shale were erupted with the fragments of lava, but debris of plutonic rocks, so common among the tuffs of the Navajo volcanoes to the north, is very rare. (Williams, 1936, p. 119.)

The igneous rocks in the Hopi Buttes area are studded with phenocrysts of augite, and many carry recognizable crystals of olivine. Few of these rocks contain biotite and still fewer contain hornblende. Feldspar is generally absent; where present, it is in the form of microlithic sanidine. Normal plagioclase basalt occurs only along the southern margin of the area, in the direction of the basalt fields along the southern edge of the Colorado Plateau. The scarcity of feldspar among the Hopi Buttes rocks sets them apart from those of the Navajo field to the north, in which orthoclase and

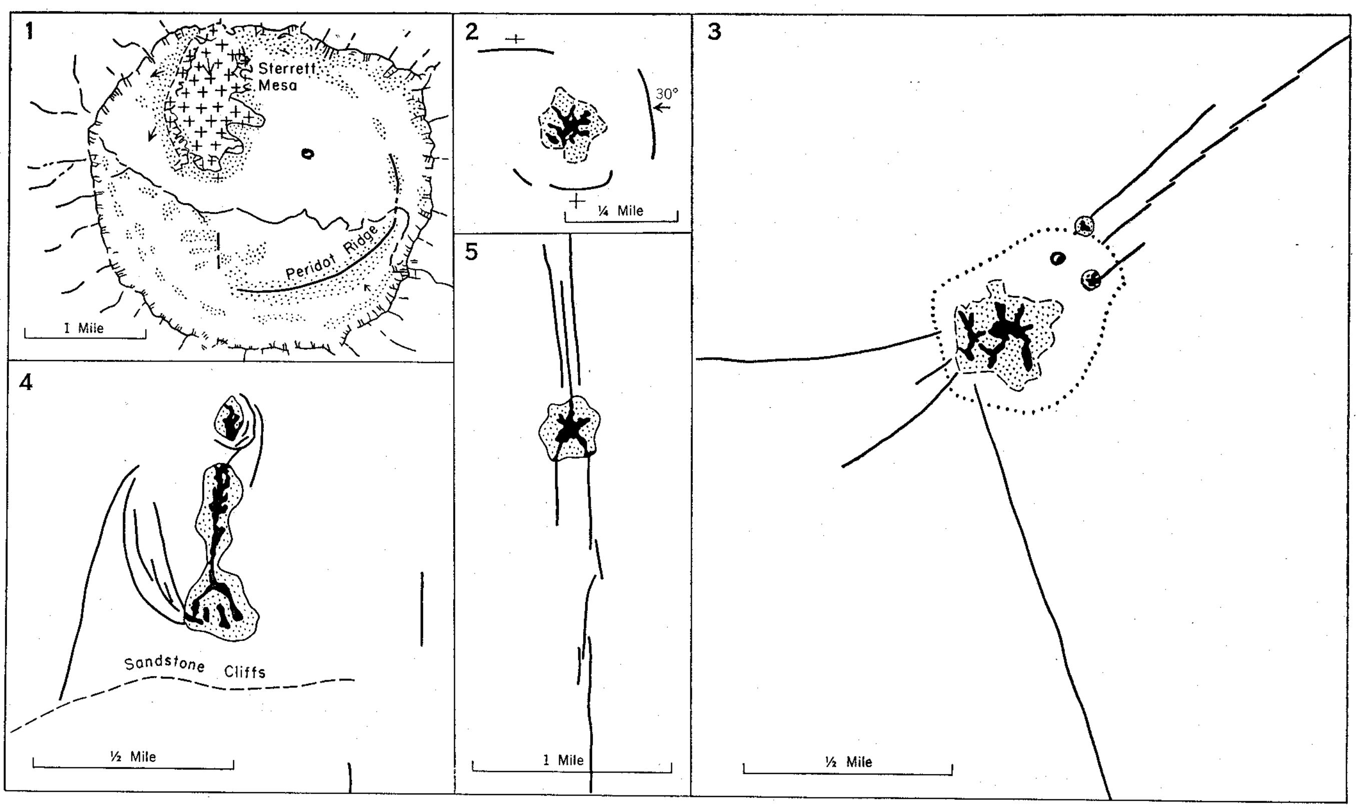


FIGURE 36.—Maps of some volcanic necks in the Navajo-Hopi fields. (1) Buell Park. Arcuate dike of leucite minette; other dikes of minette; lava cap on Sterrett Mesa ends southward in a depression among pyroclastic rocks; tuff-breccias, stippled. (2) Tuff-breccia neck, 5 miles north of Flying Butte, Hopi country. Rises through horizontal shales of the Chinle formation. Bordered by thin dikes of monchiquite. Diagrammatic only. (3) Shiprock. Neck of minette tuff-breccia and dikes of minette. (4) Boundary Butte. Similar neck bordered by arcuate, vertical dikes. (5) Wildcat Peak. Tuff-breccias neck associated with dikes of alnoite, monchiquite, and related rocks.

sanidine are almost ubiquitous. Of the colorless constituents in the Hopi lavas, analcite, a mineral rare in the rocks of the Navajo field, is by far the chief constituent. Leucite, sporadically present in the Navajo field, is not known in the Hopi Buttes area. The typical lavas in the Hopi Buttes area are superficial equivalents of monchiquite; the lavas of the Navajo area are equivalents of minette. Petrographically, the rocks can be classified as mostly limburgite, analcite basalt, and monchiquite; some olivine-augite basalt can be found toward the south. Chemically, the rocks are very much alike. An average of three analyses (in percent) is given in the following table (Williams, 1936, p. 124–128, 166).

SiO_2	39.80	CaO	11.21
Al_2O_3	12.00	Na_2O	3.96
Fe_2O_3	4.30	K_2O	1.19
FeO	8.70	TiO_2	4.01
MgO	10.23		

In these rocks, there is less silica, and more soda and potash, than in the basalt in the San Francisco district.

Several clusters of volcanic centers north and east of the Hopi Buttes are described together as the Navajo volcanic fields. In contrast to the Hopi Buttes, they are at once distinguished by the paucity of lava flows. Most of the Navajo volcanic necks are composed of coarse tuff breccia, or agglomerate (not of columnar lava) and are crowded with fragments of plutonic rocks—chiefly of a granitic type. Also, whereas monchiquitic rocks are typical of the Hopi Buttes, in the Navajo fields these rocks are far subordinate to minette. And whereas the vents in the Hopi Buttes area have a northwest-southeast alignment (Hack, 1942, p. 67), those in the Navajo field are similar to those in the Mount Taylor district and seem to be scattered without regard to pre-existing structures. None is located along a fault. (Williams, 1936, p. 130–131.)

The average of eight analyses (in percent) of rocks from the Navajo volcanic field is given in the following table (Williams, 1936, p. 166):

SiO_2	51.88	MgO	8.76
Al_2O_3	11.45	CaO	8.45
Fe_2O_3	3.00	Na_2O	2.26
FeO	3.56	K_2O	5.41

The rocks of the Navajo volcanic field are potassic, whereas those in the Hopi Buttes area to the southwest, and in the laccolithic mountains to the north, are sodic. On the other hand, the diorite porphyry of the Carrizo Mountains, located in the midst of the Navajo volcanic field, is chemically like the diorite porphyry of the other laccolithic mountains to the north and is unlike the rocks in the Navajo field.

The rocks involved in the explosive eruptions that terminated the igneous activity at the North La Sal Mountain had an unusually large potash content. A similar relationship is found in the volcanic fields. The potash-rich Navajo volcanic field produced fewer lava flows and more explosive eruptions than did the soda-rich volcanic fields. We can only conjecture as to whether the presence of more potash led to greater explosive activity, or whether the greater explosive activity resulted in the liberation of more potash and soda.

In the northern part of the Colorado Plateau there are other alkalic basalts similar to those in the Navajo-Hopi region. These lie north of the laccolithic mountains. In the San Rafael Swell are dikes and sills of analcite diabase and analcite syenite. An average (in percent) of two analyses, one of each type, is as follows (Gilluly, 1927, p. 205):

SiO_2	46.65	MgO	6.80
Al_2O_3	15.75	CaO	8.95
Fe_2O_3	3.58	Na_2O	3.78
FeO	4.36	K_2O	3.46

Similar sodic-potassic rocks are associated with the Browns Park formation just northeast of the Colorado Plateau in the vicinity of Craig, Colorado. In this part of Colorado there are normal basalts also (Ross, 1926).

In the High Plateaus are numerous lavas and volcanic cones; these are of several different ages, probably many of late Tertiary, but some of Quaternary age. The older lavas and volcanic cones antedate the faulting; some of them overlie the Wasatch formation with angular unconformity. (Gregory, 1950, pl. 2).

The lava flows along the Hurricane fault in southwestern Utah (fig. 47) are part of a volcanic field that extends westward into the Basin and Range province. Some of the lavas that were erupted from centers west of the Hurricane fault became displaced by the Hurricane fault, and they now cap the cliffs formed by the upthrown block. However, the displacement of these lavas is not so great as the displacement of the underlying rocks; therefore it is clear that there was prevolcanic, as well as postvolcanic, movement on the Hurricane fault. In general, the eruption of lavas in the southern part of the High Plateaus was contemporaneous with the horst and graben faulting that developed those plateaus. So far as known, all these lavas in the southern High Plateaus are normal basalt consisting of labradorite, olivine, augite, and magnetite. Many of the flows are less than 50 feet thick. Cinders, lapilli, and other pyroclastic deposits occur at some of the cones, but the quantity of these is small compared to similar deposits in the Navajo or Hopi Buttes fields

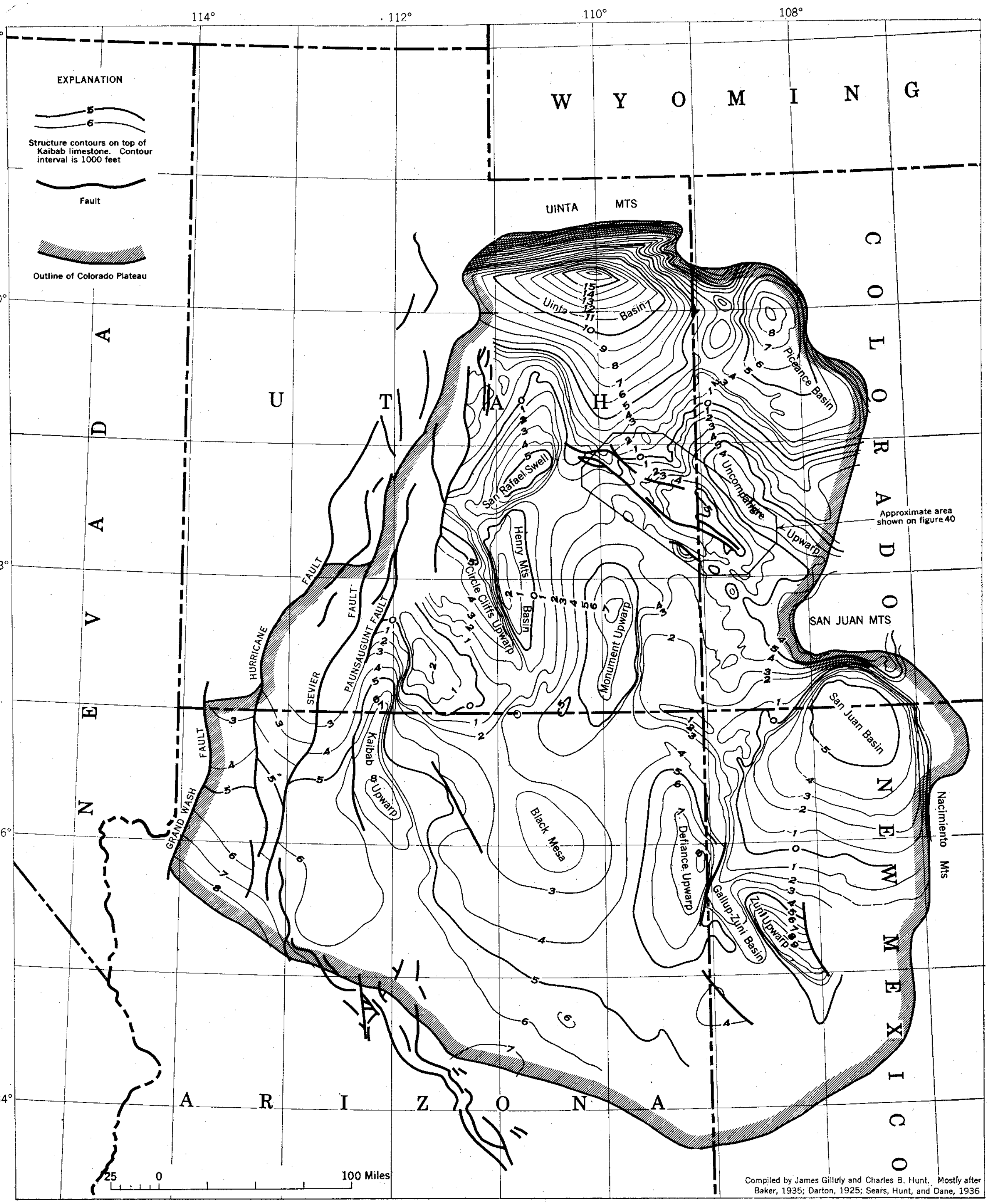


FIGURE 37.—Structure-contour map of the Colorado Plateau.

where the rocks are alkalic. (Gregory, 1950, p. 133–140.)

Farther north in the High Plateaus (in central Utah) the lavas are largely latite and rhyolite, and these are older than the basaltic lavas (see p. 49); an analysis of one of these basaltic lavas in the central High Plateaus is given on page 49.

QUATERNARY IGNEOUS ROCKS

The igneous rocks of Quaternary age are of interest in this report chiefly because of their recency. So far as known all of them are normal basalt. These rocks occur as flows along the bottoms of present-day valleys; some of them are so fresh that they appear to have been erupted in historic time. Among them are the flows along the San Jose River south of Mount Taylor, N. Mex. Others are south of the Zuni Mountains. Similar flows in Arizona occur near the Mogollon Rim, in the San Francisco Mountain district, in Grand Canyon, and at Peach Springs. There is a fresh-looking flow on the bottom of a canyon—Johnson Canyon—east of Kanab, Utah. Quaternary basaltic lavas just north of the Colorado Plateau include some that are associated with the Lake Bonneville deposits in western Utah, and one that is in the valley of the Eagle River near its junction with the Colorado River at Dotsero, Colo. No doubt many of the lava flows along the southern rim of the Colorado Plateau in New Mexico and Arizona are of Pleistocene or Recent age.

One of the most recent eruptions occurred at Sunset Crater (fig. 1, 34) in the San Francisco field, Arizona. This eruption, dated 1160 A. D., buried a Pueblo II occupation layer under 6 feet of cinders. (McGregor, 1936; Colton, 1945). The flow at McCartys, south of Mount Taylor, may be less than 1,200 years old (Nichols, 1946, p. 1049–1086).

Many of the lava flows in the southern part of the High Plateaus are of Quaternary age; some of the lavas, and perhaps most of the cones, are of very late Pleistocene age and may be Recent. At several places, thin narrow flows follow the stream beds. Many of the flows have been faulted. (Gregory, 1950, p. 133–140).

STRUCTURAL GEOLOGY

GENERAL FEATURES

The Colorado Plateau is part of the geanticline that extends from Kansas to California, including the High Plains, Rocky Mountains, and Basin and Range province. The Basin and Range province can be interpreted as a collapsed segment of the geanticline, and this collapsed segment ends along fractures at the edges of the Colorado Plateau. Except along the Rio Grande depression, which is part of the collapsed area, the Colorado Plateau has remained "fastened" to the Rocky Mountains.

The principal structural elements of the Plateau are of five kinds (fig. 37). The first, and most extensive, are the broad basins represented by the Uinta, San Juan, and Navajo Basins. Together, they comprise a quarter of the Plateaus. They trend toward the west or northwest. The Uinta Basin is the lowest, and the Navajo Basin (shown as Black Mesa in fig. 37) is the highest.

Between these large basins are clusters of upwarps (the second kind of feature) including the San Rafael Swell, Circle Cliffs, Kaibab, Monument, Defiance (fig. 21), and Zuni upwarps (fig. 38), and between these upwarps are basins such as the Henry Mountains and Gallup-Zuni Basins (fig. 39). These are asymmetrical folds, some trend northward, others trend northwestward. All of the upwarps, except that at the Zuni Mountains, have their steep flanks facing eastward.

The third kind of structural feature is represented by the northwestward-trending anticlines and faults in east-central Utah, in the area underlain by thick salt deposits (fig. 40).

The fourth kind is represented by the northward-trending fault blocks of the High Plateaus. These features represent a zone transitional between the Colorado Plateau and Basin and Range province (fig. 41).

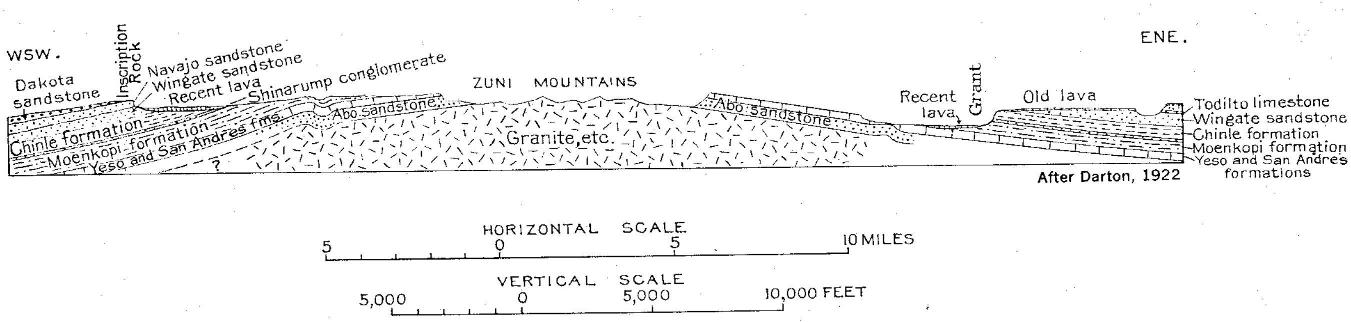


FIGURE 38.—Section across the Zuni Mountain upwarp, N. Mex.

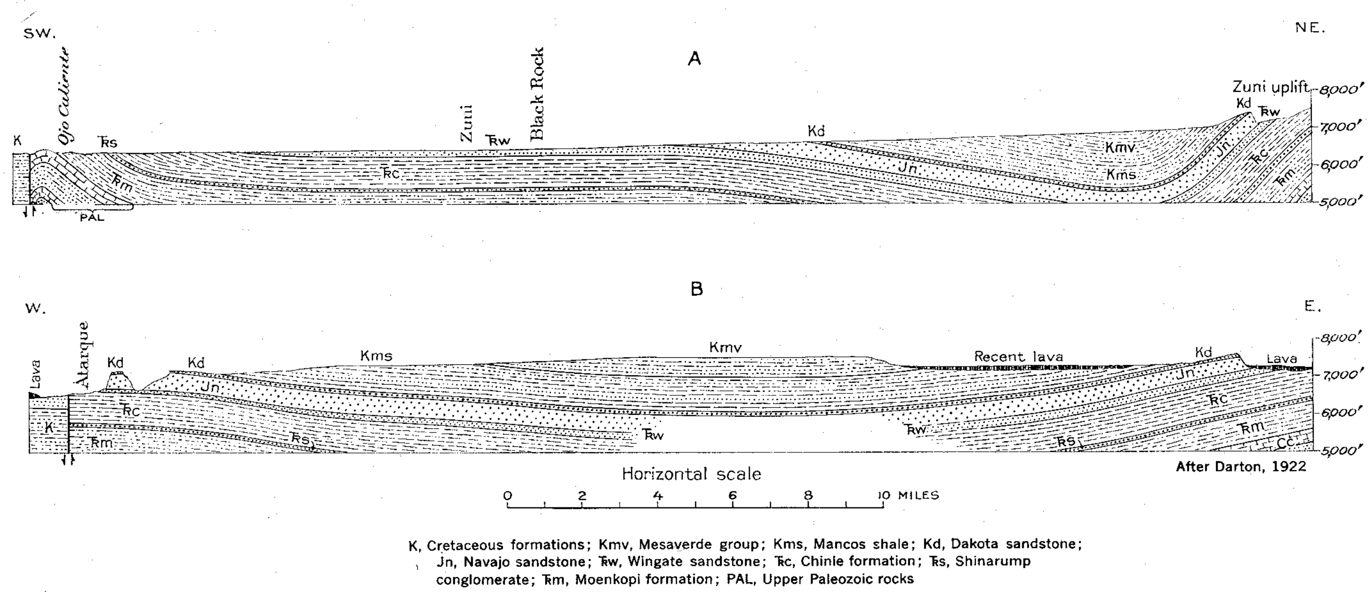


FIGURE 39.—Sections across the Gallup-Zuni Basin, N. Mex. (A) near Zuni; (B) near Atarque.

And fifth, and last, there are the domes and other folds related to the intrusions at the laccolithic mountains, most of which are in the central part of the Colorado Plateau (figs. 29, 30).

Although these five structural elements of the Colorado Plateau are the product of Cenozoic deformation, they were in large part controlled by pre-Cenozoic structures.

PRE-CENOZOIC STRUCTURAL ELEMENTS

The pre-Cenozoic structural elements of the Colorado Plateau mostly have northwesterly trends, and these elements undoubtedly controlled the direction, and probably the location of those Cenozoic elements that trend northwestward. Development of these northwest-trending features started at least as early as Paleozoic time, and they may date from the pre-Cambrian. They persisted through the Mesozoic and guided the depositional basins and facies changes in the Mesozoic formations.

The best known of these features is that of the Uncompahgre Plateau and the basin to the southwest, known as the Paradox Basin. The Uncompahgre Plateau, part of a larger ancient highland area that extends southeastward into the Southern Rocky Mountains, was anticlinally raised in late Mississippian or early Pennsylvanian time. The lithology, thickness, and distribution of the Pennsylvanian, Permian, and Triassic sedimentary rocks adjacent to this highland show that the uplift began at least as early as early Pennsylvanian time and continued through Permian and into Triassic time. Paralleling this uplift, on the southwestern side, was a trough in which the salt-bearing sediments of the Pennsylvanian Paradox member of the Hermosa formation accumulated (Baker, 1935, p. 1495).

In the Zuni Mountains (fig. 38) and Defiance upwarp (fig. 9), Permian redbeds rest on pre-Cambrian crystalline rocks, thus suggesting that these areas also were uplifted in Pennsylvanian time. These uplifts probably are part of a northwestward-trending arch that marked the northeast limit of the early Paleozoic formations in the southern and southwestern parts of the Colorado Plateau.

The present Grand Canyon seems to be near the crest of a broad arch created during Pennsylvanian time, because Pennsylvanian formations thin out by overlap on its northeast flank (Baker, 1935, p. 1495).

Three Mesozoic features have been recognized on the Colorado Plateau and probably there are others. One of these is the early Triassic uplift at the Uncompahgre Plateau. Another is represented by the unconformity that is reported to be between the Carmel formation and Navajo sandstone along the eastern side of the Defiance upwarp (p. 15). The third known Mesozoic feature is along the south rim of the Plateau and is recorded by the overlap of the Upper Cretaceous formations onto Jurassic, Triassic, and Permian formations southwestward from Zuni to the Mogollon Rim south of Holbrook, Arizona (fig. 11). This overlap indicates northeastward tilting of the southwestern part of the Colorado Plateau prior to Late Cretaceous time. Perhaps the northeast change in facies of the Upper Cretaceous formations in the San Juan Basin (Sears, Hunt, and Hendricks, 1941) also is a result of this tilting; the strandline marking the edge of the

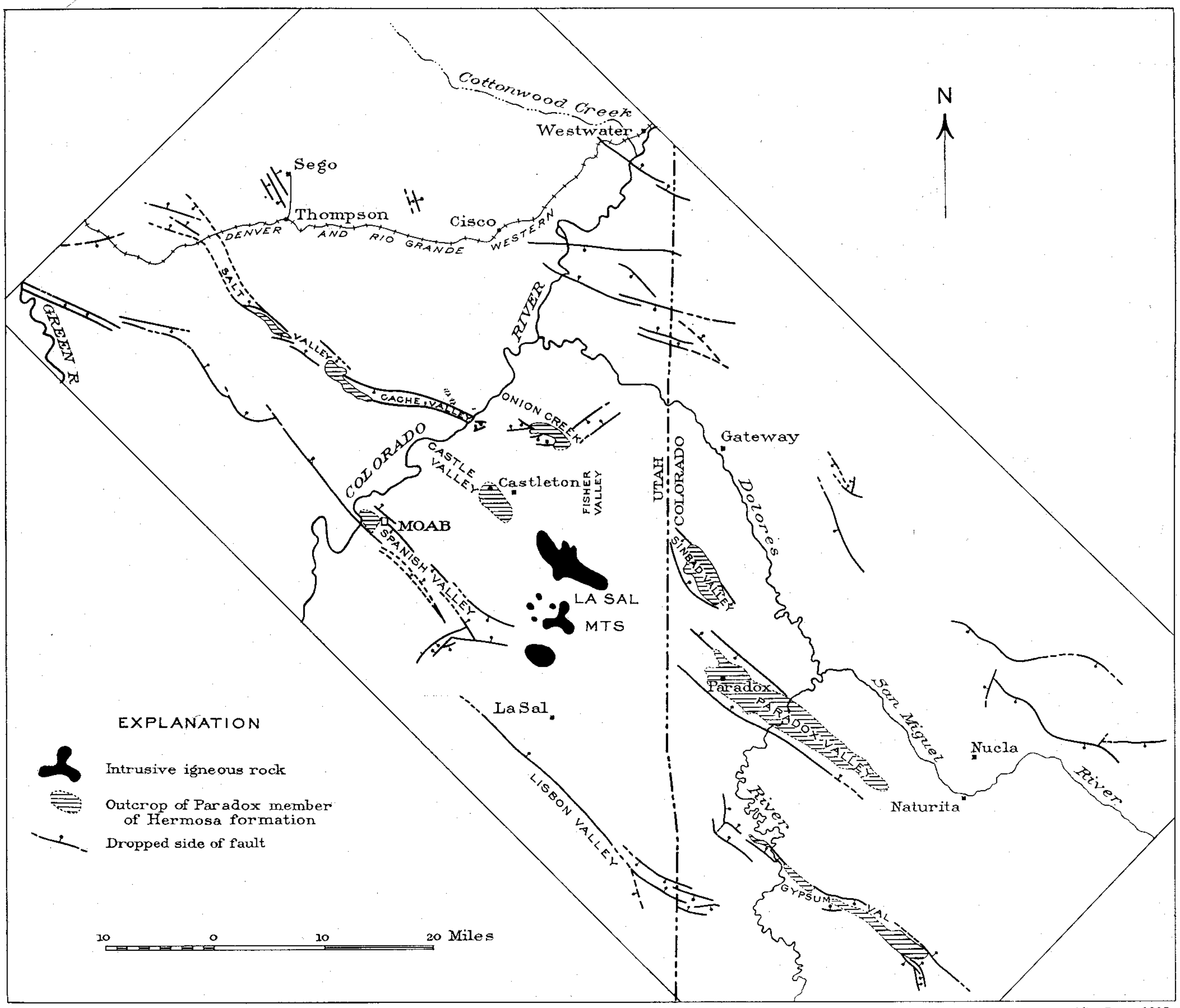


FIGURE 40.—Generalized map of part of eastern Utah and western Colorado, showing relation of principal faults to outcrops of the Paradox formation, the La Sal Mountains, and the southwest flank of the Uncompahgre Plateau.

Late Cretaceous geosyncline in that part of the Plateaus trended northwestward and parallel to the strike of the pre-Cretaceous tilting.

Reconstruction of pre-Cenozoic structural features along the western edge of the Colorado Plateau is difficult. There were deep geosynclinal troughs west of the Plateau during Paleozoic time, but there were none within the area of the Plateau. The western edge of the late Cretaceous geosyncline in Utah was approximately at the position of the present western edge of the Plateau.

In general, the Colorado Plateau constituted a shelf area during Paleozoic and Mesozoic time, and the differences between it and the Basin and Range province therefore, in large part, are inherited. On the other hand, the Paleozoic and Mesozoic structures of the Plateaus resemble those in adjoining parts of the Wyoming Basin and Southern Rocky Mountain provinces, and the differences between the Plateau and those provinces to the north and east seem to have originated in large part during the Cenozoic.

At various times during late Paleozoic and Mesozoic time in the Paradox Basin, southwest of the Uncompahgre Plateau, there was movement of salt and deformation of the overlying strata (Prommel and Crum, 1927; Harrison, 1927). But these pre-Cenozoic disturbances seem to be less significant than the Cenozoic deformation (Baker, 1933, p. 74–76).

At the end of Cretaceous time the Colorado Plateau was a piedmont area extending eastward and northeast-

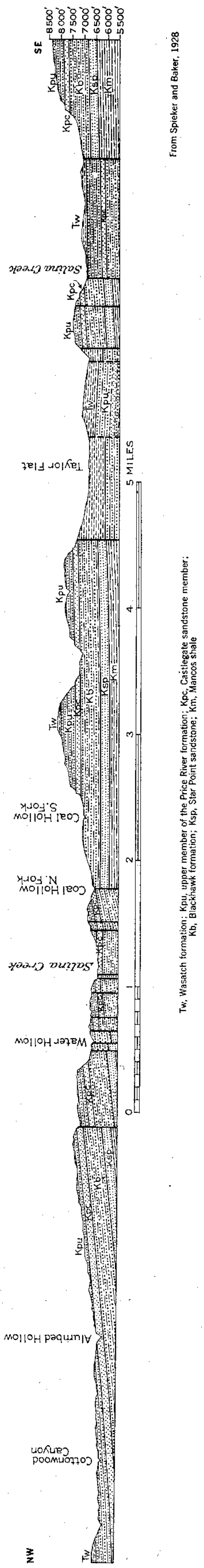


FIGURE 41.—Cross section of fault blocks in High Plateaus southeast of Salina, Utah.

ward from the foot of mountains that had been built by thrust faulting and folding in the adjoining parts of the Basin and Range province (fig. 42). When the

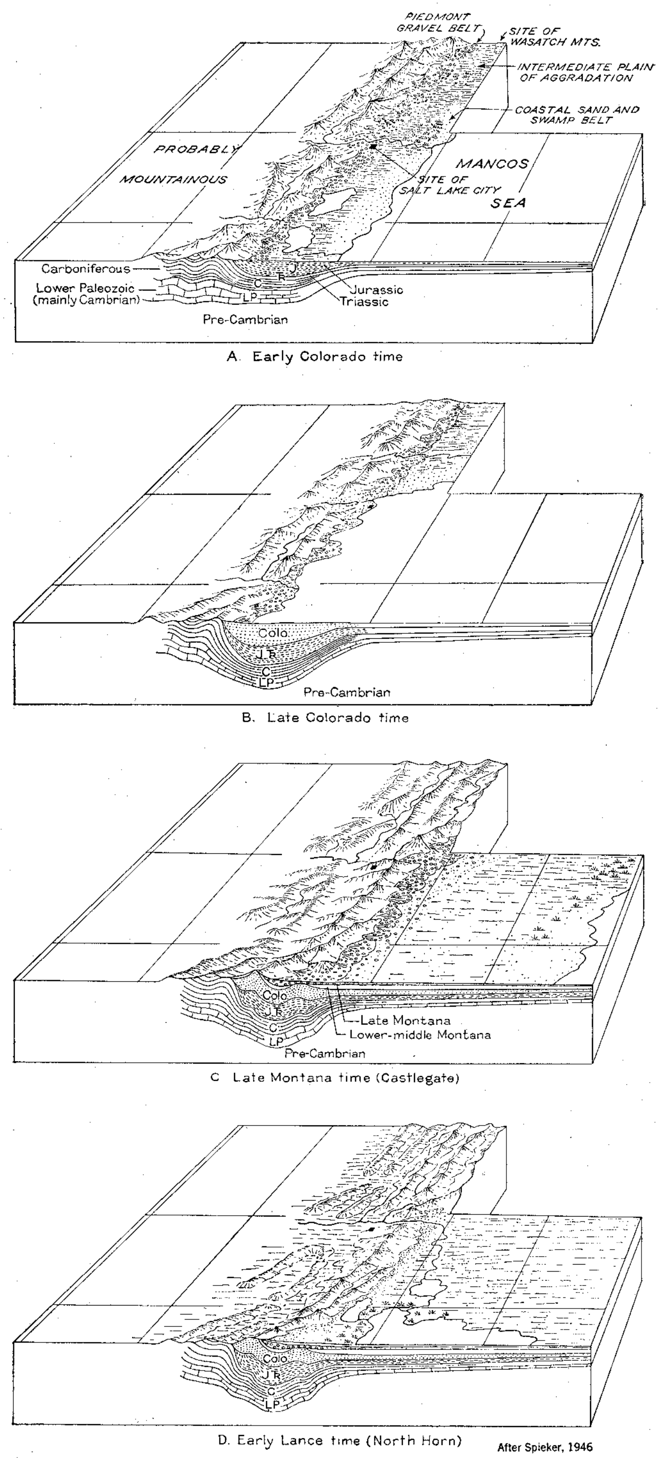


FIGURE 42.—Block diagrams showing that part of Utah north of latitude 39°30′ at four stages in Late Cretaceous time.

Uinta Mountains and Rocky Mountains were raised, beginning in early Paleocene time, the area of the Plateau became a structural basin ringed by mountains on at least three sides (fig. 54). It may have been a trough open to the south or southeast.

CENOZOIC OROGENIC STRUCTURES

EARLY TERTIARY STRUCTURES

Early Cenozoic deformation, recorded by an angular unconformity at the base of the Wasatch or older Tertiary formations, is known at four places in the Colorado Plateau. These are: the south flank of the San Juan Mountains, west flank of the Circle Cliffs upwarp, northeast flank of the upwarp at the head of the Fremont River, and west side of the Wasatch Plateau. The beds above the unconformity at the Circle Cliffs upwarp probably are of early Eocene or late Paleocene age. At the north rim of the San Juan Basin and at the west side of the Wasatch Plateau there is reasonable certainty about the age of the beds above the unconformity. It also is certain that uplift of the Uinta Mountains began during, if not prior to, Wasatch time because, although the unconformity is concealed by overlap of younger formations, the facies changes in the Green River and other formations in the Uinta Basin show that the Uinta Mountains were in existence and were a major source of the sediments in those Tertiary formations.

Probably the Circle Cliffs, Defiance, and Zuni upwarps date from the same period because they lie along the same pre-Cenozoic arch.

The unconformable overlap of the Animas formation onto the McDermott and older formations on the north flank of the San Juan Basin indicates uplift of that flank in Late Cretaceous or earliest Tertiary time. The andesitic debris in the McDermott and Animas formations indicates that the uplift was accompanied by vulcanism in the San Juan Mountains. Post-Wasatch uplift of the San Juan Mountains is indicated by the southward dip of the Wasatch formation into the San Juan Basin.

On the western side of the Wasatch Plateau, the Flagstaff limestone rests with angular unconformity on folded older rocks. The limestone is younger than the Animas, and therefore this deformation recorded on the western side of the Wasatch Plateau could be younger than that recorded on the southern flank of the San Juan Mountains. However, there was earlier folding during Cretaceous time to the west of the Wasatch Plateau (fig. 42).

The lacustrine Flagstaff limestone and Green River formation record downwarping, first along the northwestern edge of the Colorado Plateau and slightly later in the Uinta Basin area. This downwarping is regarded as a part of the epeirogenic episode and is discussed more fully on page 63.

Although the Uinta Mountains began rising long before Green River time, there was post-Green River upwarp also, as recorded by the overlap of the Uinta formation onto the Mesozoic formations that are turned up along the southern side of the mountains. There is some uncertainty about the position of this unconformity, but it is inferred to be at the base of the Bridger; there is an angular unconformity at the base of the Bridger on the northern side of the Uinta Mountains (Sears and Bradley, 1924, p. 96). Later upwarp of the Uinta Mountains is recorded by the folding of the Duchesne River formation; this post-Duchesne River upwarp may have occurred during Oligocene time.

The northward dip of the Bridger and younger fluviatile Eocene formations into the Uinta Basin is assumed to indicate subsequent upwarp of the area to the south, instead of continued downwarping of the Uinta Basin. The Wasatch formation and equivalent Colton formation are arched around the north end of the San Rafael Swell and around the northward-trending anticline that separates the Uinta and Piceance Creek basins (fig. 37). Moreover, the Green River formation is warped downward in the syncline that plunges northward from Green River, Utah. Perhaps the Bridger, Uinta, and Duschesne River formations also are affected by this syncline, but this is not certain. The syncline is assumed to reflect late Eocene or Oligocene upwarp on the San Rafael Swell and on the anticline separating the Uinta and Piceance Creek basins. There also appears to have been at least two earlier stages of upwarp of these anticlines. The first upwarp probably was pre-Wasatch; and there probably was post-Green River and pre-Bridger upwarp also. The amount of upwarp in early Tertiary time must have been slight considering the concordance between the early Tertiary and Cretaceous strata around the north ends of these northward-trending folds. The apparent superposition of the San Rafael and Muddy Rivers across the San Rafael Swell suggests deposition of a layer of Tertiary deposits unconformably on the older folded rocks; this layer probably was no older than the Bridger formation.

Mention has already been made of the late Cretaceous and early Tertiary upwarp in the San Juan Mountains as recorded by the lowermost Tertiary formations in the northern part of the San Juan Basin. Post-Wasatch upwarp of the flanks of the San Juan Basin is recorded by the basinward dips of that formation. Upwarp of the Zuni Mountains is assumed to have started in pre-Wasatch time, but there also must have been later upwarp to produce the northward dip of the Wasatch formation. There was post-Wasatch upwarp of the Nacimiento Mountains along the eastern side of the

San Juan Basin, and along the Defiance upwarp along the western side. The post-Wasatch upwarps probably were the result of repetitive movements in Eocene and Oligocene time, such as occurred in the northern part of the Colorado Plateau. The Nacimiento Mountains may have contributed debris to the late Eocene (or Oligocene) Galisteo formation. Folding and faulting of the salt anticlines southwest of the Uncompahgre Plateau may be assumed to have occurred contemporaneously with the movements of upwarp on the Uncompahgre Plateau. Deformation there is believed to have resumed in early Eocene time and to have recurred in later Eocene and in Oligocene time. The folding was accompanied, or immediately followed, by graben faulting. In late Tertiary time, when canyons were cut into the salt beds, the salt flowed laterally from under the anticlines, and collapse structures became superimposed on the anticlinal structures. (Cater, F. W., 1955b).

The principal unwarp at the Grand Hogback at Meeker (fig. 14), and at some anticlines northwest of Meeker, are post-Green River in age.

LATE TERTIARY STRUCTURES

The major orogenic structural features in the interior of the Colorado Plateau seem to have been developed almost completely before late Tertiary (Miocene and Pliocene) time. The Bidahochi formation, for example, is younger than the Defiance upwarp. There is some evidence that the Bidahochi and related deposits have been warped slightly, but late Tertiary deformation in the interior of the Plateau probably amounted to no more than warping, perhaps as a result of slight further uplifting of the upwarps but more likely as a result of differential movements of an epeirogenic sort (p. 63). In contrast, there was extensive and considerable deformation around the edges of the Colorado Plateau during late Tertiary time.

In the Mount Taylor district, the general northward tilt and the minor folding occurred after deposition of the Wasatch formation but before the eruptions of Mount Taylor and the eruptions of the basalt on its flanks. Twenty-five miles east of Mount Taylor, however, the San Juan Basin structures abruptly terminate at a faulted monocline marking the west edge of the Rio Grande depression (figs. 43, 44, 45). East of this monocline, the Upper Cretaceous formations are abundantly faulted in blocks that roughly parallel the faulted monocline. The Santa Fe formation overlaps these faulted beds and is itself much faulted. The deposition of the Santa Fe formation and the faulting that accompanied its deposition are younger than the

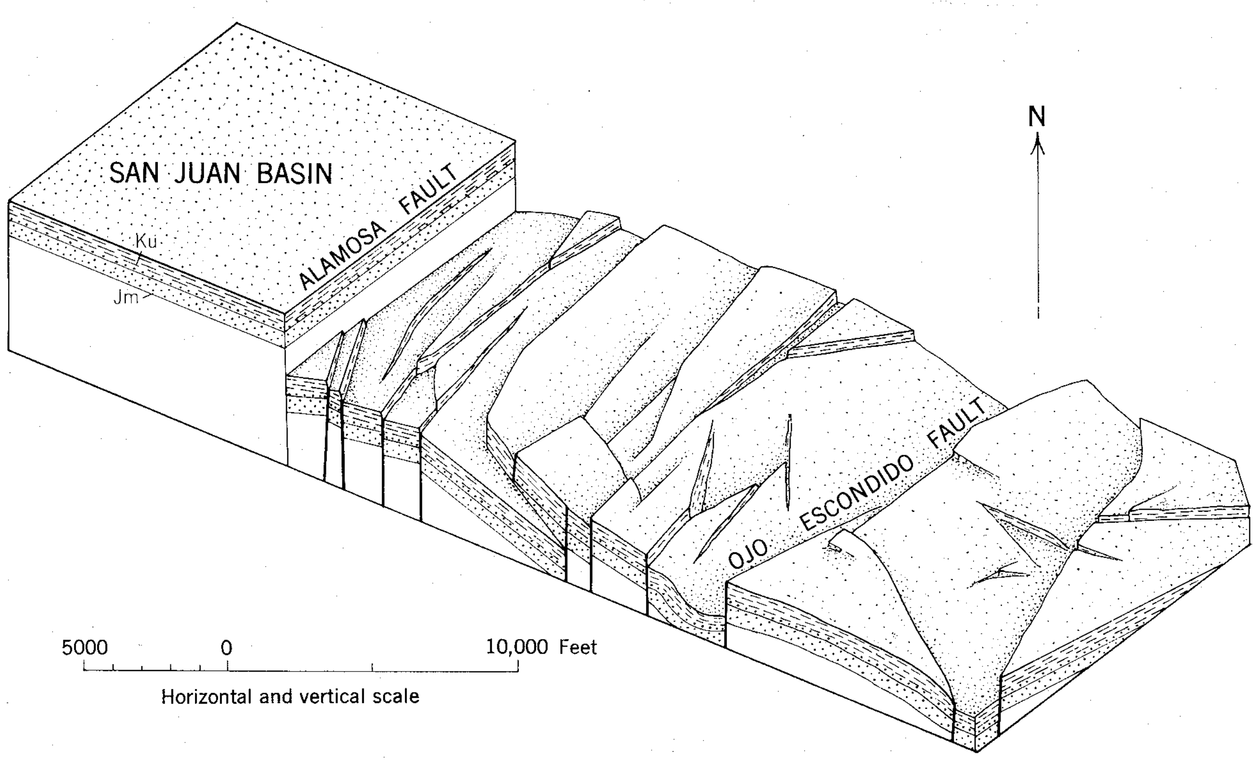


FIGURE 43.—Block diagram illustrating the faulted east edge of the Colorado Plateau, east of Mount Taylor, N. Mex. The Alamosa fault provides a sharp boundary between the Colorado Plateaus (represented by the San Juan Basin) and the faulted Basin and Range province (Rio Grande depression) east of the fault.

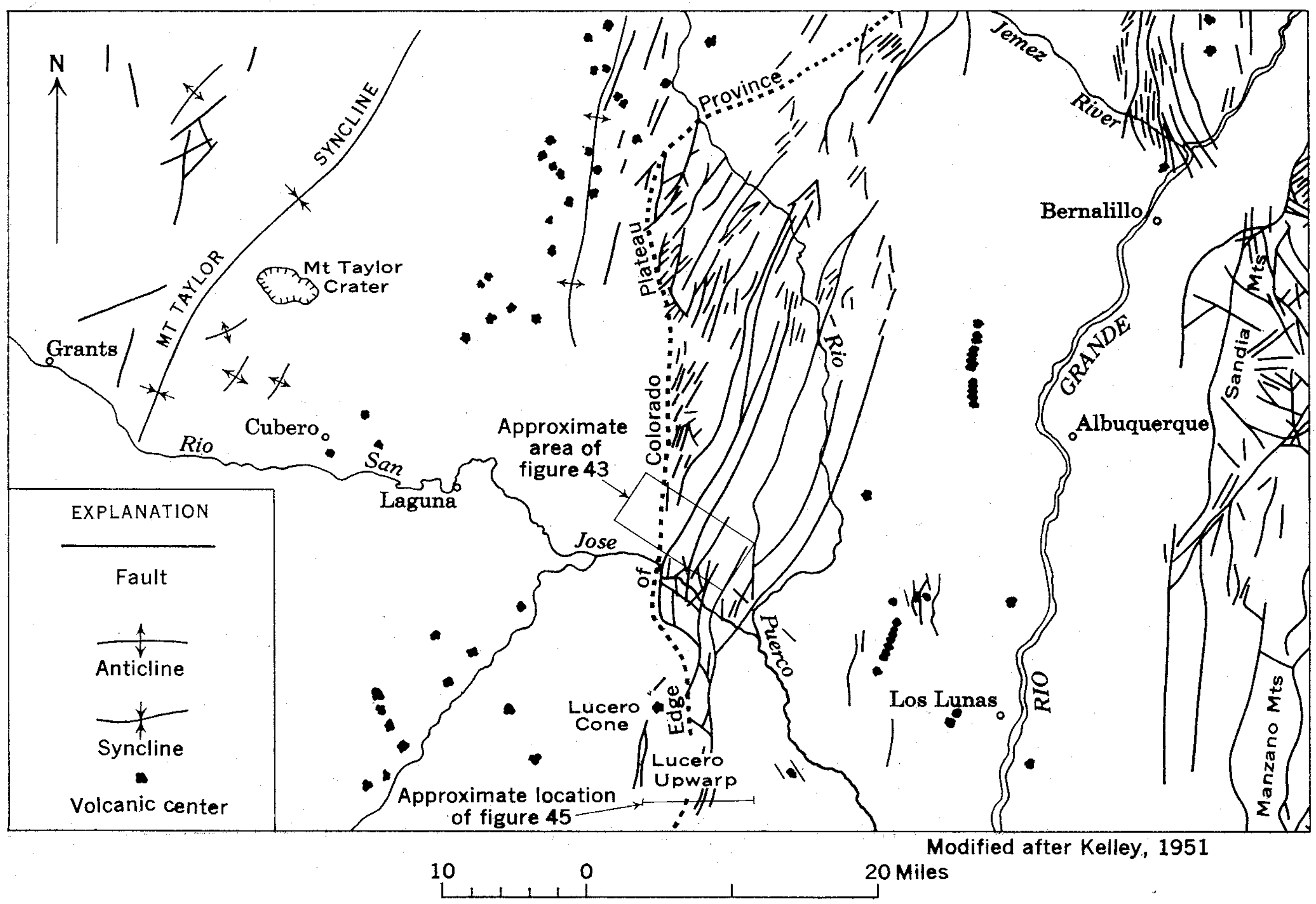


FIGURE 44.—Tectonic map of part of the San Juan Basin and the Rio Grande depression.

structures of the San Juan Basin immediately west of the monocline. The sequence of events in this area is illustrated in figure 46.

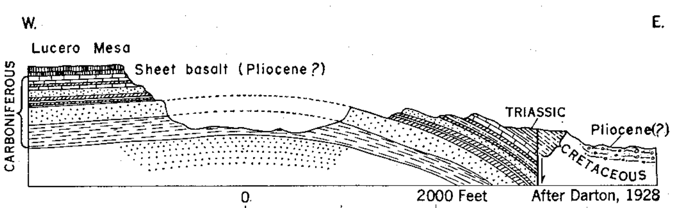


FIGURE 45.—Diagrammatic section illustrating faulting east of Mesa Lucero. The basalt and the erosion surface on which it lies are probably younger than the fault at the right.

Similar late Tertiary deformation at the edge of the Colorado Plateau occurred along the Hurricane Cliffs in southwestern Utah. Displacement on the Hurricane fault, which marks the western edge of the Plateau, apparently started in Miocene time but continued intermittently into Pliocene time. The sequence of events is illustrated in figure 47.

The horst and graben faulting in other parts of the High Plateaus is post-Wasatch in age (fig. 41) and probably is mostly of late Tertiary age. This faulting may have continued into Quaternary time (p. 61). The Sevier and Paunsaugunt faults (fig. 37) had a history similar to that of the Hurricane fault. They displace the Wasatch and Brian Head formations and some of the overlying lavas. The Sevier River formation in central Utah also is faulted.

The Grand Wash Cliffs and Grand Wash trough, marking the west edge of the Colorado Plateau at the mouth of Grand Canyon, were faulted while the fill in the trough was being deposited (fig. 22). This fill has been correlated with the Muddy Creek formation and presumably is no older than late Miocene and may be somewhat younger than early Pliocene; deformation continued, however, while the fill was being deposited.

In the depression at Peach Springs, Ariz., are highly tilted, tuffaceous sandstone and conglomerate containing volcanic rocks that lithologically resemble the Muddy Creek formation. Apparently there was late Tertiary and perhaps early Quaternary deformation in this trough too.

At the north edge of the Colorado Plateau deformation immediately preceded deposition of the Browns

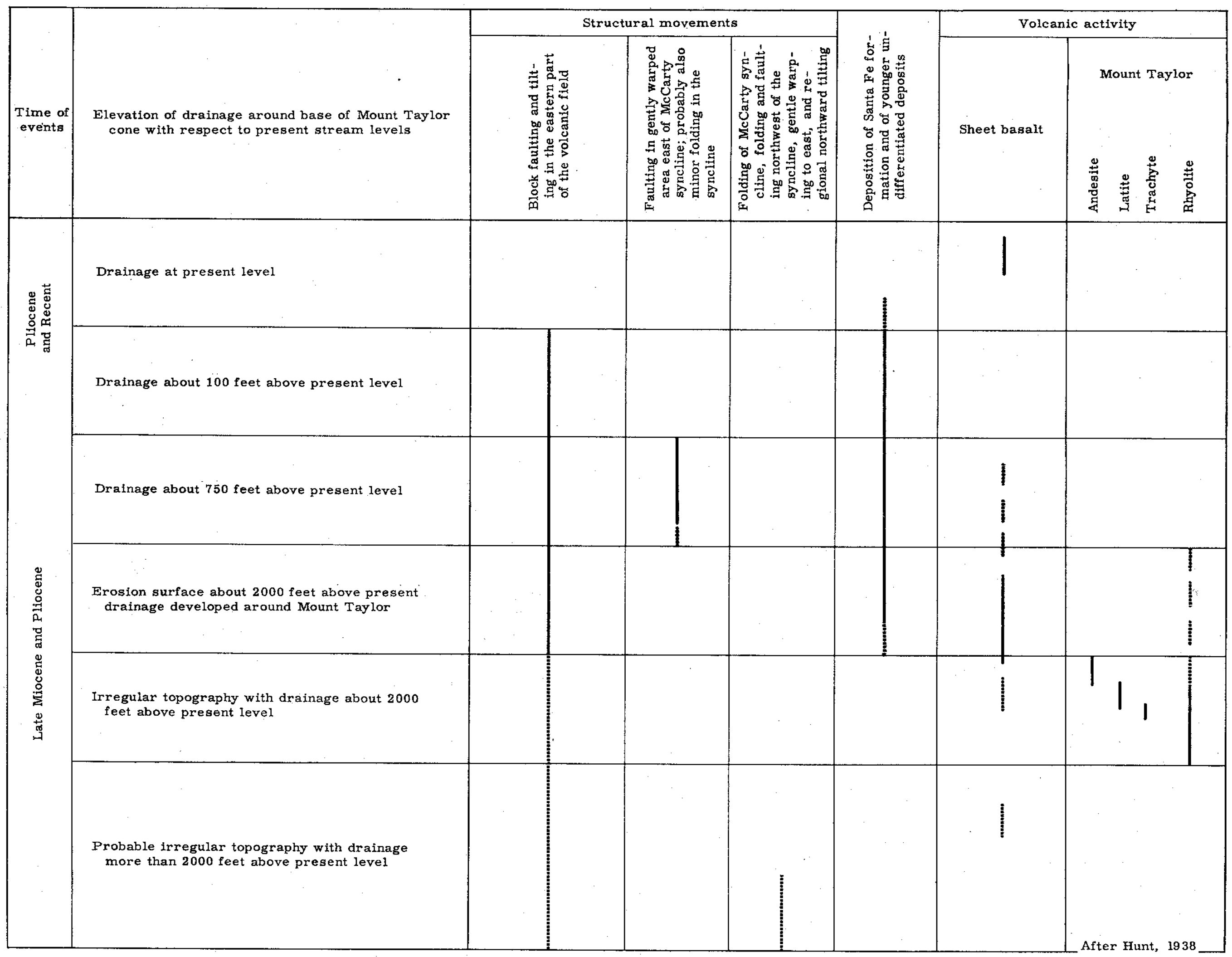


FIGURE 46.—Sequence of late Tertiary and Quaternary events in the Mount Taylor volcanic field. The length of line represents approximately the duration of each activity; solid lines indicate fairly definite information; dotted lines indicate considerable uncertainty.

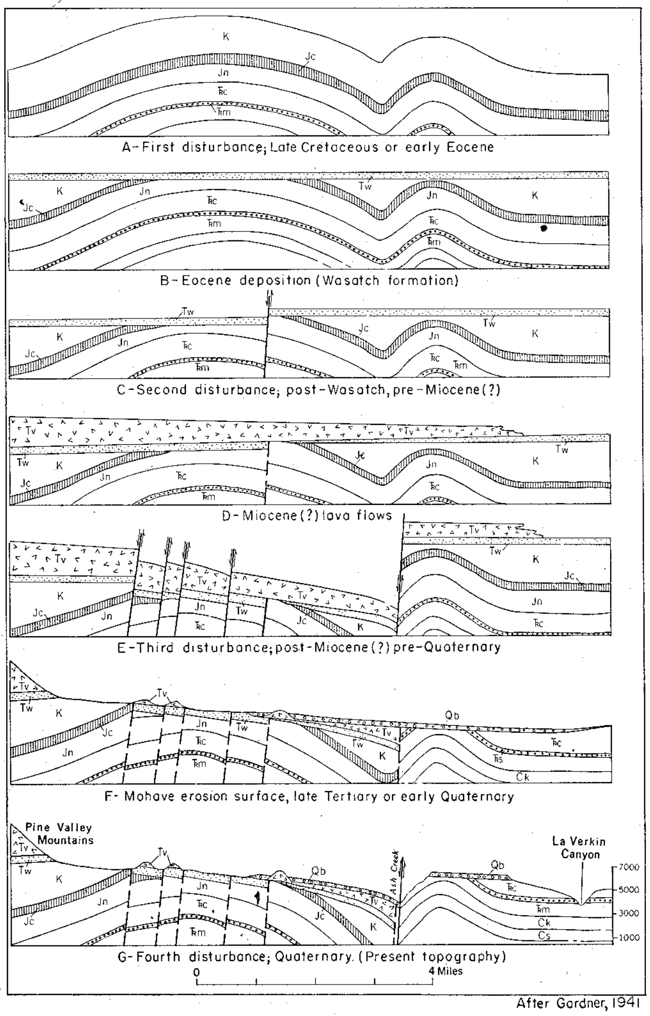


FIGURE 47.—Structure sections across the Hurricane fault zone showing four stages in its development. The basalt lavas (Qb) west of the fault have been bent and dropped almost 2,000 feet below the undistorted remnant of the same flow east of the fault. Downturning of Miocene (?) lavas (Tv) is even greater, thus indicating two periods of downflexing.

Park formation, deformation that must have controlled the lithology and distribution of the formation. The collapse of the Uinta Arch preceded deposition of the Browns Park formation, but later movements affected that formation as well as the older rocks. Some of the domes immediately northeast of the Piceance Creek Basin formed in late Tertiary time, but prior to deposition of the Browns Park formation. They affected the Green River formation but are overlapped by the Browns Park.

In the San Juan Mountains late Tertiary folding and faulting were accompanied by volcanism and intrusions. Part of the domal uplift of the formations in the adjoining part of the Colorado Plateau probably is of this date.

QUATERNARY STRUCTURES

The only recorded Quaternary deformation in the interior of the Colorado Plateau is in the area underlain by the salt deposits and is due to movement of the salt. One such example is the development of normal faults and grabens along the Colorado River near its junction with Green River. The drainage is poorly developed through the area of graben faulting, and well-defined old drainage channels are cut off by the faults, showing that the faulting occurred after the surface had been eroded to essentially its present position. In Salt Valley (fig. 40), a caliche-capped erosion surface has been faulted (Baker, 1935, p. 1500). In Castle Valley, Fisher Valley, Sinbad Valley, and Paradox Valley (fig. 40), Recent alluvial deposits are faulted and locally folded.

Also, in Castle Valley and in Gypsum Valley is strongly folded conglomerate believed to be of late Pliocene age (p. 30). The folding of the conglomerates is attributed to salt movement.

Upwarp of the High Plateaus undoubtedly continued into Pleistocene time. Much of the deformation in the High Plateaus is younger than the late Pliocene or early Pleistocene Sevier River formation (Callaghan, 1938, p. 103). A number of lava flows, believed to be of Pleistocene age, are faulted. South of the Paunsaugunt Plateau, in a canyon northwest of Kanab, alluvial fill that probably is of Recent age is displaced by a fault that extends downward to a slickensided fracture in the underlying rocks (Gregory, 1950, p. 143). Some drainage changes in the High Plateaus have been attributed to Pleistocene tilting (Hardy and Muessig, 1952). Late Pleistocene upwarp of the Wasatch Mountains, which are alined with, and are north of, the High Plateaus, is recorded by the tilted and faulted Lake Bonneville deposits (Hunt, Thomas, and Varnes, 1953). Also, the High Plateaus have been seismically active in historic time. Since settlement in 1851, several earthquakes have been recorded; those at Kanab in 1885 and 1891, and at Tropic, Glendale, and Panguitch in 1902, 1924, 1930, and 1931 were of special note (Gregory, 1950, p. 143).

The amount of Pleistocene upwarp in the High Plateaus may have been sufficient to account for the scarcity of pre-Wisconsin glacial deposits there (p. 35); 2,000 feet of Pleistocene upwarp is a quite reasonable inference.

Some of the faulting around the edges of the Colorado Plateau, affecting formations like the Santa Fe, Muddy Creek, and Sevier River, probably also is of late Quaternary age, because Quaternary deformation has been extensive in the Basin and Range province, both to the west and south of the Colorado Plateau. For example, the Lake Mead area, immediately west of the Grand Wash Cliffs, now is undergoing southwestward tilting in addition to basin subsidence related to loading by Lake Mead (Longwell, in preparation). The Wyoming Basin and the Rocky Mountains seem to have been more stable than the Basin and Range province, but less stable than the interior of the Colorado Plateau.

CENOZOIC IGNEOUS STRUCTURES

The typical laccolithic mountain on the Colorado Plateau is a structural dome several miles in diameter and a few thousand feet high (figs. 28, 29). In general, the domes have smooth flanks, but most of them have many small superposed anticlinal noses that were produced by the laccoliths. At the center of each of the domes is a stock, around which the laccoliths are clustered. The stocks are cross-cutting intrusions, most of them surrounded by a shatter zone consisting of highly indurated sedimentary rocks irregularly intruded by innumerable dikes, sills, and irregular masses of porphyry (Hunt, 1953b). Through the monzonite and diorite porphyry stages the mode of intrusion of both the stocks and laccoliths is assuredly by physical injection. However, in those mountains where the intrusive process reached the syenitic stages the shattered rocks around the stock are in part replaced or assimilated by the stock.

The anticlinal noses clearly are the result of arching over the laccoliths, which extend radially from the stocks as tongue-shaped masses. The big mountain domes are attributed to deformation accompanying physical injection of the stocks, because the sedimentary formations turned up around the stocks cover the same area as they did in their original horizontal position. This evidence is especially forceful because of the fact that although the stocks are of different widths at the different mountains, the amount of upwarp at the domes is almost in direct ratio to the width of the stocks (Hunt, 1946, p. 11, 12). (See fig. 28.)

The laccoliths are concordant injected masses that lifted their roofs by arching. Many of the laccoliths possess a very simple, linearly bulged, tongue-shaped form, but where the intrusions are crowded the forms are complex. This is especially true in the La Sal Mountains. Also, some of the intrusions have steep sides along which the roof rocks were faulted upward. These intrusions are bysmaliths, but they are similar to the laccoliths in all respects except this faulting (fig. 31).

Coherence and competency of the invaded rocks appear to have been a major factor in controlling the stratigraphic distribution of the laccoliths. Incompetent formations were favorable. In the Henry Mountains, Abajo, and El Late Mountain the laccoliths spread mostly in the incompetent Upper Cretaceous shaly strata. The intrusions at the middle mountain of the La Sal Mountains did likewise, but the North and South La Sal Mountains rose in salt anticlines and spread mostly in the salt beds of the Pennsylvanian Paradox member. At the North La Sal Mountain the intrusions breached the overlying rocks and erupted (Hunt and Waters, in preparation).

Because the stratigraphy and structure of the Colorado Plateau is fairly uniform, the similarity in form of intrusion, geologic structure, and rock types at the several laccolithic mountains in the Plateau reflect close similarities of the igneous processes involved. The mountains seem to represent a series of examples of one igneous process that was arrested at various stages of its development (Hunt, 1946, p. 16). Figure 28 illustrates some of the differences in stage represented in the different mountains.

The volcanoes, in contrast, did not produce major structures in the country rocks. Mount Taylor volcano is located in a syncline; San Francisco Mountain is on a dome, or broad arch, but neither of these underlying structures is believed to be related to the igneous activity. The fact that the pipes that fed these volcanoes did not dome the rocks around them indicates that their mechanism of intrusion was notably different from that of the stocks that produced domes at the laccolithic mountains, yet the rock types in the stocks and volcanoes are similar, both chemically and mineralogically. The diameters of the pipes feeding the volcanoes are not known, but they probably are comparable to some of the stocks; for example, the stock at Mount Holmes is only 1,000 feet in diameter. The sequence of rock types erupted by the volcanoes is the reverse of the sequence intruded at the laccolithic mountains. In the latter, diorite porphyry was intruded first, followed by monzonite porphyry, and later by syenite porphyry. At the volcanoes, the first eruptions were rhyolitic and progressed through latite to andesite. Apparently, the reason for the difference in structure between the volcanoes and the stocks at the laccolithic mountains must be sought in some subcrustal phenomena that also produced a difference in the sequence of the differentiates that were pushed upward.

Little is known about Mount Trumbull and the small eruptive centers around it. They rest on a pedestal of rocks that had been deformed before the mountains erupted, and they are surrounded by centers of basaltic eruptions, some of which are of Quaternary age. In these ways, Mount Trumbull resembles Mount Taylor and San Francisco Mountain.

The volcanoes in the Navajo and Hopi Buttes fields (fig. 26) were mostly of the explosive type known as diatremes. On the other hand, in the volcanic fields where normal basalt was erupted the amount of pyroclastic material is small in proportion to the amount of lavas. The differences between these volcanoes may be due to differences in the physical-chemistry of the eruptives, because the volcanoes in the Navajo and Hopi areas are alkalic. However, the structural and hydrothermal effects of these small volcanoes, either of the alkalic type or normal basalt, are restricted to drag effects and minor baking along the walls of the pipes or dikes.

Neither the laccolithic mountains nor the volcanic centers show any distributional correlation with the orogenic structural features on the Colorado Plateau. The Henry Mountains are in a structural basin, the Abajo Mountains are to one side of an upwarp, the La Sal Mountains are in the midst of the salt anticlines, El Late Mountain and Navajo Mountain are in areas of gentle homoclinal dips, the Carrizo Mountains are at the northward-plunging end of an upwarp, the La Plata, Rico, and San Miguel Mountains are on the flank of the San Juan Mountain dome. A more diversified set of structural environments would be hard to find in an area of structural features as simple as those on the Colorado Plateau. The volcanoes seem equally independent of the orogenic structures.

Nevertheless, there is an apparent order in the regional distribution of the different kinds of igneous centers. The laccolithic mountains are clustered in the central part of the Plateau, and most of them lie in a belt between the San Juan Mountains and the volcanic pile in the High Plateaus (fig. 26). The normal basalt volcanoes are distributed around the edge of the Plateau. The volcanoes and minor intrusions of the alkalic basalt type lie in a belt between the laccolithic mountains and the belt of normal basalts.

CENOZOIC EPEIROGENIC STRUCTURES

Among the epeirogenic events in the structural history of the Colorado Plateau are the downwarping of the north part (and southern part of the Wyoming Basin) to produce the Green River lake, the broad arching or doming of the central part of the Plateau in southeastern Utah, the upward warping of the southern and southwestern rims of the Plateau, and the general upwarp and northeastward tilting of the Plateau as a whole.

At the close of Late Cretaceous time the area covered by the Colorado Plateau must have stood at, or near, sea level because it was a coastal plain. The west edge of the Colorado Plateau (the part represented by the High Plateaus) must have been downwarped to accommodate the lakes in which were deposited the Flagstaff limestone and lacustrine beds of the Wasatch formation in the southern part of the High Plateaus. The western part of the Uinta Basin also was downwarped, because Flagstaff limestone extends eastward nearly to the Green River. The downwarped area includes most of the northwest quarter of the Plateau; the amount of downwarping probably equaled the thickness of the Flagstaff limestone, which is about 1,500 feet. The gradational contact between these lacustrine deposits and the overlying fluviatile deposits of the Wasatch formation suggests that the cessation of deposition in the lakes was a result of filling rather than a result of upwarp.

Downwarping, however, spread eastward across the north end of the Colorado Plateau to accommodate the Eocene lake in which the Green River formation was deposited (fig. 56). This downwarping, which must have amounted to as much as 5,000 feet, embraced all the Uinta Basin and extended an unknown distance to the south. If it extended halfway from the Uinta Basin to the southern borders of Utah and Colorado it involved the northern quarter of the Colorado Plateau. It extended far to the north into the Wyoming Basin, although it was interrupted by the Uinta Mountains which had begun to rise in early Eocene time.

The San Juan Basin portion of the Colorado Plateau was above sea level in earliest Tertiary time, when the upper beds of the Animas formation was deposited in the northern part of the basin. The north flank of the San Juan Basin had been raised by doming of the San Juan Mountains, and this doming must also have raised the east-central part of the Colorado Plateau. There is no evidence that the San Juan Basin was high above sea level. The Wasatch formation of the San Juan Basin, which lithologically resembles the Wasatch formation of parts of the Uinta Basin, probably was deposited before the region was upwarped to any great extent. In early Eocene time, in the San Juan Basin, the drainage probably was toward the south or southeast.

What was happening in the way of regional upwarp in the Arizona portion of the Plateau is pure conjecture, but the occurrence of gravels containing pre-Cambrian quartzite on the Mogollon Rim suggests that this part of the Plateau was low lying and was receiving debris from mountains to the south.

Downwarping of the Uinta Basin ceased in middle Eocene time, and thereafter fluviatile sediments represented by the Bridger, Uinta, and Duchesne River formations were deposited. Presumably this deposition helped aggrade some of the structural depressions that were being developed between the orogenic upwarps to the south. Absence of deposits younger than the Duchesne River formation suggests erosion, at least nondeposition, beginning in Oligocene time.

The structural elevation of the Colorado Plateau in southeastern Utah averages about the same as in the basin under Black Mesa. The southeastern Utah and northern Arizona portions of the Plateau therefore represent a platform that is considerably higher than the San Juan or Uinta Basins. This platform, which is as old as early Eocene and perhaps older, may have been a highland that contributed to the Eocene sediments in the Uinta Basin and to the Nacimiento formation in the San Juan Basin (p. 24). It seems likely that the north flank of this platform roughly marked the southern limit of the Green River lake, but the Green River formation and the fluviatile Bridger, Uinta, and Duchesne River formations probably extended in a southerly lobe at least as far as the southern edge of the Henry Mountains structural basin. The laccolithic mountains seem to be clustered near the north edge of this structural platform.

The upwarping of the southwestern and southern rims of the Colorado Plateau is assumed to have been contemporaneous with the general uplift of the Plateau block as a whole, and perhaps of the entire geanticline. The uplifting is thought to be contemporaneous with the late Tertiary and Quaternary block faulting that seems to represent the collapse of the Basin and Range segment of the geanticline. As a result of this uplifting and accompanying warping, the Colorado Plateau became saucer shaped and was tilted northeastward. From the Uinta Basin and San Juan Basin the strata rise southward and southwestward to the high rims bordering the Plateau on those sides (fig. 37). The High Plateaus can also be thought of as a high rim, but they were lifted by faulting instead of by epeirogenic warping.

The process by which a block of the earth's crust as large as the Colorado Plateau is raised so many thousands of feet is even more uncertain than the time of uplift. The elevation might be due to the lateral transfer of materials into the subcrust beneath the Plateaus. It might be due to melting and expansion of subcrustal layers. It might be due to arching caused by lateral compression.

PHYSIOGRAPHY

CLIMATE AND WATER SUPPLY

The greater part of the Colorado Plateau is now semiarid (fig. 4), but earlier in the Cenozoic the climate was very different. At the beginning of Tertiary time the Colorado Plateau area was essentially at sea level and was bordered by mountains on the north, east, west, and southwest sides. In Eocene(?) time the San Juan Mountains were high enough for the development of the glaciers that deposited the Ridgeway till. Presumably, there was glaciation on the other bordering ranges during this time.

In Paleocene and Eocene time the climate of the Plateau area, which was at sea level, appears to have been humid, warm temperate or sub-tropical, and the flora of the Green River and Bridger beds indicates a climate similar to that in the present-day southeastern United States (Berry, 1925). It has been estimated that during the middle Eocene time the northern part of the Colorado Plateau was characterized by cool, moist winters and relatively long warm summers, that the mean annual temperature fluctuated seasonally from a mean that was about 65° F., and that the rainfall varied seasonally from a mean annual precipitation of about 38 inches (Bradley, 1929, p. 93–95). Throughout the Paleocene and Eocene the low-lying Plateau area had lakes and marshy floodplains, and received the discharge from the mountains; such conditions are indicated not only by the physical geology but also by the heavy-footed, amblypod fauna of that period.

However, if the adjoining mountains had been 10,000 feet high we might expect them to have had a mean annual temperature of about 32° F. and a mean annual precipitation of about 60 inches. At such high altitudes, there could have been ice fields, or glaciers, during the time of the early Tertiary lakes. Early Tertiary glaciation in the San Juan Mountains is recorded by the Ridgeway till. The widespread conglomeratic gravels, other than those of volcanic origin, in the lower Tertiary formations also could be interpreted as the product of alpine glacial or periglacial activity because it is difficult to imagine how such gravel deposits would form in the absence of vigorous frost action.

By middle Oligocene time, judging by evidence from neighboring regions, the climate of the Colorado Plateau had become semiarid. Beginning in Miocene time, and continuing through middle Pliocene time, the climate of the western United States seems to have become drier and more continental (Axelrod, 1950, p. 228, 266).

Very likely, as this change occurred, the influence of the topography on the local climate became increasingly important. For example, the epeirogenic rise of the Colorado Plateau during late Cenozoic time probably resulted in a climate that was less dry and cooler than that of the Basin and Range province to the southwest, which, then as now, was arid and semiarid. The orogenic rise of the High Plateaus probably caused a rain shadow that, as at present, kept the interior of the Colorado Plateau as dry as the Basin and Range province, but, because of its greater altitude, it was cooler and the effective moisture was greater. Such local conditions reflecting physiographic controls may have largely masked the general change in world climate towards cooler and moister conditions in late Pliocene time.

Fossil vertebrates of late Pliocene age from southern Arizona suggest that the climate there was warm and moist, similar to that now existing in southern Mexico (Gidley, 1922). However, to the degree that the plateau had been raised epeirogenically towards its present level by late Pliocene time, the climate on the plateau may be inferred as cooler than that in southern Arizona.

During Pleistocene time the effective moisture on the Colorado Plateau must have been considerably greater than at the present time, because during some of the glacial stages snow accumulated at altitudes as low as 6,000 feet. These accumulations were seasonal and in sufficient volume to produce debris avalanches like those east of Hite (p. 38). Further evidence of much more effective moisture during the Pleistocene is provided by the spring deposits interbedded with the Pleistocene valley fill in the vicinity of Hite, Utah (p. 38).

The Recent epoch started with a period that was drier and warmer than the present. During this early dry period, extensive dunes developed and extensive arroyo cutting occurred. It was followed by a period when effective moisture was greater than at present—the period when the prepottery, Recent alluvium was deposited. This, in turn, was followed by a dry period around 1300 A. D., during which arroyo cutting was resumed. Dry, warm conditions have prevailed during the last 600 years, except for one brief interruption represented by the deposition of alluvium during the 16th and 17th centuries.

Rates of weathering probably are roughly proportional to the effective moisture. Therefore, weathering must have been greater during the early Tertiary than during the later Tertiary or Quaternary. Weathering was at a minimum during the Miocene and early Pliocene. During the Pleistocene, weathering was most effective during the interglacial stages. Since the beginning of Wisconsin time, weathering has been of little effect on the Colorado Plateau.

Erosion probably is at a maximum when there is a climatic change that causes a decrease in effective moisture, because it is the weathered products that are most easily eroded. We might assume therefore, that the rate of general lowering of the land surface by erosion was greater during early Tertiary time than it was during late Tertiary time. On the other hand, the relatively arid conditions that prevailed during the Miocene and Pliocene would have favored erosion in those parts of the Plateau where the surface formations were unconsolidated or weakly consolidated, and would have favored erosion along the main stream courses.

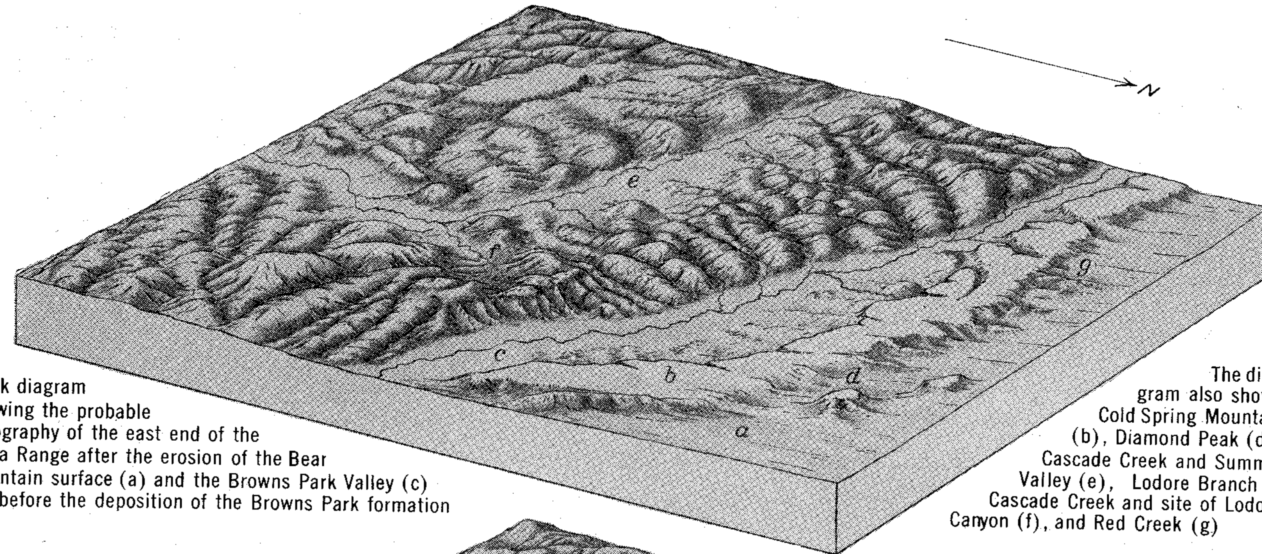
During the latter part of Pleistocene time the erosion history of the valleys seems to have an alternation of deposition of fill and removal of that fill. The canyons, of course, became extended headward, and in the mountains the valleys that contained glaciers became deepened, but the general land surface does not seem to have been lowered much, and the main stream courses seem to have been cut essentially to their present depths before late Pleistocene time.

The ground waters in latest Cretaceous time probably were saline with the residue of the marine waters of the Late Cretaceous sea. During early Tertiary time, conditions were moist, the ground-water table must have been high and was freshened by the introduction of fresh water. In Miocene time, as the Plateau became raised epeirogenically, and as the climate became less humid, the water table presumably was lowered, was divided into basins by the upwarps, and probably became alkaline. During late Pliocene and Quaternary time, the water table has fluctuated. During periods when moisture was effective, there must have been considerable movement of ground water down the flanks of the upwarps into the basins. These groundwater movements produced some large springs, as along the Colorado River near Hite, and they must have raised the water table in the basins and reduced the alkalinity of the water.

ANTEPOSITION

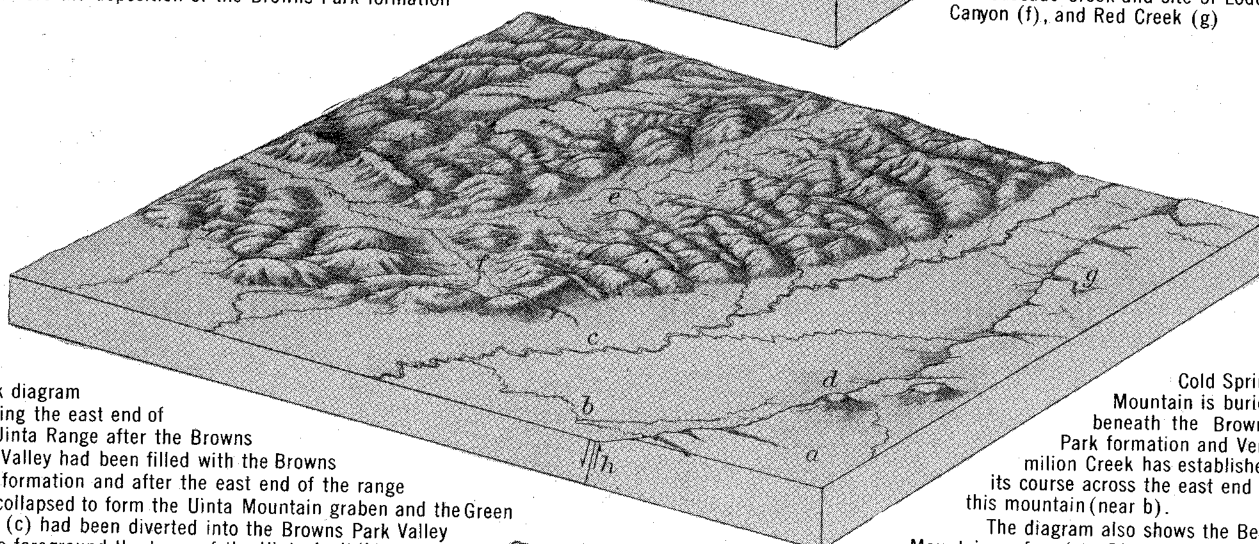
The streams of the Colorado River system (fig. 1) cross the Plateau seemingly indifferent to the various orogenic structures encountered. This fact has been commented upon frequently in geologic literature. Powell attributed the lack of adjustment to antecedence. He postulated that the river and its principal tributaries were able to maintain their course across uplifts by downward cutting while the uplifting was in progress. Later, Davis provided reasons for doubting the antecedence of the drainage and postulated that it had been superimposed from strata that unconformably lay across the folds. Actually, neither theory alone seems to be adequate to explain all the anomalies of the Colorado River drainage system, but a combination of the two concepts, which I refer to as "anteposition," seems to offer explanations for most of the anomalies. The process, illustrated in figure 49, can be applied to the Colorado Plateau only by inference. The process, however, has been recognized elsewhere, as along the Ventura River in California (Putnam, 1942).

The canyons through the uplifts that lie across the Colorado River drainage system are thousands of feet deep. If these canyons are entirely the result of super-



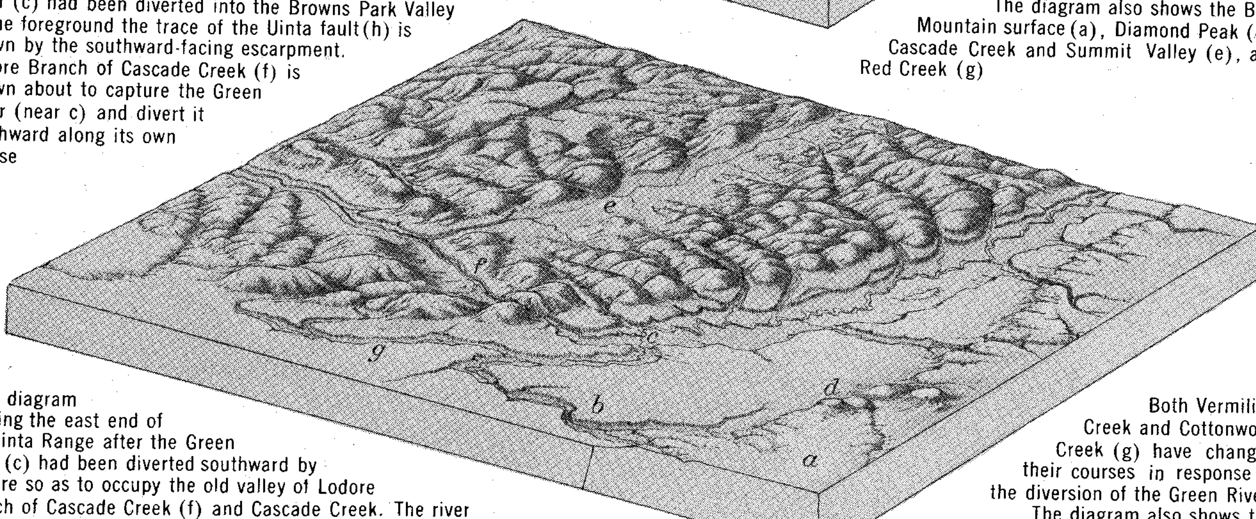
A. Block diagram showing the probable topography of the east end of the Uinta Range after the erosion of the Bear Mountain surface (a) and the Browns Park Valley (c) but before the deposition of the Browns Park formation

The diagram also shows Cold Spring Mountain (b), Diamond Peak (d), Cascade Creek and Summit Valley (e), Lodore Branch of Cascade Creek and site of Lodore Canyon (f), and Red Creek (g)



B. Block diagram showing the east end of the Uinta Range after the Browns Park Valley had been filled with the Browns Park formation and after the east end of the range had collapsed to form the Uinta Mountain graben and the Green River (c) had been diverted into the Browns Park Valley In the foreground the trace of the Uinta fault (h) is shown by the southward-facing escarpment. Lodore Branch of Cascade Creek (f) is shown about to capture the Green River (near c) and divert it southward along its own course

Cold Spring Mountain is buried beneath the Browns Park formation and Vermilion Creek has established its course across the east end of this mountain (near b). The diagram also shows the Bear Mountain surface (a), Diamond Peak (d), Cascade Creek and Summit Valley (e), and Red Creek (g)



C. Block diagram showing the east end of the Uinta Range after the Green River (c) had been diverted southward by capture so as to occupy the old valley of Lodore Branch of Cascade Creek (f) and Cascade Creek. The river has entrenched itself in the soft beds of the Browns Park formation and thus accelerated the dissection of the adjacent region. Vermilion Creek at (b) has discovered Cold Spring Mountain through which it has begun to cut Irish Canyon

Both Vermilion Creek and Cottonwood Creek (g) have changed their courses in response to the diversion of the Green River. The diagram also shows the partly dissected Bear Mountain surface (a), Diamond Peak (d), and Cascade Creek in Summit Valley (e)

After Bradley, 1936

FIGURE 48.—Block diagrams illustrating stages in the development of Lodore Canyon, as interpreted by Bradley.

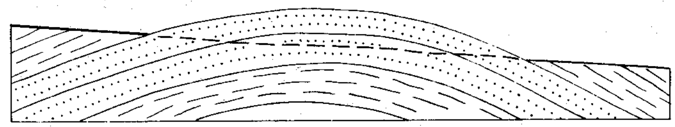
position the fills deposited upstream must have been built as high as the canyon rims on top of the uplifts. Such an amount of fill upstream from many of the canyons is unlikely. Bradley (1936, p. 188–189) recognized this difficulty in offering his interpretation for the origin of Lodore Canyon (fig. 48). He points out that the Browns Park formation probably was not deposited to the height of the rim of Lodore Canyon, and he attributed the canyon to headward cutting by drainage on the south side of the Uinta Mountains. However, it is equally possible, and in my judgment it is more probable, that Lodore Canyon antedates the Browns Park formation, a condition analogous to stage 1 in figure 49. As a result of downfaulting of the Browns Park area, the floor of Lodore Canyon stood about a thousand feet higher than the area upstream, the drainage became ponded, and the Browns Park formation was deposited in this basin (analogous to stages 2 and 3 in fig. 49). The old canyon floor would be a natural spillway when the fill upstream was built to that level. When that stage was reached (stage 4 in fig. 49), aggradation upstream would cease, and canyon cutting would be resumed. The new stream course upstream from the spillway can become superposed; the course below the spillway has the aspects of antecedence. Such a combination might be referred to as anteposed.

COLORADO AND GREEN RIVERS

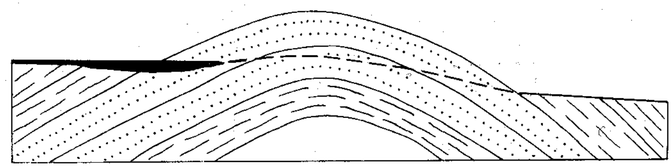
The courses of the Colorado and Green Rivers and their tributaries provide evidence that superposition or anteposition (or both) of the drainage onto the bedrock structures has occurred during at least two stages widely separated in time. The younger stage of superposition is judged to have been from formations equivalent in age to the Browns Park or Bidahochi formations. The older stage of superposition was from formations older than these, possibly as old as the Bridger.

The Colorado River enters the Colorado Plateau at Rifle, Colorado, where it crosses the Grand Hogback (fig. 1). From there, it cuts across the eastern end of the Uinta Basin in a southwesterly course to Grand Junction (its junction with the Gunnison River). At Grand Junction, the river turns westward in a strike valley along the north side of the Uncompahgre Plateau, turns southwestward into a canyon that crosses the end of the Plateau, and then continues a southwesterly course into southeastern Utah.

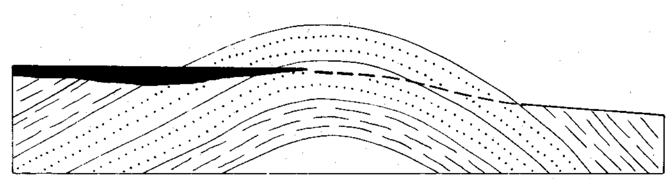
The course from Rifle to Grand Junction could be due to superposition. If this is true, the surface of superposition probably was at the level of the Tertiary lavas capping Grand and Battlement Mesas, roughly a mile higher than the present level of drainage.



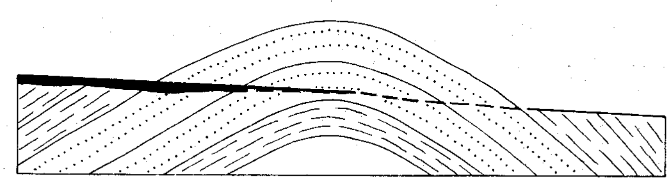
Stage 1. Stream course established in a canyon across an upwarp



Stage 2. Renewed upwarp arches stream bed causing aggradation upstream (black area)



Stage 3. Aggradation continues until fill has been constructed to level of the floor of the arched canyon



Stage 4. Canyon cutting is resumed when stream begins spilling over the elevated canyon floor. Upstream from the high point in the arched bed of the canyon the new stream course may be superimposed. Downstream from the high point the course is antecedent

FIGURE 49.—Diagrams illustrating anteposition.

Transversely across the Uncompahgre Plateau, and alined with the Colorado River above Grand Junction is a broad abandoned river valley know as Unaweep Canyon, 500 to 1,000 feet deep in pre-Cambrian rocks, and 2,500 feet higher than the Colorado River to the north and the Dolores River to the south. Peale (1877, p. 58–59) considered the possibility that it represented a former northward course of the Dolores River, but decided that it was more probable that it represented a former southward course of the Gunnison or the Colorado River. The occurrence of basaltic pebbles in gravel in Unaweep Canyon, 4 miles above Gateway

(Cater, oral communication), and the absence of basaltic pebbles in the gravels along the Dolores River and its tributaries, also suggests that the canyon drained southward rather than northward. If so, the abandonment of Unaweep Canyon probably resulted from capture of the Colorado River by a stream that drained towards the Henry Mountains basin and eroded headward in the soft rocks around the northwest end of the Uncompahgre Plateau. This stream became incised into a canyon that cuts across the northwestward-plunging end of the Plateau, probably by superposition. The floor and rims of this canyon are much lower than Unaweep Canyon, however, both evidently are due to superposition. They provide evidence of two stages of superposition in this area, and the younger stage must represent superposition from deposits at least as old as the Browns Park formation.

The Colorado River, below its junction with Green River, obliquely crosses the Henry Mountains basin. In late Eocene time this part of the Colorado Plateau was structurally between 5,000 and 10,000 feet higher, on the average, than the Uinta Basin, but the deposition of nearly 10,000 feet of Eocene deposits in the Uinta Basin probably raised its surface to a level equal to, or above, that of the Henry Mountains basin. The Henry Mountains basin probably received drainage from the Uinta Basin, as well as from the uplifts to the east and west. In any case, regardless of its sources, the ancestral drainage would have aggraded the Henry Mountains basin until a low point of the rim was reached. Structurally, the lowest point on the rim is at the south end of the Waterpocket fold, and this is where the Colorado River leaves the basin.

The course of the Green River across the southern part of the Uinta Basin is along the axis of a synclinal trough that involves the upper Eocene formations. This part of the river's course therefore, may have been inherited from the stage when the folding occurred. Southward drainage along this syncline could have been started as early as Oligocene time.

The present course of the Colorado River, after it leaves the Henry Mountains basin, is southwestward to the Kaibab upwarp (Strahler, 1948) and across the high southwest flank of the Colorado Plateau. This flank is high, both structurally and topographically; in fact, it is one of the highest places on the southern rim of the Colorado Plateau. How the river established its course across the Grand Canyon section is one of the major problems of Cenozoic history.

TRIBUTARY STREAMS

The Yampa River (fig. 1) emerges from the foothills of the Rocky Mountains, enters rather open country, and crosses two anticlinal upwarps with apparent disregard for rock structure. At one of the anticlines, instead of continuing its course in soft beds around one end of the upwarp, the river turns into a short canyon through hard Paleozoic rocks in the upwarp. Fifteen miles downstream the river cuts across the second upwarp instead of taking an easy course around it. (Hancock, 1915, p. 184.)

These upwarps crossed by the Yampa River are pre-Browns Park in age, because that formation lies essentially horizontally around their base. That they were once buried by the Browns Park formation is suggested by occurrences of that formation at elevations equal to, or greater than, that of the highest Paleozoic beds along the rim of the river canyon in the upwarp. There is little reason, therefore, to doubt that the Yampa River was superimposed on these folds from the Browns Park formation, and that the canyons through these folds are post-Browns Park in age. (Hancock, 1915, p. 186–188.)

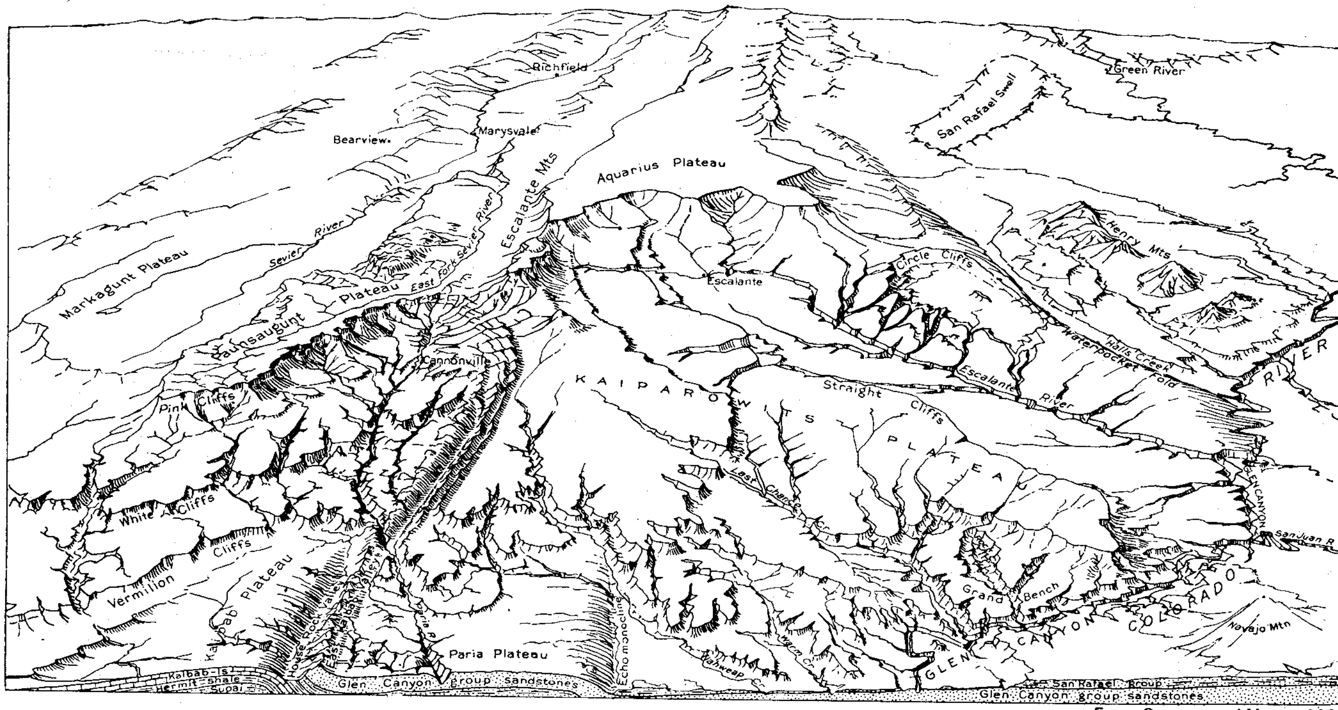
The western tributaries of the Green and Colorado Rivers illustrate several quite different relationships.

In the western part of the Uinta Basin is the Duchesne River, which flows eastward approximately along the trough of the Uinta Basin. Its position seems to be that of a normal consequent stream on the folded upper Eocene formations. Minnie Maud Creek, the stream next south of the Duchesne River, also seems to be a normal consequent stream in a strike valley in the northward-dipping Eocene formations.

However, the western tributaries next to the south—the Price, San Rafael, and Muddy Rivers—have courses that are the result of superposition. Price River flows obliquely across the north end of the San Rafael Swell. San Rafael and Muddy Rivers cross the structurally highest parts of the swell. These courses probably are due to superposition from Tertiary strata that overlapped unconformably across the swell, or their history may be more complex and may involve one or more periods of anteposition. In either case, the Tertiary beds were of Bridger age or younger, because the older Tertiary formations seem to have been domed by uplift of the San Rafael Swell.

The Dirty Devil and Fremont Rivers illustrate another condition, because they flow in a wide arc around the north end of the Henry Mountains; this part of their course is attributed to monoclinal shifting as a result of the Henry Mountains intrusions. The headward part of the Fremont River has been eroded into an upwarp—the Capitol Reef uplift—probably by headward erosion.

A strike valley, 35 miles long, on the eastern side of the Waterpocket fold (fig. 50) is a consequent structurally controlled valley, but the creek in the valley,



From Gregory and Moore, 1931

FIGURE 50.—Generalized view of south-central Utah looking north from the Utah-Arizona boundary line.

Halls Creek, leaves the strike valley at two places and meanders into canyons cut into the fold. These anomalous canyons, evidently the product of superposition, obviously are younger than the consequent strike valley, and, in turn, this strike valley probably is younger than the canyons of the streams that are incised across the high parts of the big upwarps. Perhaps the canyons along Halls Creek correlate with the post-Browns Park canyons along the Yampa River and with the canyon along the Colorado River at the northeast end of the Uncompaghre Plateau.

The Escalante River (fig. 50) crosses the Circle Cliffs upwarp in a course similar to the courses of the streams that cross the San Rafael Swell, and it probably was superposed from the early Tertiary formations that occur in the basin west of the upwarp. The headward part of the Paria River is discordant to the structure and may be the result of superposition or headward erosion (figs. 50, 51); the lower part of the river's course seems to be in a normal strike valley.

Most of the tributaries on the east side of the Colorado River are longer than those on the west, and they illustrate similar physiographic relationships. The Gunnison and San Miguel Rivers follow strike valleys on the sides of the Uncompaghre uplift but the course of the Dolores River is anomalous. It flows southwestward down the flank of the San Juan Mountains and then turns 135° to the north. Perhaps the river originally continued southwestward but became diverted when the La Plata and El Late Mountains were domed by the intrusives.

The course of the San Juan River also is anomalous. The San Juan Basin, structurally, is one of the lowest parts of the Colorado Plateau. In Animas time, there was drainage from the San Juan Mountains southward into the basin. In Puerco and Torrejon time, there seems to have been drainage into the basin from the west. In Wasatch time, there was drainage southward from the San Juan Mountains, and this drainage seems to have continued southward across the southern part of the San Juan Basin. By middle Eocene time, several thousand feet of Tertiary sediments had been deposited in the basin. At some later time, though, the land surface in the San Juan Basin was higher than the basin of the Colorado River in southeastern Utah, and the drainage off the south side of the San Juan Mountains was turned westward to join the Colorado River. To reach the Colorado River, this drainage had to cross the Monument Upwarp (fig. 52). If it be assumed that the river was superimposed across the upwarp, the surface from which it was superimposed was as high or higher than the rim of the canyon through the upwarp, which is about 6,000 feet in altitude and about 2,500 feet higher than the river. Such a surface could have been cut by the Dolores River before the intrusions formed at El Late Mountain. In any case, the westward course of the San Juan River appears to be at least as old as the volcanics in the Mount Taylor field

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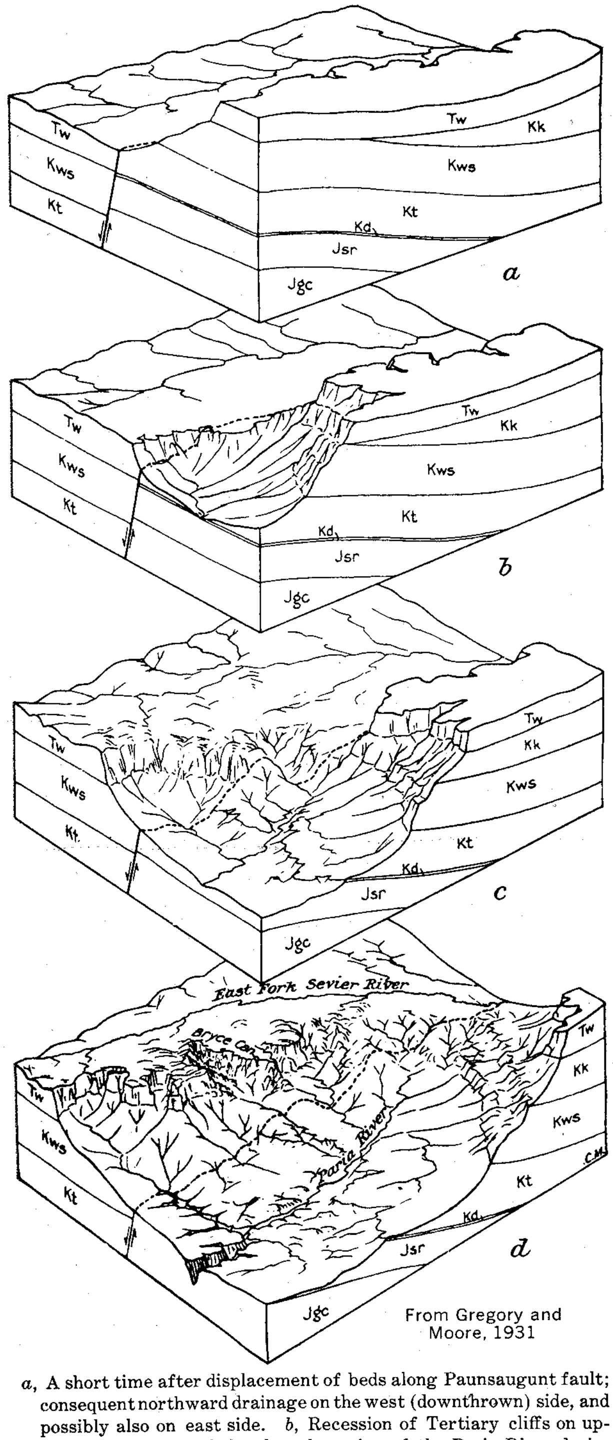

a, A short time after displacement of beds along Paunsaugunt fault; consequent northward drainage on the west (downthrown) side, and possibly also on east side. *b*, Recession of Tertiary cliffs on upthrown side through headward cutting of the Paria River drainage favored by steep gradient to the Colorado River and weak Cretaceous rocks below Tertiary. *c*, A later stage, showing erosion of the block west of the fault as well as further recession of cliffs on the upthrown block. *d*, Present stage. Not much headward cutting is needed for the Paria to capture the waters of the upper East Fork of the Sevier River. Tw, Wasatch formation; Kk, Kaiparowits formation; Kws, Wahweap and Straight Cliffs sandstones; Kt, Tropic shale; Kd, Dakota(?) sandstone; Jsr, San Rafael group; Jgc, Glen Canyon group

FIGURE 51.—Generalized block diagrams representing stages in the physiographic history of upper Paria Valley.

and the other volcanics along the south and east sides of the San Juan Basin.

A much younger set of superimposed canyons occurs along Chinle Creek and Chaco River. Chinle Creek follows a strike valley northward along the west side of the Defiance Upwarp, but it joins San Juan River by turning into a canyon on the flank of the Monument Upwarp. The course of Chaco River is similar to that of Chinle Creek. Below Pueblo Bonito, the river flows northward along a strike valley, but it joins San Juan River by turning into a canyon in the upturned rocks to the west. The strike valleys along Chinle Creek and Chaco River are consequent and are the result of general degradation after the San Juan River had become superimposed across, and incised into, the upwarps that lie across its course. The canyon at the mouth of each strike valley evidently is the result of superposition from a fill or erosion surface that was developed during the cutting of the strike valley, and these canyons must postdate the incision of the San Juan River into the upwarps. The later stage of superposition probably was from deposits equivalent to the Bidahochi formation, which occurs as fill in nearby valleys. However, the superposition of the San Juan River across the big upwarps occurred earlier—probably much earlier.

Another condition is illustrated by the Little Colorado River, which is in a strike valley with long, consequent-like tributaries draining northward to it from the Mogollon Rim. This valley is older than the Bidahochi formation. It must be nearly as old as the volcanoes in the San Francisco Mountain area because the Mesozoic formations, whose escarpments form the strike valley, had been eroded from the volcanic district before the eruptions occurred. Moreover, the Bidahochi formation records that the plateau surface in that area had been eroded nearly to its present form by the time the Hopi Buttes volcanoes were erupting.

In general, it appears that the drainage is fairly well adjusted to the orogenic structures in the San Juan Basin and in northeastern Arizona; it is fairly well adjusted to the Tertiary deposits in the Uinta Basin. It is strikingly inconsequent on and apparently superimposed or anteposed (or both) across the folds in the other parts of the Plateau. At several localities there is good evidence of at least two stages of superposition. The younger stage occurred about the time that the Browns Park or Bidahochi formations were deposited; the older stage preceded this by sufficient time for erosion of the general level of the Plateau a thousand feet or more lower than the tops of the upwarps.

In contrast to the lack of adjustment of the drainage to many of the orogenic structures is the rather complete adjustment of the drainage to the structural fea-

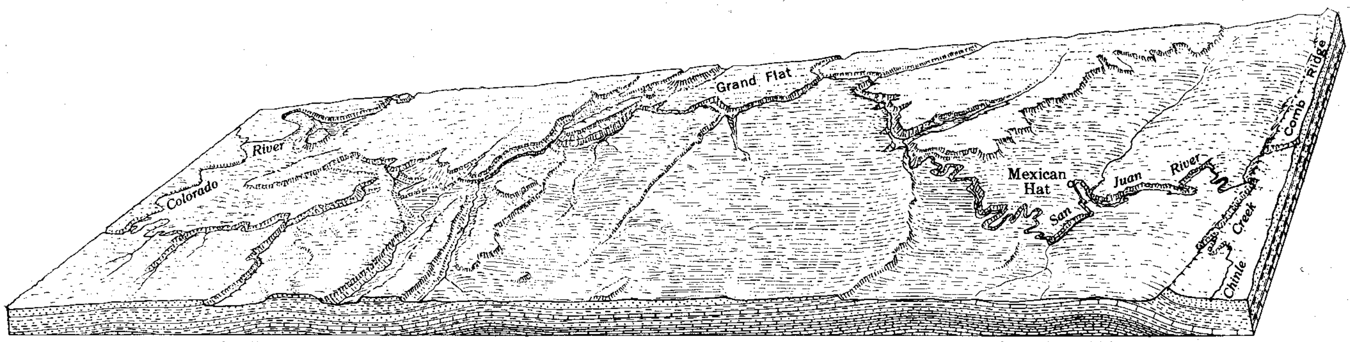

FIGURE 52.—Block diagram of the San Juan Canyon across the Monument Upwarp.

tures produced by the igneous intrusions. The Fremont and Dirty Devil Rivers swing in a wide arc around the north end of the Henry Mountains. The Dolores River swings in a similar arc around the La Sal Mountains. The San Juan River follows the syncline between El Late and Carrizo Mountains. The headward parts of the San Miguel and Dolores Rivers are separated by the intrusions and igneous structures at the San Miguel Mountains. Chinle Creek and Chaco River are in strike valleys on each side of the Carrizo Mountains. The general effect of these drainage adjustments is that the stream courses were monoclinally shifted off the igneous structures. Only at the Rico Mountains is drainage superimposed on an igneous structure in a manner analogous to that of the Yampa, Muddy, or San Rafael Rivers. The drainage also is consequent around the volcanoes at Mount Taylor and San Francisco Mountain.

The relationship, or lack of relationship, of the Colorado River to the epeirogenic or regional structure of the plateau as a whole is anomalous and seems to be that of an antecedent or anteposed stream. The plateau tilts northeastward, and the Colorado and Green Rivers enter it at the Uinta Basin, which structurally is the lowest part of the plateau. From here, the rivers flow southwestward onto the epeirogenic platform in southeastern Utah and northeastern Arizona. At Grand Canyon, the Colorado River flows across one of the structurally highest parts of the rim of the plateau. This relationship is not that of a superposed stream, unless it be postulated that virtually the entire Colorado Plateau, and all the ranges crossing the lower Colorado River, are exhumed. It seems more likely that the river's course is partly the result of antecedence and partly the result of anteposition dating from an early stage in the epeirogenic upwarp of the Plateau.

EROSION AND GEOLOGIC TIME

About 80 percent of the Colorado Plateau has been eroded to formations below the middle of the Upper Cretaceous; about 60 percent is lower than the base of the Cretaceous; about 35 percent is lower than the base of the Jurassic; and about 25 percent is lower than the base of the Triassic. It is judged therefore, that about 8,000 feet of Mesozoic rocks has been removed from the Plateau. To this amount must be added the thickness of Paleozoic rocks and the thickness of those Tertiary rocks, especially the lower Tertiary, that were transported onto the Plateau from the bordering mountains. The total Cenozoic degradation on the Plateau therefore must average about 10,000 feet.

The rate of erosion of bedrock on the Colorado Plateau during the period 1935–48, as determined by sedimentation studies at Lake Mead, has been at the rate of 1 foot every 2,150 years (Gould, report in preparation). At this rate, 21½ million years would be required to erode 10,000 feet of rock from the Plateau.

On the basis of lead-uranium ratios in radioactive minerals the duration of the Cenozoic era is calculated to have been 60 million years. The Paleocene and Eocene epochs are estimated to comprise the first 23 million years of this era, and an age of 31 million years has been calculated for the early Oligocene. (Bradley, 1929, p. 109–110.)

Through Paleocene and Eocene time, and perhaps into Oligocene time, the Colorado Plateau was subject to aggradation rather than degradation, because it was a low-lying trough surrounded by newly formed mountains. Degradation was dominant during about half of Cenozoic time; at the present rates of erosion, about a third of Cenozoic time would be required to accomplish the erosion on the Colorado Plateau.

SOILS

The dependence of soils upon the geologic history of their locale, and upon the geologic formations from which they are derived, is well illustrated on the Colorado Plateau where soils of three quite different ages can be recognized. The youngest soils are those that have developed during Recent time. Next oldest are those that developed during Wisconsin time, and the oldest recognizable soils are pre-Wisconsin. In the Recent and Wisconsin soils, the degree of weathering is so slight that the parent material still dominates those profiles; there are, therefore, about as many varieties of these soils as there are variations in the parent materials.

Recent soils characteristically are shallow, and their profiles are only weakly developed. They are best developed on alluvial parent materials, and generally they consist of no more than a darkened layer, enriched in organic matter, above very slightly oxidized and lighter-colored parent material. The depth of this layer commonly is less than 6 inches, and only infrequently does it exceed about 18 inches. Other Recent soils have profiles similar to those of the alluvial soils only at those places where the parent material is not consolidated. Soils that are similar to those on alluvium are found on upland flats, on some of the Tertiary formations, or on some of the older formations where they have been blanketed by eolian deposits. Dune sand that was deposited during early Recent time commonly is weathered and the old dunes are stabilized. They are more compact and more stained with iron oxide than the sand in the younger dunes.

On the Colorado Plateau, during Recent time, erosion in general has been more vigorous than weathering. Soil development has not been able to keep pace with the erosion, and, as a result, vast areas on the Plateau are bare rock. This is especially true in the Canyon Lands section. It has been estimated, for example, that about 25 percent of the Henry Mountains region is bare rock. In the Uinta Basin and Navajo sections many of the formations are poorly consolidated as compared with those in the Canyon Lands, and Recent soils blanket a high proportion of these sections. The High Plateaus, Grand Canyon, and Datil sections receive much more moisture than do the sections in the interior of the Colorado Plateau, and these areas also have extensive Recent soils. However, all of them are shallow and weakly developed.

The next older group of soils are those that developed during Wisconsin time. These are even less extensive than the Recent soils. Where developed on unconsolidated parent materials they commonly are 3 feet deep. In these soils the organic-rich, darkened, top layer generally is more than a foot thick and is underlain by a somewhat reddish zone and (at altitudes below about 8,500 feet) by a lime-enriched zone 2–3 feet thick. The lime in the subsoil may occur as nodules, as veinlets, or it may be finely disseminated throughout the subsoil. It forms a conspicuous layer, although not so conspicuous as the lime zone under the pre-Wisconsin soils.

The climate of Wisconsin time was much more moist than that of Recent time, and the soils of that period are deeper and their profiles more fully developed.

Still thicker and more fully developed than the Wisconsin soils are those that formed in pre-Wisconsin time. In general, these consist of an upper layer, a few feet thick, of reddish clay that is mostly hydromica. Below this clay layer is strongly lime-enriched, weathered parent material; the lime occurs both as carbonate and as sulphate. At altitudes above about 8,500 feet there is no lime zone and the old soils are acid. Pre-Wisconsin soils are preserved only locally in the Colorado Plateau. The most extensive remnants are on the uplands between the Abajo and El Late Mountains and on the uplands southwest of the San Miguel River where extensive areas are covered by several feet of pre-Wisconsin eolian or alluvial deposits—on which has developed a pre-Wisconsin soil. Pre-Wisconsin soils also are extensive on the pediment gravels around the foot of the mountains; good examples can be found around the Henry Mountains, along the foot of the Book Cliffs, in the Uinta Basin, and in southwestern Utah. Where these soils have been mapped, they have been classed as the Mesa or Harrisburg [soil] series (Youngs and Jennings, 1939; Hendrickson and others, 1925; Strahorn and others, 1924, Youngs and others, 1942). Weathering of basalt in the San Francisco area has yielded 2 feet of residual clay having the following chemical composition, in percent. (Analyst, F. N. Guild; after Robinson, 1913, p. 39, 150.)

SiO_2	54.28	CaO	2.08
Al_2O_3	18.16	Na_2O+K_2O	2.24
Fe_2O_3	9.52	H_2O+CO_2	13.01
MgO	1.53	Total	100.82

An analysis of the basalt from which this clay was derived is given on p. 49. In southwestern Utah the soils developed on deeply weathered basalt are classed as the Veyo soil series (Youngs and others, 1942).

The fuller development of the pre-Wisconsin soils as compared to the Wisconsin soils, and the fuller development of the Wisconsin soils as compared to the Recent soils, immediately suggests that the differences between them are due to differences in age. But until more is known about the climates and other conditions under which the soils developed there is no justification for attributing their differences solely to age. There are parallels between soil development and glacial deposits; in each case, the older ones are more fully developed than the younger ones. In glacial deposits this difference certainly is not due to difference in age; indeed, if the reverse were true, the record of the earlier and lesser ice advance would have been destroyed by the later one. The same reasoning can be applied to soils. The considerable depth and development of the pre-Wisconsin soils, even where buried by younger deposits, probably reflects the intensity of the processes involved; the length of time that the processes operated may have been no greater than the duration of the processes that gave rise to the younger and less well developed soils.

The variegated early Tertiary fluviatile sediments may have been derived from red soils developed on the surrounding uplands and deposited in a humid warm-temperate to subtropical lowland. The red stain would be preserved where little organic matter was incorporated in the flood-plain deposits of the aggrading streams, whereas drab colors would result from reduction of the ferric oxide in sediments rich in decomposing plant debris (Van Houten, 1948, p. 2084).

CENOZOIC HISTORY OF THE PLATEAU—A HYPOTHESIS

The foregoing description of the Cenozoic sedimentary deposits, igneous rocks, and structural and physiographic features of the Colorado Plateau reveals tremendous gaps in the record, but also reveals the gross outlines of the Cenozoic history.

In pre-Cenozoic time, the Colorado Plateau province had been a shelf area. At the beginning of Cenozoic time, and during the early Tertiary, the Plateau area was a basin or trough probably not far above sea-level and surrounded by newly formed mountains whose higher parts were subjected to glacial, or periglacial, conditions. The trough, or basin, was the product of folding that began in Late Cretaceous time and continued during the early Tertiary. In its lower parts, several thousand feet of lacustrine and fluviatile sediments were deposited. After Eocene time conditions changed markedly. General aggradation ceased and general degradation began. Igneous activity, in the form of volcanism and intrusions, became extensive. There was extensive faulting, especially along the west and south edges of the province; and epeirogenic uplift began. The erosion, igneous activity, faulting, and uplift have continued to the present time.

It is supposed that exterior drainage started when the Plateau began to be uplifted epeirogenically, and that the major courses of the streams probably were established before this uplift had progressed very far. It also is supposed that the canyon cutting began at that time and that it has continued to the present time. The history of sedimentation in the Colorado Plateau is almost the opposite of that in the Basin and Range province. The Basin and Range province appears to have been a highland, which was undergoing erosion during Paleocene, Eocene, and Oligocene time, and which was extensively aggraded during late Miocene and early Pliocene time. The Plateau, on the other hand, was aggraded during the early Tertiary and was degraded later.

To fill in details in this gross outline of the Cenozoic history of the Plateau requires much interpretation, and the following effort therefore is a hypothesis.

Figure 53 is a diagrammatic representation of the Colorado Plateau area just before Cenozoic time. During Late Cretaceous time the area had been submerged beneath the sea. The axis of the Late Cretaceous geosyncline lay east of the Plateau area, but the sea spread westward to about the western edge of the Plateau. Mountains in western Utah and in southern Arizona were the source of the sediments that accumulated on the coastal plain and in the sea. By Late Cretaceous time the area had become a coastal plain, and the sea lay to the east. At this stage, volcanism in the area of the Rocky Mountains may have produced volcanic islands, but major uplift of the Rockies had not yet started.

In early Paleocene time (fig. 54), folding, which had started much earlier in western Utah, progressed eastward to the area of the Plateau. The northwestward-trending Circle Cliffs upwarp was formed, and apparently fully so, because its folded rocks are truncated by nearly horizontal Paleocene lake beds (Flagstaff limestone). Formation of a volcanic highland, probably accompanied by upwarping, had started in the San Juan Mountains in latest Cretaceous time and continued to grow during Paleocene time. This highland shed volcanic sediments (Animas formation) on the Colorado Plateau. Pre-Wasatch deposits in the Uinta Basin indicate that mountains were forming to the east and to the west of the basin, and also at the Uinta Mountains. A mountainous area south of the Plateau that may be of this age is recorded by the deposits of gravel on the Mogollon Rim which were derived from pre-Cambrian rocks.

Presumably, other folds within the Plateau also began to form at this time. These include the San Rafael Swell, Uncompahgre Plateau, and the Monument, Kaibab, Defiance, and Zuni upwarps. As a result of Paleocene folding, earlier eastward drainage on the Late Cretaceous coastal plain became disintegrated and ponded in the basins between the upfolds.

Slightly later, the western part of the Plateau was downwarped and became the site of a lake in which was deposited the Flagstaff limestone (fig. 55). Presumably, bays of the lake spread eastward in basins between the upwarps. The limits of the lake, as shown on the diagram (fig. 55), are wholly conjectural except in the area of the Uinta Basin, where the lacustrine sediments have been found to grade eastward into the

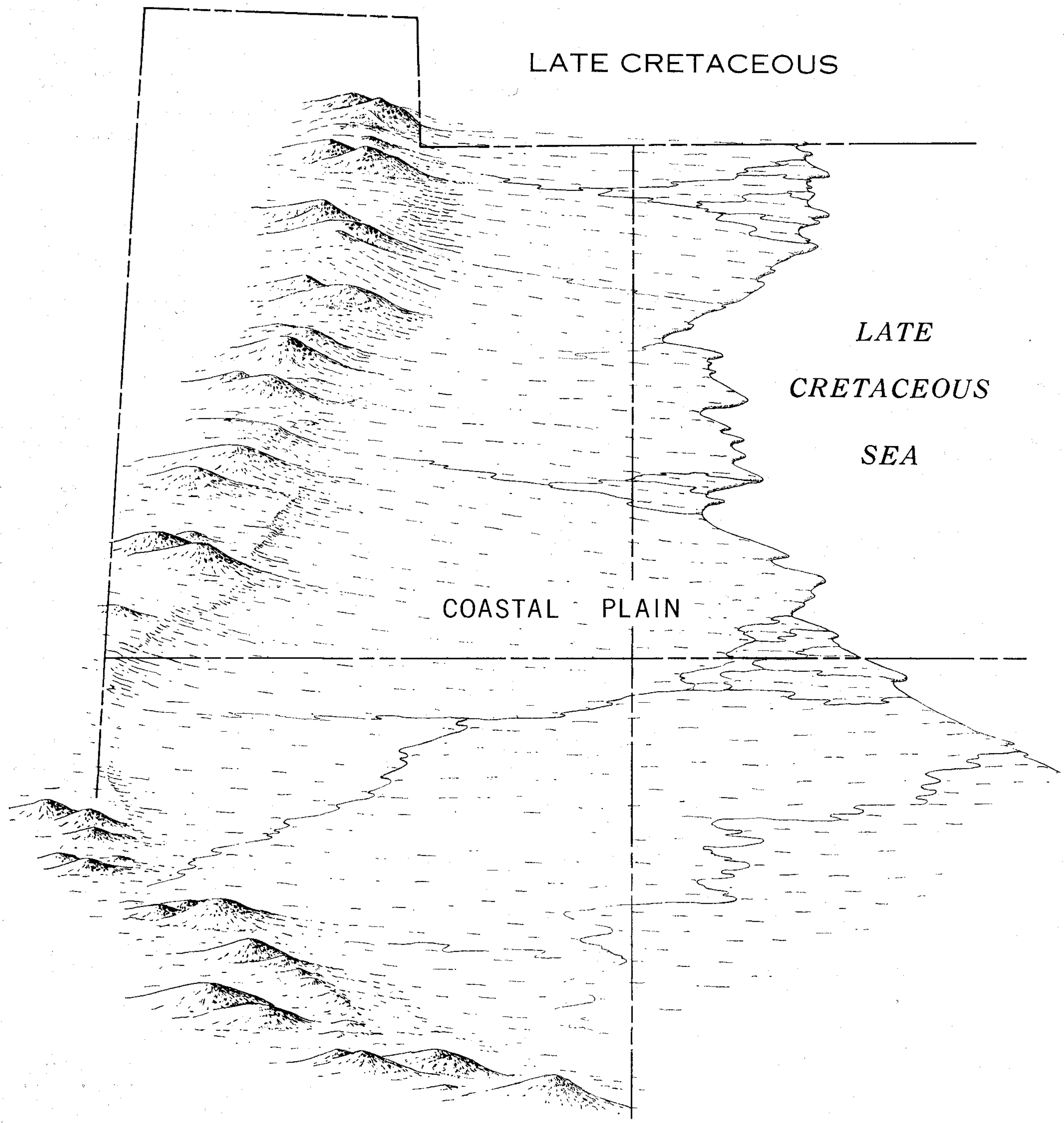

FIGURE 53.—The Colorado Plateau area in Late Cretaceous time. The area was part of a coastal plain that extended eastward from the foot of mountains in central Arizona and central Utah. The edge of the Late Cretaceous Sea was to the east in Colorado.

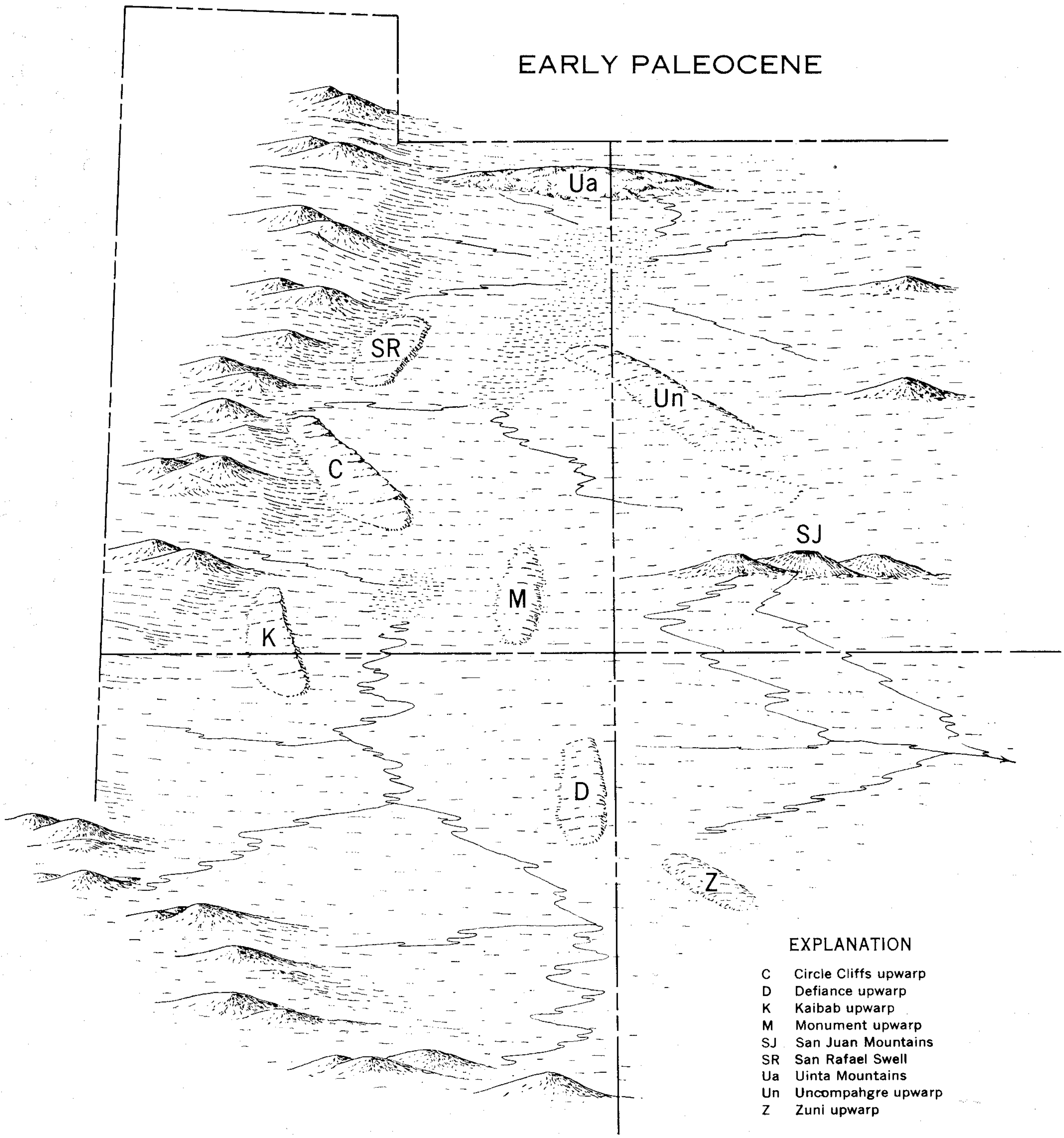

FIGURE 54.—The Colorado Plateau area in early Paleocene time. The principal folds on the Plateau had begun to form. There were volcanic mountains and (perhaps) uplifts in the area of the Rocky Mountains.

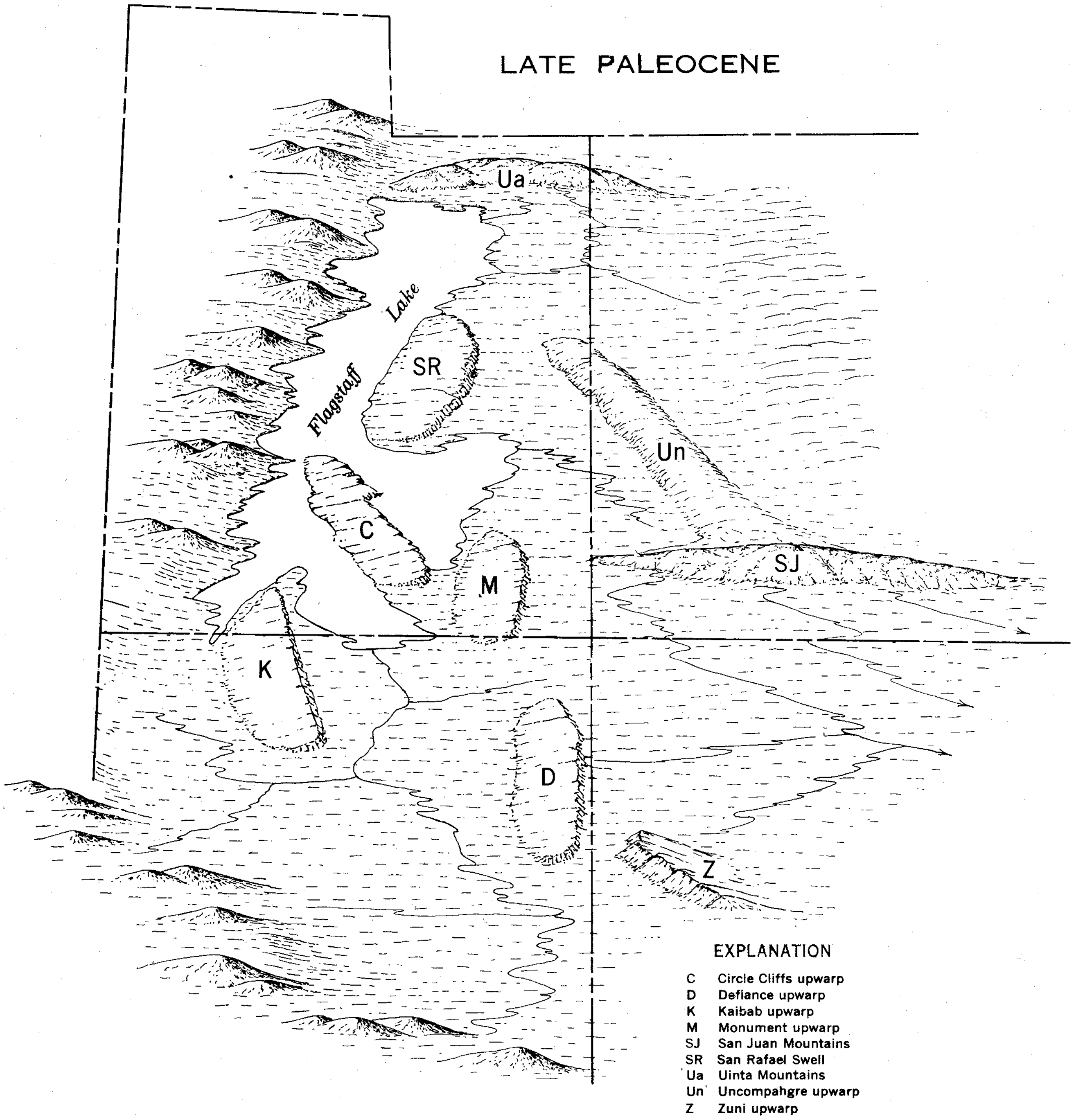

FIGURE 55.—The Colorado Plateau area in late Paleocene time. The Flagstaff lake was formed along the western edge of the Plateau area.

fluviatile Wasatch formation. Presumably, the Arizona part of the Plateau drained northward into this lake but the New Mexico portion seems to have drained southeastward because the Nacimiento formation in the San Juan Basin can be attributed to erosion of uplifted Upper Cretaceous formations on the south side of the San Juan Mountains and on the east side of the Monument, Defiance, and Zuni upwarps. The Nacimiento Mountains had not yet been uplifted.

In early and middle Eocene time the downwarping of the northern part of the Plateau spread eastward, and the huge Green River lake was formed (fig. 56). This lake spread far northward into Wyoming and may have drained eastward into the area of the Great Plains province. The Uinta Mountains may have been completely surrounded, or they may have been a peninsula connected by an isthmus with the Rocky Mountains. The eastern edge of the lake was at the west foot of the Rocky Mountains, in Colorado. The south shore probably was in southeastern Utah along the north flank of the structural platform that comprises southernmost Utah and northern Arizona. Bays probably extended southward in the basins between the upfolds. The lake also may have spread westward between the early Tertiary mountain ranges in northwestern Utah. The catchment area of the Colorado Plateau portion of the Green River lake probably was not very different from that of the Flagstaff lake.

At some stage during the early Tertiary, glaciation in the San Juan Mountains deposited the Ridgway till. Perhaps the Green River lake was maintained in part by glacial meltwaters. The paleobotanical and other evidence of a mild climate around the shores of the lake is not inconsistent with the occurrence of glaciers in the mountains if the mountain summits were 10,000 feet higher than the lake.

The Green River lake came to an end in middle Eocene time, in part perhaps because of uplift; in part because of filling. Thereafter, fluviatile sediments were deposited in the northern part of the Colorado Plateau (fig. 57). In late Eocene time, uplift was renewed at the Uinta Mountains, the San Rafael Swell, and on the Douglas Creek anticline (which is a northward extension of the Uncompahgre uplift). To what extent the renewed uplift was synchronous with the deposition of the Bridger, Uinta, and Duchesne River formations is not clear, but the Green River formation and the earliest of the late Eocene formations were involved in this deformation. The Nacimiento upwarp occurred at about this time, and presumably there was renewed upwarp at some of the other folds too.

Deposition in the Uinta Basin of 5,000 feet of sediments of the Green River formation, and of some additional thousands of feet of later Eocene fluviatile deposits, probably built the surface of this part of the Colorado Plateau higher than that of the Henry Mountains basin and other basins to the south. These basins probably became the site of relicts of the Green River lake; the fill deposited in them would partly bury the adjoining upfolds. By Oligocene time, the basins may have become the sites of playas, and perhaps many of the uplifts had largely become buried (fig. 58).

The next events in the history of the Plateau are wholly conjectural because Oligocene and early Miocene deposits have not been recognized on the Plateau, and deposits of this age are scarce in the adjoining areas.

During Oligocene time, block faulting had begun in the Basin and Range province, and the resulting basins could have captured some streams near the edges of the Colorado Plateau. The Plateau must have continued to receive sediments from the Rocky Mountains, Uinta Mountains, and from any remnant highlands that persisted along the southwest and west sides. Parts of the southeastern portion no doubt drained into basins along the Rio Grande valley, where basin deposits such as the late Eocene or Oligocene Galisteo formation were deposited.

During early Miocene time, as block faulting progressed in the Basin and Range province, the Colorado Plateau probably became well defined as a structural unit and reached an altitude distinctly higher than the basins, though perhaps not so high as the ranges (fig. 59). Epeirogenic uplift of the Plateau began at this stage, and as the Plateau broke away from and was raised higher than the basins to the west, south, and southeast, large areas on the Plateau must have begun draining to those basins. At this point, aggradation on the Plateau ended and degradation began.

The superposition of the main streams across the large upwarps is presumed to have occurred at about this stage in the history of the Plateau. Among these superposed streams are the courses of the San Rafael and Muddy Rivers across the San Rafael Swell, and the course of Unaweep Canyon across the Uncompahgre upwarp. Also, at some early stage (presumably about this time) there must have been drainage westward across the Monument upwarp, no doubt in the form of a stream rising on the west or southwest side of the San Juan Mountains. Perhaps the Dolores River originally flowed southwestward across the Monument upwarp. Tributaries to it, eroding headward in the strike valleys south of the San Juan Mountains, could have captured streams that formerly had taken southerly and southeasterly courses. Some such explanation must be found for the San Juan River (fig. 60), which

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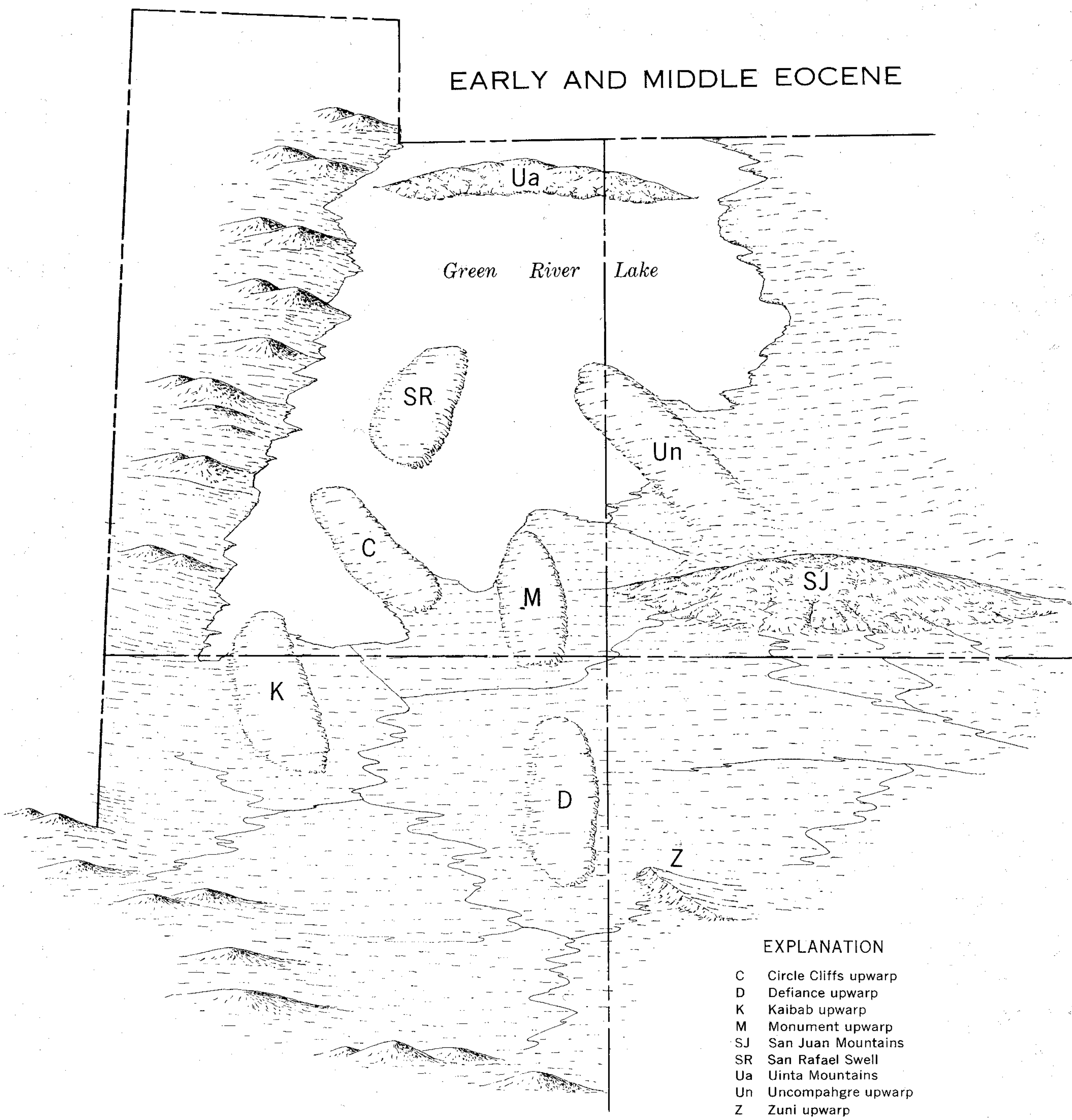


FIGURE 56.—The Colorado Plateau area in early and middle Eocene time. Downwarping of the Uinta Basin produced the Green River lake, which covered most of the north part of the Plateau area. Most of the uplifts, like the San Rafael Swell, probably stood higher than the lake and shed sediments into it.

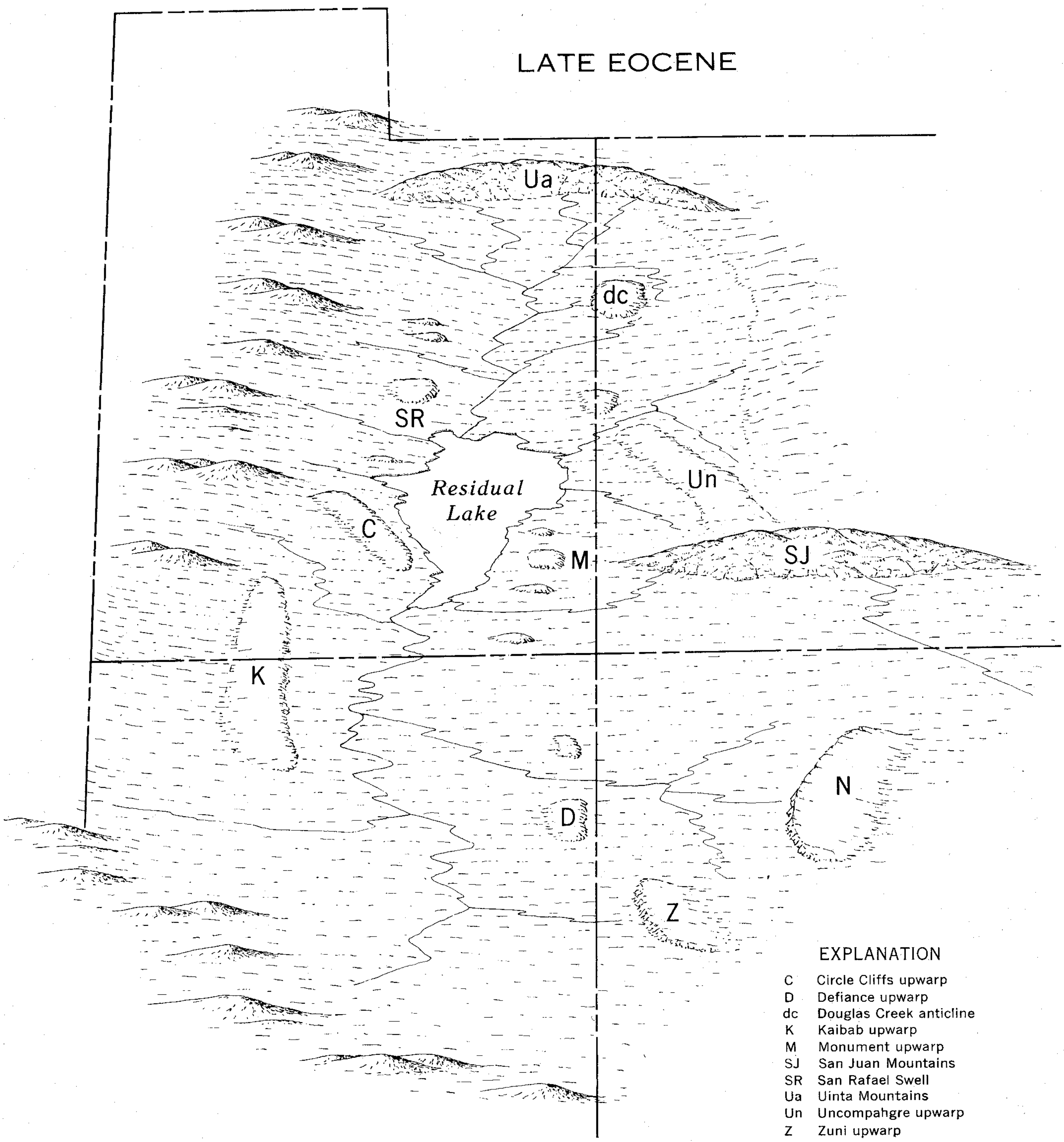


FIGURE 57.—The Colorado Plateau area in late Eocene time. Deposition of 5,000 feet of sediments in Green River lake, and deposition of a few thousand feet of fluviatile sediments, probably raised the surface of the Uinta Basin higher than some of the basins farther south on the Plateau. The Henry Mountains Basin between the Circle Cliffs and Kaibab uplifts, or the Escalante basin, may have been the lowest parts of the area. The Nacimiento Mountains were raised in middle or late Eocene time.

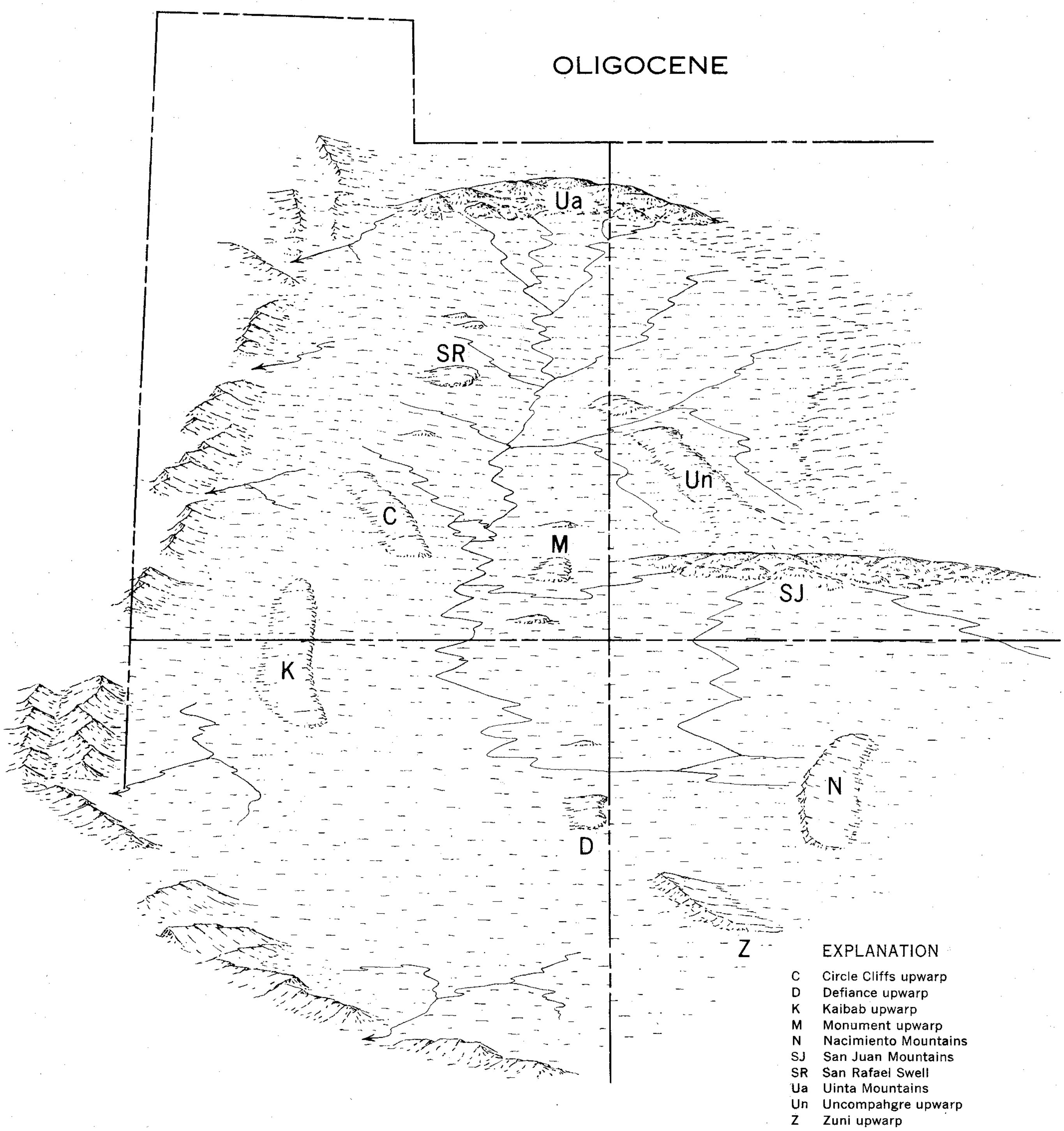


FIGURE 58.—The Colorado Plateau in Oligocene time. The beginning of block faulting in the Basin and Range province may have developed some basins that were lower than the area of the Plateau, and drainage around the edge of the Plateau may have been diverted into the basins. Presumably, this occurred although the Plateau area was still in part a trough and was still receiving sediments from the surrounding mountains.

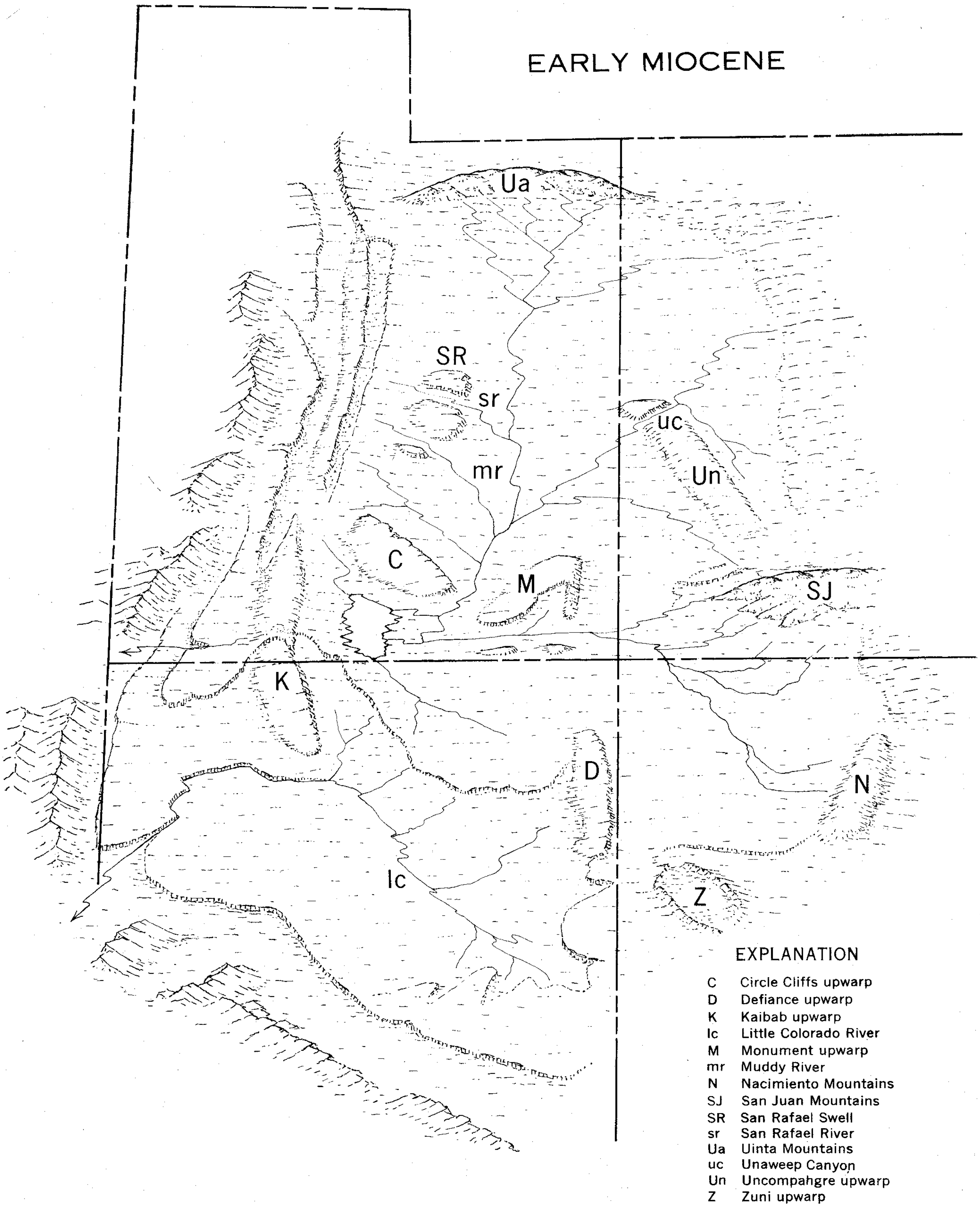


FIGURE 59.—The Colorado Plateau in early Miocene time. By early Miocene time, block faulting in the Basin and Range province had started; the basins are assumed to have been lower than the Colorado Plateau, but the ranges probably continued to be higher. Considerable movement had taken place along the boundary faults, and epeirogenic uplift presumably was started. The Little Colorado River was in existence (see fig. 60) and presumably drained westward approximately along the present course of the Colorado River. The High Plateaus were becoming outlined.

takes a course westward across a high upwarp on the Colorado Plateau instead of a southward course across the San Juan Basin to the Rio Grande.

The laccolithic intrusions in the interior of the Plateau and the beginning of volcanism in the southern and western parts of the Plateau are assigned to middle Miocene time (fig. 60). The drainage system gives every indication of having shifted monoclinally in adjustment to the laccolithic intrusions, except at Rico Dome. The detour made by the Dolores River around the La Sal Mountains, the detour of the Dirty Devil River around the Henry Mountains, the relation of Chinle Creek and San Juan River to the Carrizo Mountains, and the course of the San Juan River along the structural trough between the Carrizo and El Late Mountains are examples of the way the drainage is adjusted to the igneous structures. The abrupt northward bend in the Dolores River at the southwest foot of the San Juan Mountains may be due to diversion as a result of the intrusions at El Late and La Plata Mountains.

The La Plata Mountains form part of the divide between the Animas and Dolores Rivers. The San Miguel Mountains form part of the divide between the headwaters of the Dolores and San Miguel Rivers. The incision of the Dolores River into the dome at Rico might be attributed to superposition from one, or more, of the series of Miocene volcanic rocks in the San Juan Mountains, or from an erosion surface extending southward from the San Miguel Mountains, where the intrusions are at much higher elevations.

Clearly, the drainage pattern on the Colorado Plateau bears a very different relation to the igneous structures than it does to the orogenic structures. Therefore, the stream courses may in general be assumed to antedate the igneous intrusions.

The Little Colorado River valley was in existence before the eruptions in the San Francisco volcanic district. Formations overlying the Permian had already been stripped from that area before the eruptions occurred, and a valley had been eroded between the area of volcanism and the cliffs of Jurassic and Upper Cretaceous formations to the northeast. There is no evidence that the Little Colorado River has shifted its course more than slightly (in a down-dip direction) since the eruptions occurred.

In the Mount Taylor area the eruptions had been preceded by northward tilting of the south flank of the San Juan Basin, and on this south flank the Tertiary formations had been stripped back to a position north of the area of eruptions. The San Juan River has not drained southward since the eruptions occurred in the Mount Taylor district; presumably, that drainage already was turned to the west.

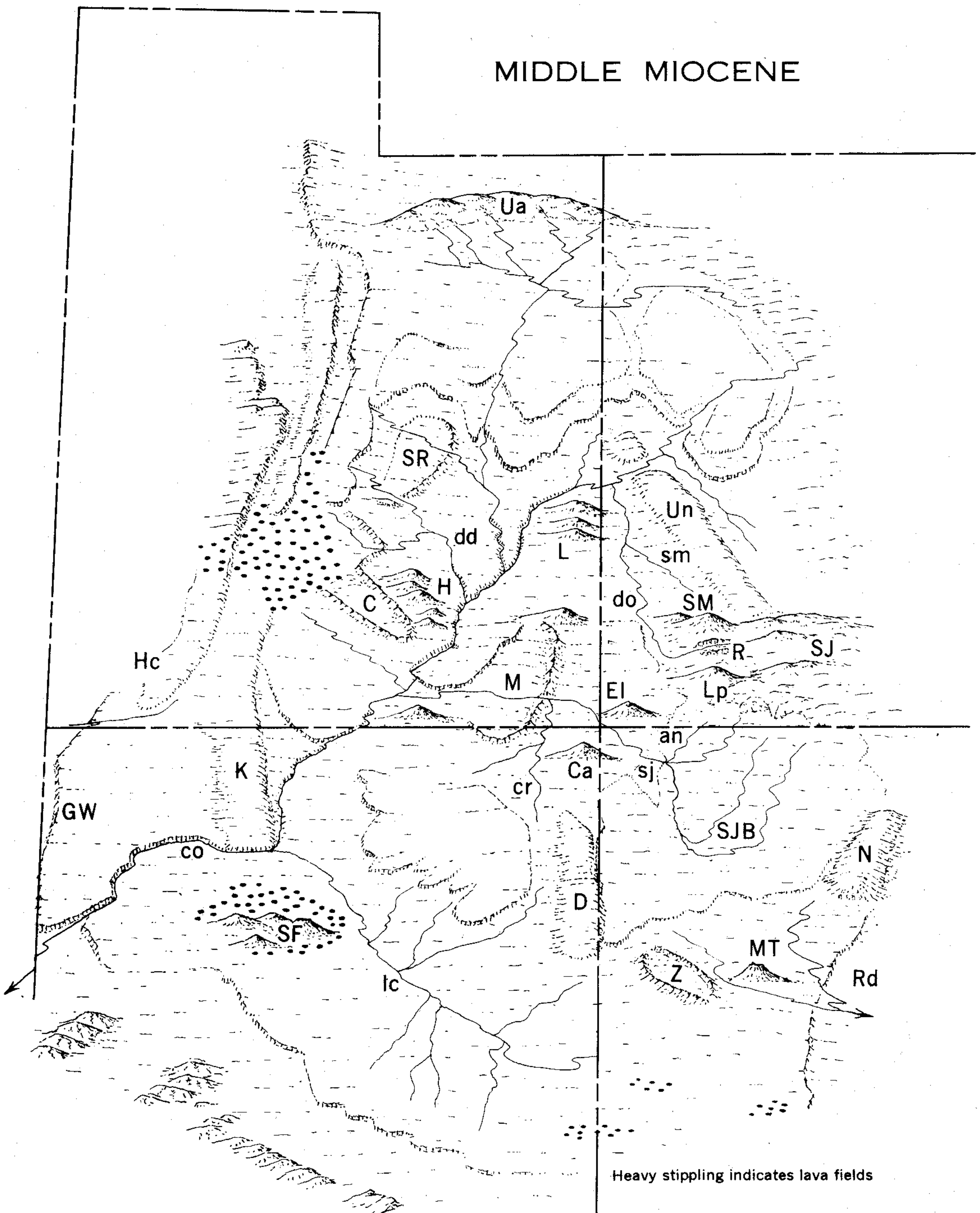
There is no obvious reason why igneous activity in the interior of the Plateau took the form of intrusive stocks and laccoliths, whereas the activity around the margins of the Plateau took the form of volcanism. Nor is there evident reason why the differentiation sequence at the large, central-type volcanoes progressed from acid to basic, whereas the differentiation sequence in the intrusive stocks and laccoliths progressed from basic to acid. Lastly, there is no evident reason for the grossly different ratios of soda and potash in the intrusions and eruptives in different parts of the Plateau.

In the High Plateaus, upwarp accompanied by extensive volcanism and some intrusive activity apparently began during Miocene time, but both upwarp and volcanism continued into Quaternary time. There could have been some westward drainage across the area of the High Plateaus until the upwarps and volcanism began, but we can be sure that there has been no significant drainage westward since that time.

Epeirogenic upwarp of the Plateau also is judged to have started at about this stage because faulting began along the Grand Wash Cliffs, Hurricane Cliffs, and Rio Grande depression.

The conditions call for exterior drainage from the Colorado Plateau, and there seems to be no possible course for the drainage other than the course now followed by the Colorado River. Yet, there is evidence that the Colorado River did not discharge into the trough west of Grand Wash Cliffs while the Miocene and Pliocene(?) formations were being deposited there. This raises one of the major, and still unsolved, problems of Cenozoic history—the problem of the age of the Colorado River.

Blackwelder (1934) and Longwell (1946) have pointed out that the Colorado River could not have emerged from the foot of Grand Canyon while the Muddy Creek formation was being deposited there, because the formation in that area is locally derived and contains no Colorado River gravels. They concluded that the Grand Canyon stretch of the river must be younger than the deposits in Grand Wash trough. This problem, therefore, has certain parallels with the problem of the irresistible force and the immovable object. The Muddy Creek formation in Grand Wash trough is the immovable object; the irresistable force is the evidence upstream that the Colorado River must have discharged through Grand Canyon before late Tertiary time. The possibility that the river may once have discharged from the Plateau through the depression at Peach Springs (p. 30) does not help solve the main



EXPLANATION

an	Animas River	H	Henry Mountains	SF	San Francisco Mountain
C	Circle Cliffs upwarp	Hc	Hurricane Cliffs	SJ	San Juan Mountains
Ca	Carrizo Mountains	K	Kaibab upwarp	sj	San Juan River
co	Colorado River	L	La Sal Mountains	SJB	San Juan Basin
cr	Chinle Creek	lc	Little Colorado River	SM	San Miguel Mountains
D	Defiance upwarp	Lp	La Plata Mountains	sm	San Miguel River
dd	Dirty Devil River	M	Monument upwarp	SR	San Rafael Swell
do	Dolores River	MT	Mount Taylor	Ua	Unita Mountains
El	El Late Mountain	N	Nacimiento Mountains	Un	Uncompahgre upwarp
GW	Grand Wash Cliffs	R	Rico Dome	Z	Zuni upwarp
		Rd	Rio Grande depression		

FIGURE 60.—The Colorado Plateau in middle Miocene 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 monoclinically 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 already had formed in Grand Canyon.

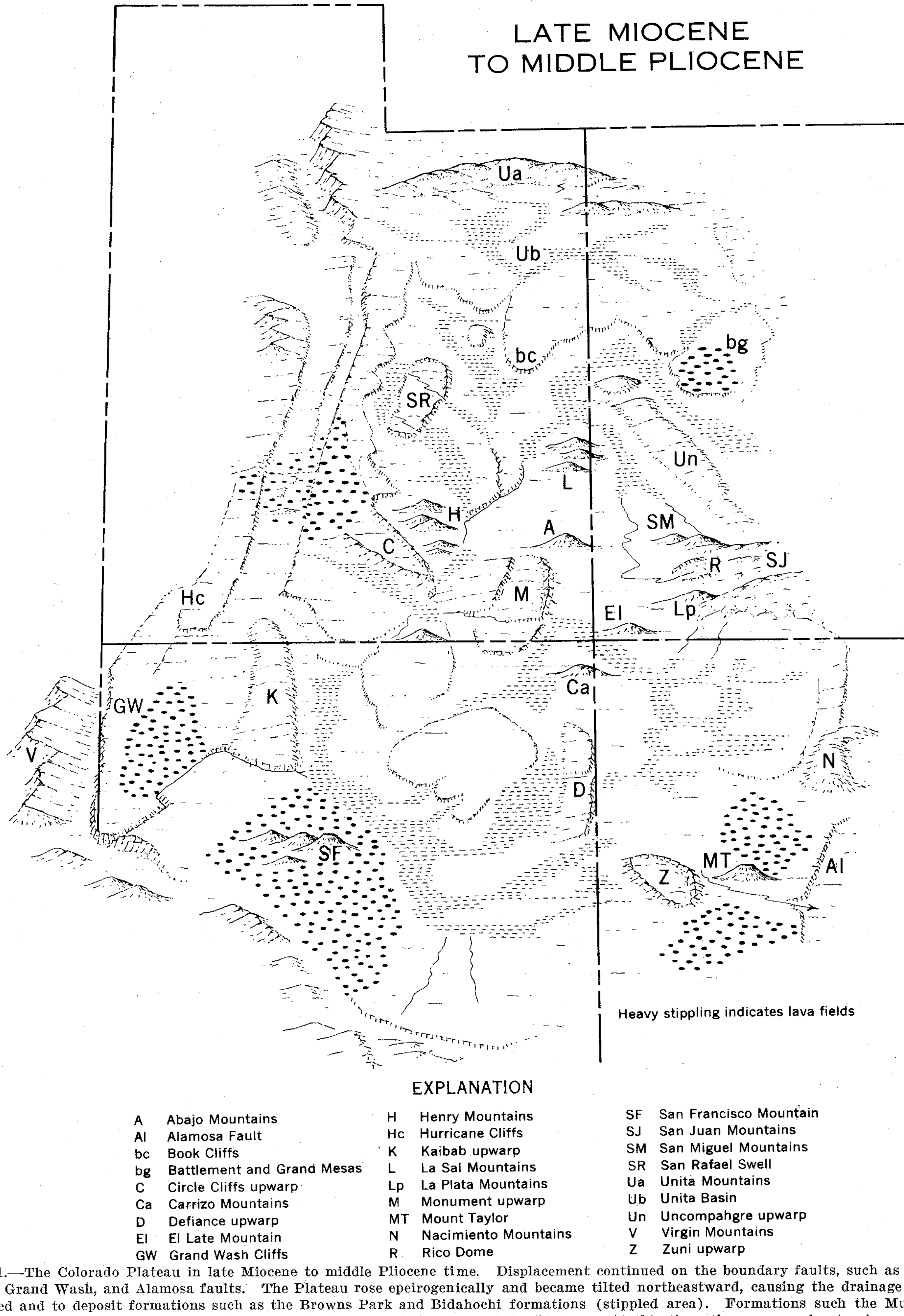


FIGURE 61.—The Colorado Plateau in late Miocene to middle Pliocene time. Displacement continued on the boundary faults, such as the Hurricane, Grand Wash, and Alamosa faults. The Plateau rose epeirogenically and became tilted northeastward, causing the drainage to become ponded and to deposit formations such as the Browns Park and Bidahochi formations (stippled area). Formations such the Muddy Creek and Santa Fe formations were deposited in the basins around the edges of the Plateau. At this time, there occurred extensive eruptions of basalt and alkalic basalt.

problem, because similar and probably correlative deposits also occur in that depression.

There seems to be only two possible ways that the Colorado River could have established its Grand Canyon course in post-Muddy Creek time—by capture by a stream eroding headward from the Grand Wash trough, or by superposition. Neither of these interpretations seems tenable.

Capture by a stream eroding headward from the Grand Wash trough requires unusual circumstances. The Grand Wash Cliffs north and south from the foot of Grand Canyon are straight for many miles, and have not been cut deeply by the streams draining westward to the basins. It would indeed have been a unique and precocious gully that cut headward more than 100 miles across the Grand Canyon section to capture streams east of the Kaibab upwarp.

Superposition also seems to be out of the question. The southwest rim of the Colorado Plateau was substantially higher than the interior of the Plateau when the Bidahochi formation and the fill in Grand Wash trough were deposited. Thus, the erosion surface, or fill, from which superposition would have to occur would have been as high as the rim of Grand Canyon—now about 9,000 feet in altitude—and of course, this surface would have to rise upstream and be still higher in Utah and Colorado. However, at much lower elevations upstream, there are Pliocene or Pliocene(?) deposits, such as the Bidahochi formation, indicating that the Pliocene topography of the Plateau was not greatly different from that of today. The canyons along the river may be antecedent, but it is more probable that they are the product of anteposition, as suggested in figure 61.

During late Miocene to middle Pliocene time (fig. 61) while formations such as the Muddy Creek and Santa Fe were being deposited, the Colorado Plateau rose higher above the basins of the Basin and Range province. As a result of this general uplift, the Plateau was tilted northeastward. The Grand Canyon course of the Colorado River could have formed earlier than the deposits in Grand Wash trough if the river had become ponded and later anteposed in its old course as a result of regional tilting northeastward of the Plateau.

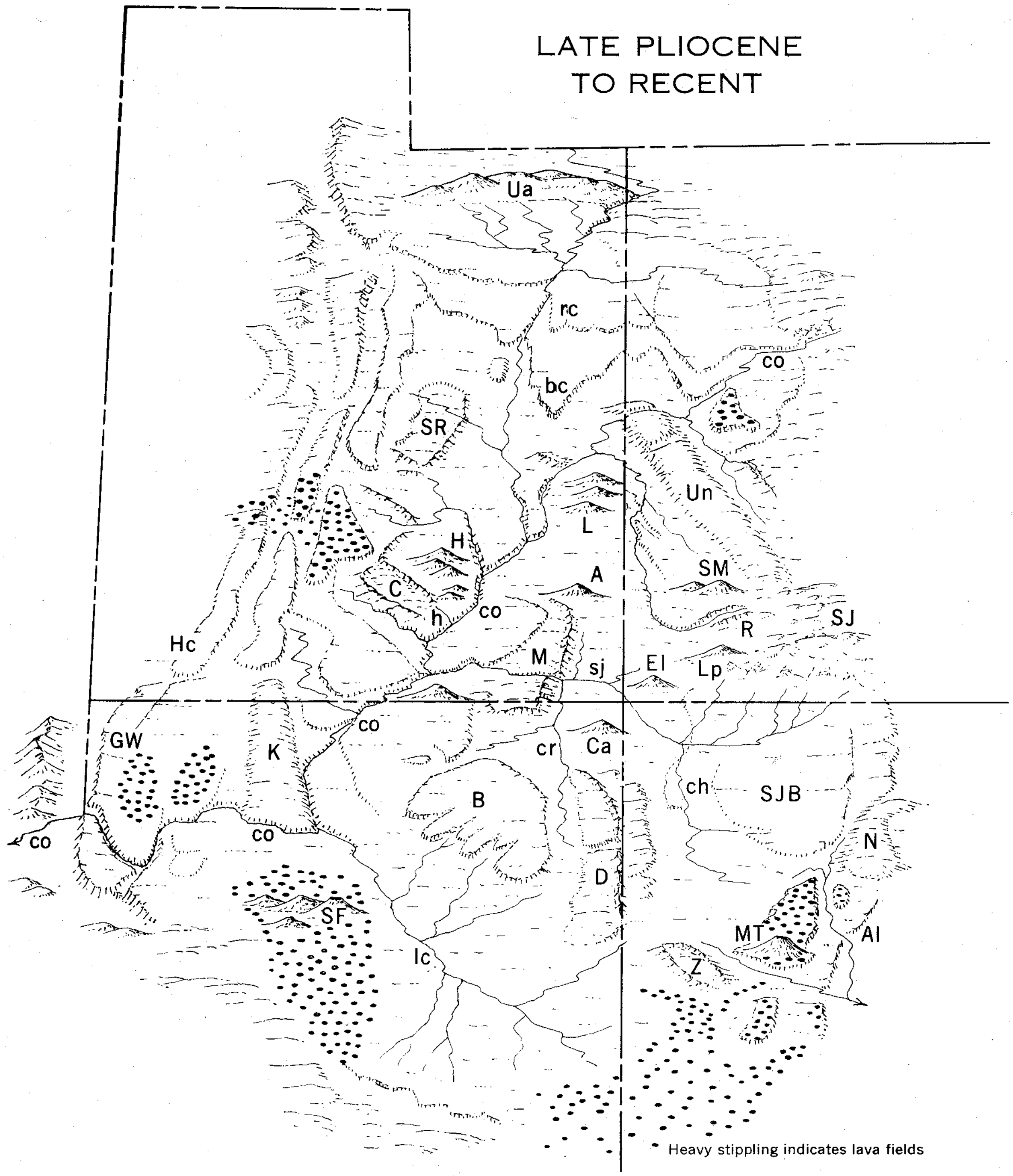
The Browns Park formation, Bidahochi formation, and the 1,000 feet of fanglomerate at the northwest foot of the La Sal Mountains record a stage or stages of aggradation on the Plateau, which supposedly took place at about the same time that the Miocene to Pliocene(?) formations were being deposited in Grand Wash trough. Deposits such as these may have been a common occurrence in the valleys on the Plateau, as suggested in figure 61. Two thousand feet of differential upwarp resulting from northeastward tilt, could easily have caused the aggradation. This amount of tilt, or even more, is suggested by the structure-contour map (fig. 37).

The ponding and aggradation, whether it occurred at one place or at many places, would have to have been for the duration of Muddy Creek sedimentation in the Grand Wash trough. Drainage out of the bed of the old canyon would be resumed when the water was raised to that level by ponding and aggradation. The first waters over the spillway could have supplied the lake that formed in Grand Wash trough when the Hualpai limestone of Longwell was deposited. Indeed, because the climate of that period was not conducive to lake development, an outside source like the Colorado River seems to be necessary to supply the water for this vast lake.

Sediments deposited when the Plateau was tilted could have produced the younger set of superposed drainage features, such as the canyon of the Colorado River across the northwest end of the Uncompahgre Plateau, the meanders that Halls Creek has incised into the Waterpocket fold on the flank of the Circle Cliffs upwarp, and the curious manner in which Chinle Creek and Chaco River turn out of strike valleys and into canyons to join the San Juan River (fig. 62). These features could readily be the product of superposition from late Tertiary deposits.

Under this interpretation, the late Pliocene to Recent history of the Colorado Plateau has witnessed no great change in the pattern or position of the drainage. The canyons have been deepened, but only along existing courses. Upwarping has continued in the High Plateaus. If upwarping has continued in the rest of the Colorado Plateau, the rise has been slow enough for the Colorado River to maintain an antecedent course across the Plateau. The maximum of igneous activity on the Colorado Plateau occurred when the extensive sheets of basalt and andesite were erupted onto the southern and western rims of the Plateau—the rims that overlook the Basin and Range province. The greatest volume of these eruptions occurred after upwarping was well under way. The last volcanic eruptions occurred within the past 1,000 years.

During Pleistocene time the canyons along the main stream courses have been deepened. The late Pleistocene history of the canyons has been an alternation of deposition of deep fill in the canyons and erosion of that fill; the amount of late Pleistocene canyon cutting in the bedrock has not been great, even along headwater courses in the mountains.



EXPLANATION

A Abajo Mountains
Al Alamosa fault
bc Book Cliffs
BM Black Mesa
C Circle Cliffs upwarp
Ca Carrizo Mountains
ch Chaco River
co Colorado River
cr Chinle Creek
D Defiance upwarp
El El Late Mountain
GW Grand Wash Cliffs
H Henry Mountains
h Halls Creek
Hc Hurricane Cliffs
K Kaibab upwarp
L La Sal Mountains
lc Little Colorado River
Lp La Plata Mountains
M Monument upwarp
MT Mount Taylor
N Nacimiento Mountains
R Rico Dome
rc Roan Cliffs
SF San Francisco Mountain
SJ San Juan Mountains
sj San Juan River
SJB San Juan Basin
SM San Miguel Mountains
SR San Rafael Swell
Ua Unita Mountains
Un Uncompahgre upwarp
Z Zuni upwarp

FIGURE 62.—The Colorado Plateau in late Pliocene to Recent time. The canyons become reoccupied and cut deeper when the ponded water reaches the level of the uplifted stream beds.

The Recent history of the Plateau has included some structural deformation, some volcanism, and a succession of stages of alluviation and arroyo cutting that apparently reflect climatic changes. Since about 1880, arroyo cutting on the Plateau has been vigorous. There is some evidence that this erosion was hastened by overgrazing, but there is good reason to believe that the hastening of erosion is attributable primarily to climatic change—another example of history repeating itself.

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INDEX