THE MOGOLLON HIGHLANDS—THEIR INFLUENCE ON MESOZOIC AND CENOZOIC EROSION AND SEDIMENTATION[1/]

By

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INTRODUCTION

The regional distribution of geologically persistent highlands in the southwestern United States and northern Mexico has been recognized since the beginning of the twentieth century and was indicated on paleogeographic maps prepared by Chamberlin and Salisbury (1906) and other investigators. Later paleogeographic maps (Schuchert and Dunbar, 1941), isopach maps (Ver Wiebe, 1932; McKee, 1951), and paleotectonic maps (Eardley, 1951; McKee and others, 1956, 1959) added considerable detail concerning the distribution and development of the highlands.

Eardley (1951, p. 12-23), in describing the regional structure of western North America, used the terms "Manhattan geanticline" (Triassic), "Cordilleran geanticline" (Jurassic and Cretaceous), and "Occidental geanticline" (Jurassic and Cretaceous) to denote broad structures lying in the area south and west of Arizona and Utah (fig. 1). These structures formed some of the chief controls of the depositional patterns in Arizona and adjoining regions. Highlands associated with these structures occupied parts of Arizona and New Mexico in Mesozoic time and persisted, although considerably modified, throughout Cenozoic time.

The term "Mogollon Highlands" was first used by Harshbarger, Repenning, and Irwin (1957, p. 44) for a highland area in Arizona and New Mexico which was a source for some of the Jurassic sediments on the Colorado Plateau. Smith (1951, p. 99) had suggested earlier that the highland source for Triassic and Jurassic sediments in the central parts of Arizona and New Mexico be called the "Navajo Highlands." The use of the term "Mogollon Highlands" is continued in this paper to denote a positive area in central and southern Arizona and nearby regions that furnished sediments to the Colorado Plateau and Basin and Range provinces throughout Mesozoic and Cenozoic time.

The Mogollon Highlands have been one of the major controls of erosion and sedimentation in the region bordered by the Cordilleran geosyncline to the west, the Mexican (Sonoran) geosyncline to the southeast, and the Rocky Mountain geosyncline to the northeast (fig. 1). The highlands were restricted progressively by regional and local structural movements dating from Early

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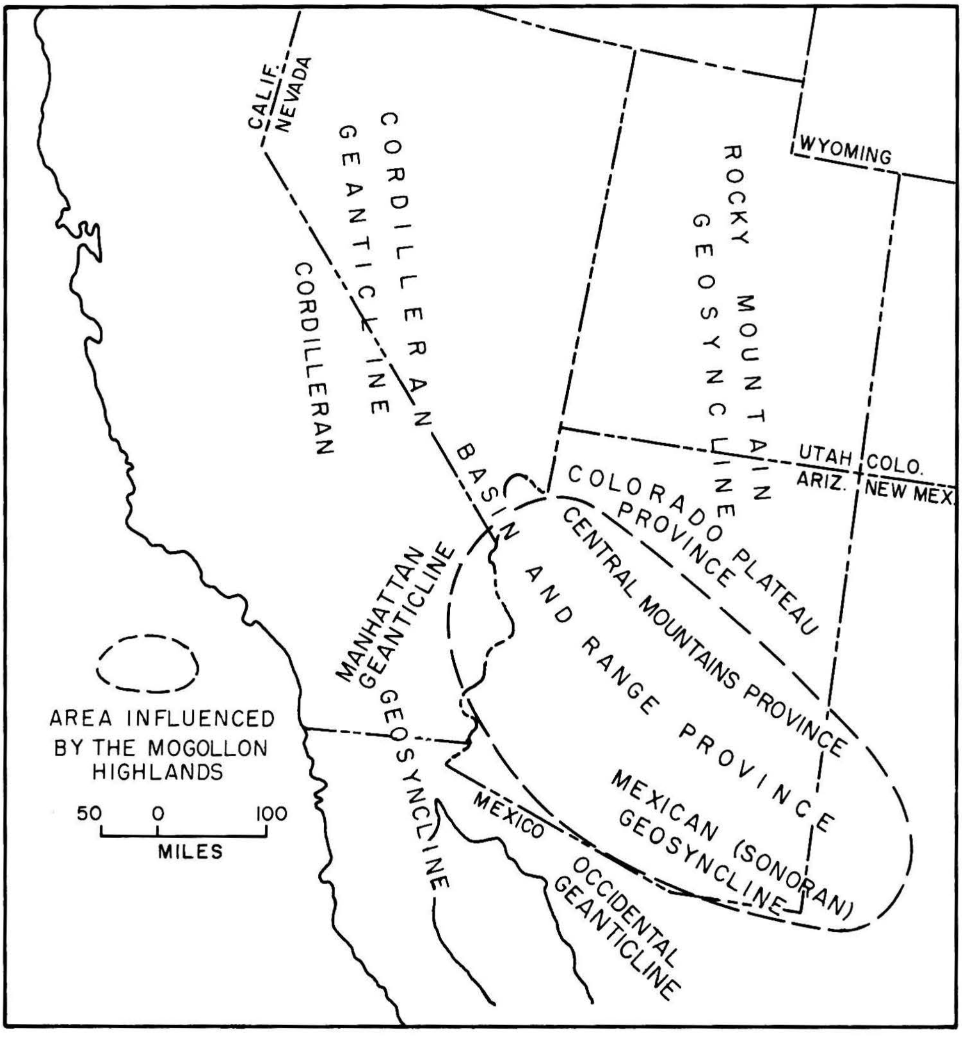


Figure 1. --Map showing the major structural features of southwestern United States and northwestern Mexico.

Cretaceous time and by the end of Tertiary time were limited to central Arizona and west-central New Mexico. The present Mogollon Highlands, occupying the area of the Central Mountains province, separate the Colorado Plateau province to the north and northeast from the Basin and Range province to the south and southwest (fig. 1).

MESOZOIC GEOLOGY

During late Paleozoic time, regional upwarping terminated Permian deposition and caused the withdrawal of the seas to the west, east, and southeast from most of Arizona and western New Mexico. Uplift tended to be centered within two broad areas; one area in southern Arizona and New Mexico—the Mogollon Highlands—and the other in Colorado—the Uncompahgre Highlands (fig. 2). This upwarping, indicated by the unconformity between Triassic and Permian rocks, was accompanied by a long period of erosion dating approximately from Late Permian and ranging into Middle Triassic time. The erosional period was restricted chiefly to Late Permian and Early Triassic time in western Nevada where Early Triassic sediments (Muller and Ferguson, 1939, p. 1583), younger than those on the Colorado Plateau, were deposited in the Cordilleran geosyncline. Eastward from the Cordilleran geosyncline the period of erosion was progressively longer, and in northeastern Arizona and northwestern New Mexico it continued through most of Early Triassic time. The Mogollon Highlands were a source for Early Triassic sediments in the southern part of the Colorado Plateau, because pebbles in the basal conglomeratic beds of the Moenkopi Formation could have been derived only from exposures in the highlands. Pebbles composed of quartz, quartzite, jasper, chert, and limestone derived from southern and southeastern sources are present in scattered outcrops of the Moenkopi between Flagstaff and the Zuni Mountains (Price, 1948, p. 34; Cooley, 1959, p. 68-69).

Triassic and Jurassic Periods

In Early and Middle Triassic time the Mogollon and Uncompahgre Highlands formed a broad upwarped area extending from south-central Arizona to southwestern Colorado (fig. 2). Triassic marine, nearshore, and continental sediments overlapped eastward from the Cordilleran geosyncline on the slopes of these highlands. The Moenkopi Formation of Early and Middle(?) Triassic age is the principal formation in the Arizona-New Mexico area deposited at that time. Its distribution and overall uniform siltstone to silty fine-grained sandstone lithology are the basis for suggesting that the highlands were rather low and more or less structurally stable.

Renewed epirogenic upwarping in Middle and Late Triassic time caused westward retreat of the Triassic seas and differentially uplifted the Mogollon and Uncompahgre Highlands. The flanks of a wide west-northwestward-sloping trough or valley between these highlands, in which the Chinle Formation was subsequently deposited, were steepened, and erosion removed an unknown amount of Moenkopi and older sediments (fig. 3). Valleys in the southern part of the Colorado Plateau were carved as much as 200 feet deep and 10 miles wide and were filled principally by the conglomeratic Shinarump Member of the Chinle Formation.

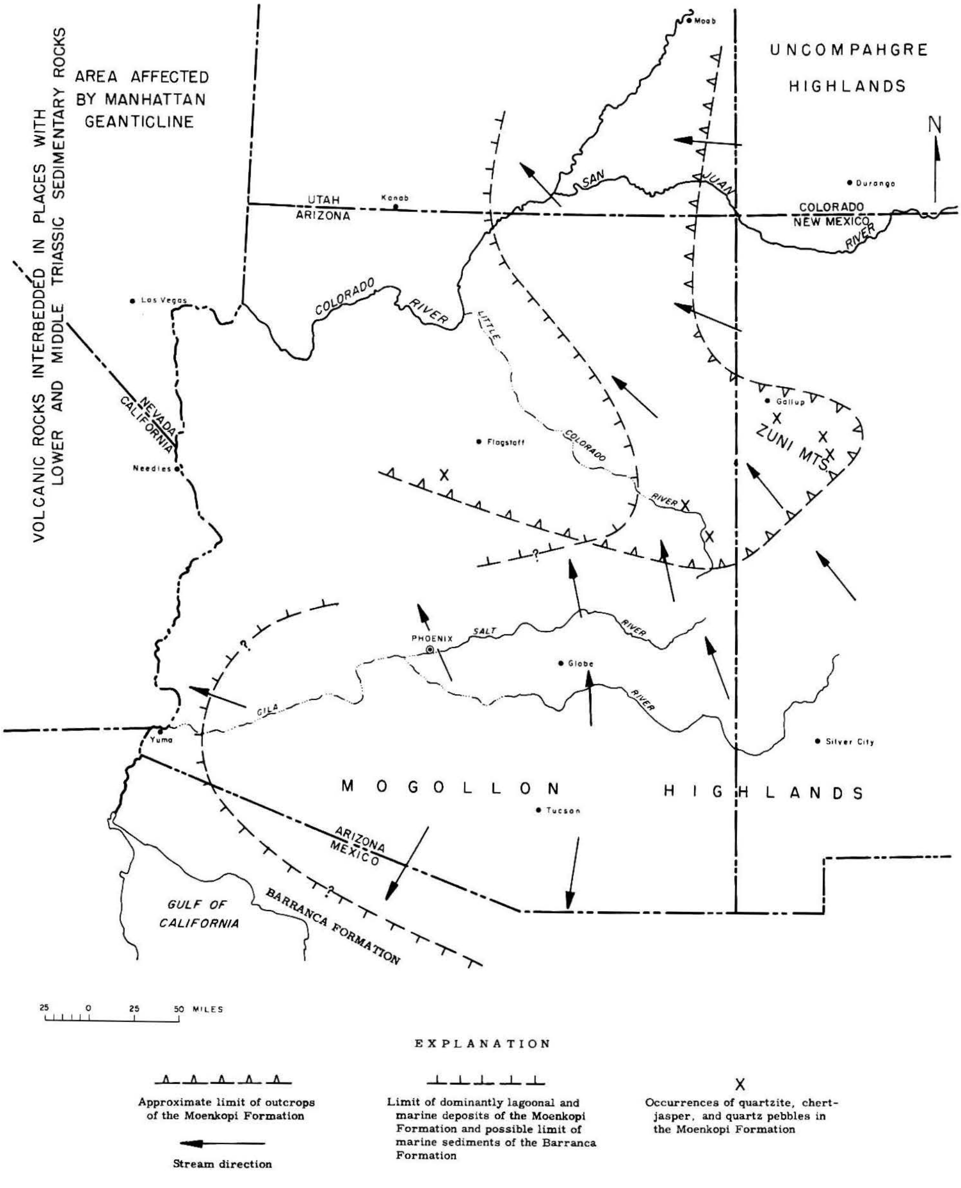
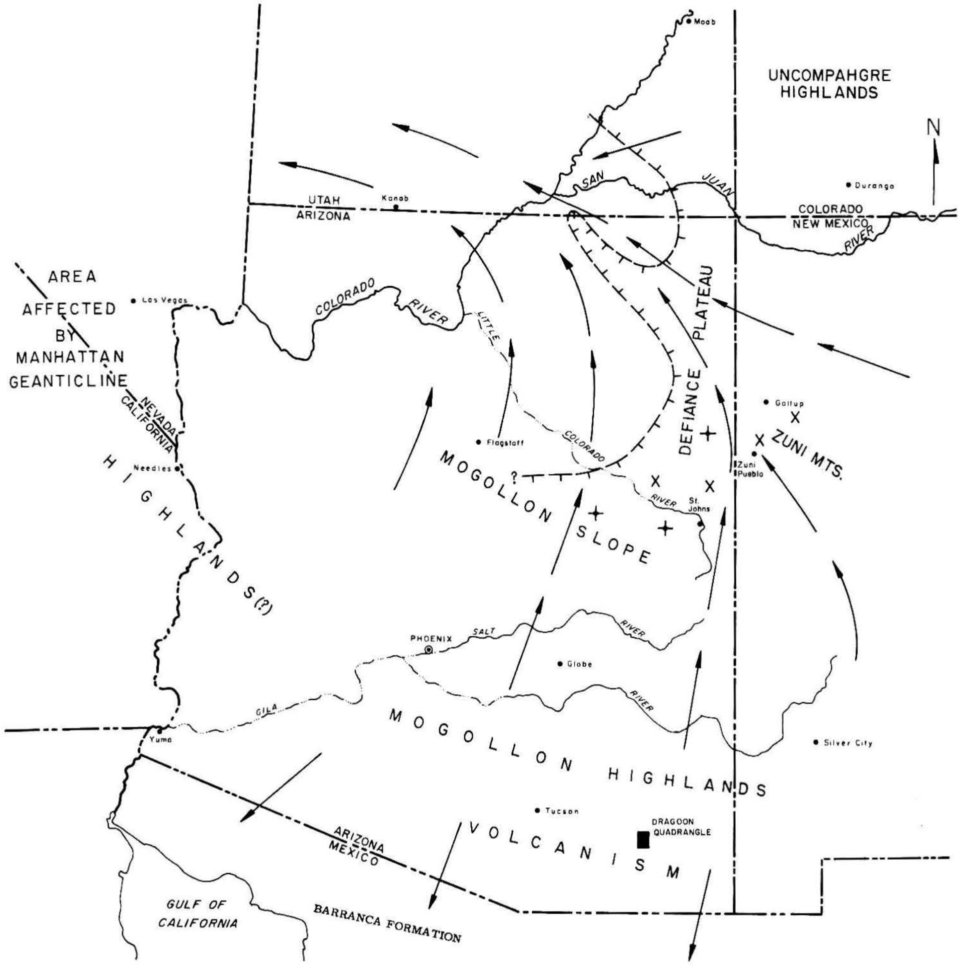


Figure 2.--Map showing drainage and geologic features during deposition of the Moenkopi Formation, Early and Middle (?) Triassic time.



EXPLANATION

Western limit of Sonsela Sandstone Bed of the Petrified Forest Member and o f the Moss Back Member of the Chinle Formation

Occurrences of cobbles having maximum diameter as much as 8 inches in the Shinarump Member of the Chinle Formation

X Occurrences of cobbles which have maximum diameters of as much as 6 inches in the Sonsela Sandstone Bed of the Chinle Formation

Stream direction of Shinarump Member and of the streams depositing Triassic sediments south of the Mogollon Highlands

Figure 3.--Map showing drainage and geologic features during deposition of the lower part of the Chinle Formation, Late Triassic time.

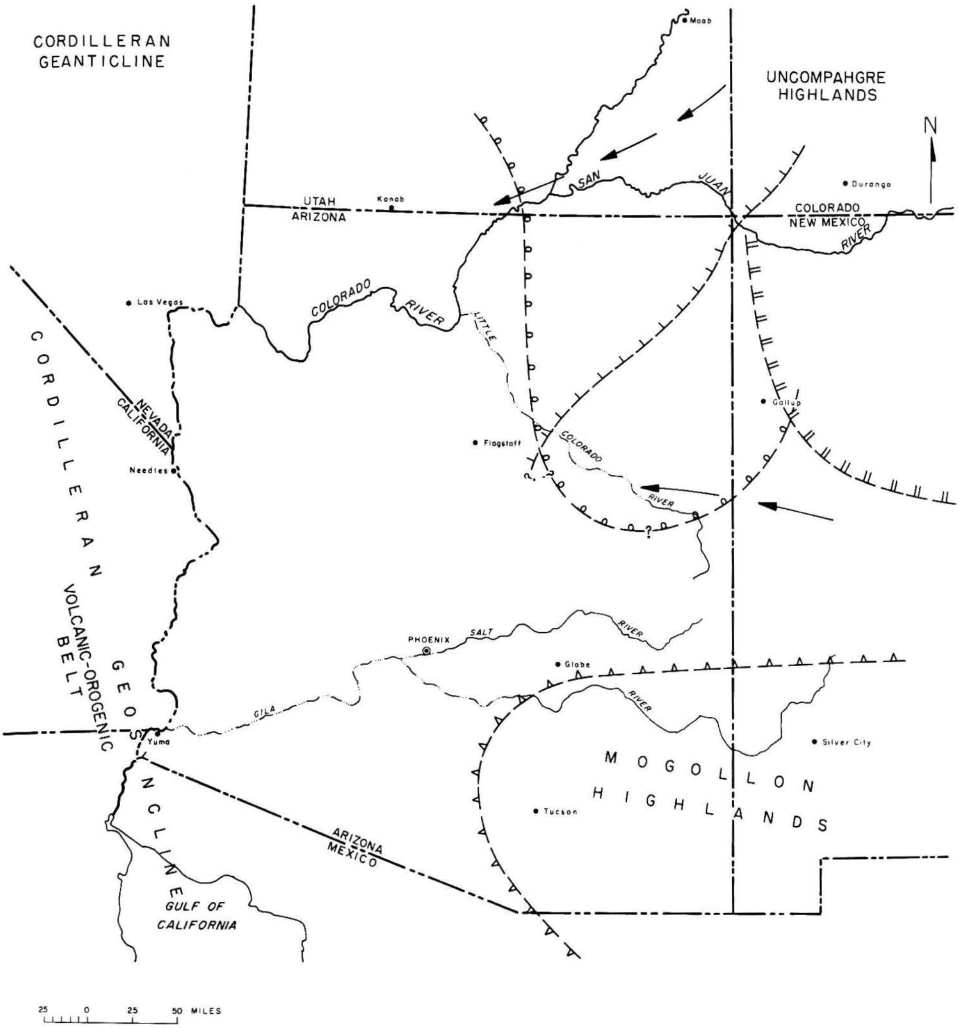
The Mogollon Highlands were the source for much of the sediments of the Chinle Formation laid down in northern Arizona and New Mexico (McKee, 1937). The relief was sufficient at times to cause deposition of conglomeratic beds in the Shinarump, Mesa Redondo, and Petrified Forest Members. The last major uplift of the highlands during Triassic time resulted in deposition of the Sonsela Sandstone Bed, the medial unit of the Petrified Forest Member, over much of northeastern Arizona and northwestern New Mexico (fig. 3).

The earliest indications of Mesozoic volcanism are in the Chinle Formation. Bentonite and ash beds are present throughout the formation and are more numerous in outcrops on the Mogollon slope than they are to the north; pebbles and small cobbles of rhyolitic to andesitic composition are included in conglomeratic beds within the Shinarump Member and in the lower part of the Petrified Forest Member only in the Mogollon slope-Zuni Mountains region (Stewart, Poole, and Wilson, 1957, p. 344; Cooley, 1957). Stream directions and other stratigraphic evidence suggest a southern source for the pebbles; one possible source area is 200 miles to the south, where Cooper (1959, p. 141-143) reported probable pre-Cretaceous-post-Lower Permian volcanic rocks composed of andesite and dacite in the Dragoon quadrangle.

The north- and northwest-trending drainages in Early, Middle, and part of Late Triassic time were diverted to the west and southwest at the close of the Triassic, probably because the Uncompahgre and adjacent regions were elevated more than the Mogollon Highlands (fig. 4). This major directional change in drainage occurred during deposition of the upper part of the Chinle Formation and continued throughout the deposition of the Wingate Sandstone and the Moenave and Kayenta Formations; the bulk of these sediments was derived from the Uncompahgre Highlands, but some sediment was contributed from the southeast, as pointed out by Harshbarger and others (1957, p. 23-25) in their discussion of the Rock Point Member of the Wingate Sandstone and the Dinosaur Canyon Sandstone Member of the Moenave Formation. This southwest drainage was interrupted from time to time by blankets of eolian deposits, notably the Lukachukai Member of the Wingate Sandstone and the Navajo Sandstone, which were derived from the northwest.

Major structural changes took place in western North America during Jurassic time (Eardley, 1951, p. 21; Imlay, 1956, pl. 8). The Cordilleran geanticline was completed from Canada to Mexico and the Mogollon Highlands were extended, forming a broad crescent-shaped arch between the Cordilleran geanticline and the stable landmass of the continental interior, thus separating the Rocky Mountain and Mexican geosynclines. Most of Arizona, New Mexico, and part of northwestern Mexico were tilted northward, and streams drained into the Rocky Mountain geosyncline; streams in the extreme southern parts of Arizona and New Mexico flowed into the Mexican geosyncline (fig. 5). Jurassic marine sediments were deposited as far south as northeastern Arizona and northwestern New Mexico in the Rocky Mountain geosyncline and as far north as the International Boundary between Mexico and New Mexico in the Mexican geosyncline.

Most Upper Jurassic sediments of the southern part of the Colorado Plateau were derived from the south and southwest from the Mogollon Highlands in Arizona and New Mexico and from an upland area called "Mohavia" (Eardley, 1951, pl. 13) in eastern California and southwestern Nevada. Near the end of Jurassic time rejuvenation of the southern highlands caused deposition of coarse material of the Morrison Formation (fig. 6). Crossbedding and the distribution of conglomerate in the members of the Morrison indicate that two principal



EXPLANATION

Inferred limit of Upper Triassic sediments

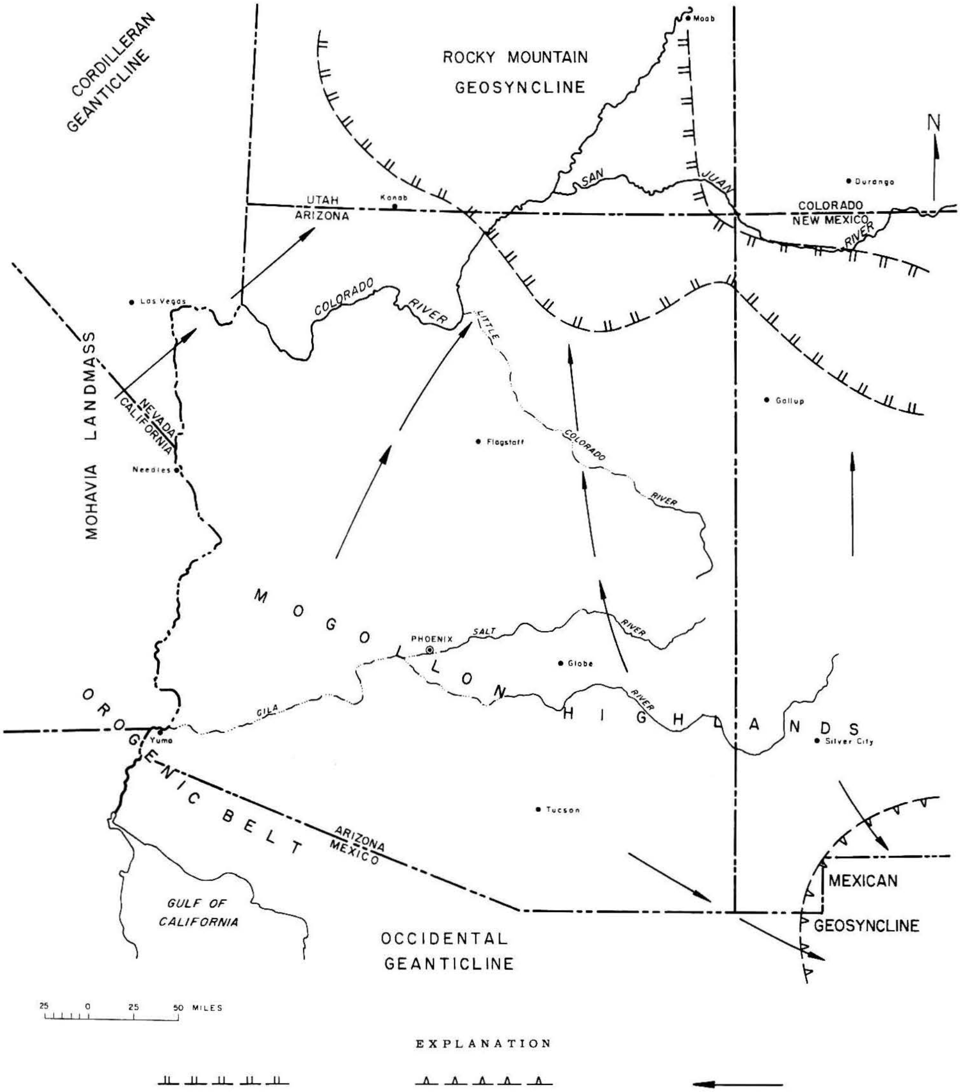
Southwestern limit of sandstone beds in the upper part of the Chinle Formation

Southeastern limit of the eolian Navajo Sandstone

Limit of the eolian Lukachukai Member of the Wingate Sandstone

Generalized direction of streams depositing fluvial sediments of the Glen Canyon Group (Rock Point Member of the Wingate Sandstone, Moenave Formation, and Kayenta Formation)

Figure 4.--Map showing drainage and geologic features during deposition of the upper part of the Chinle Formation and the fluvial units of the Glen Canyon Group, Late Triassic time.



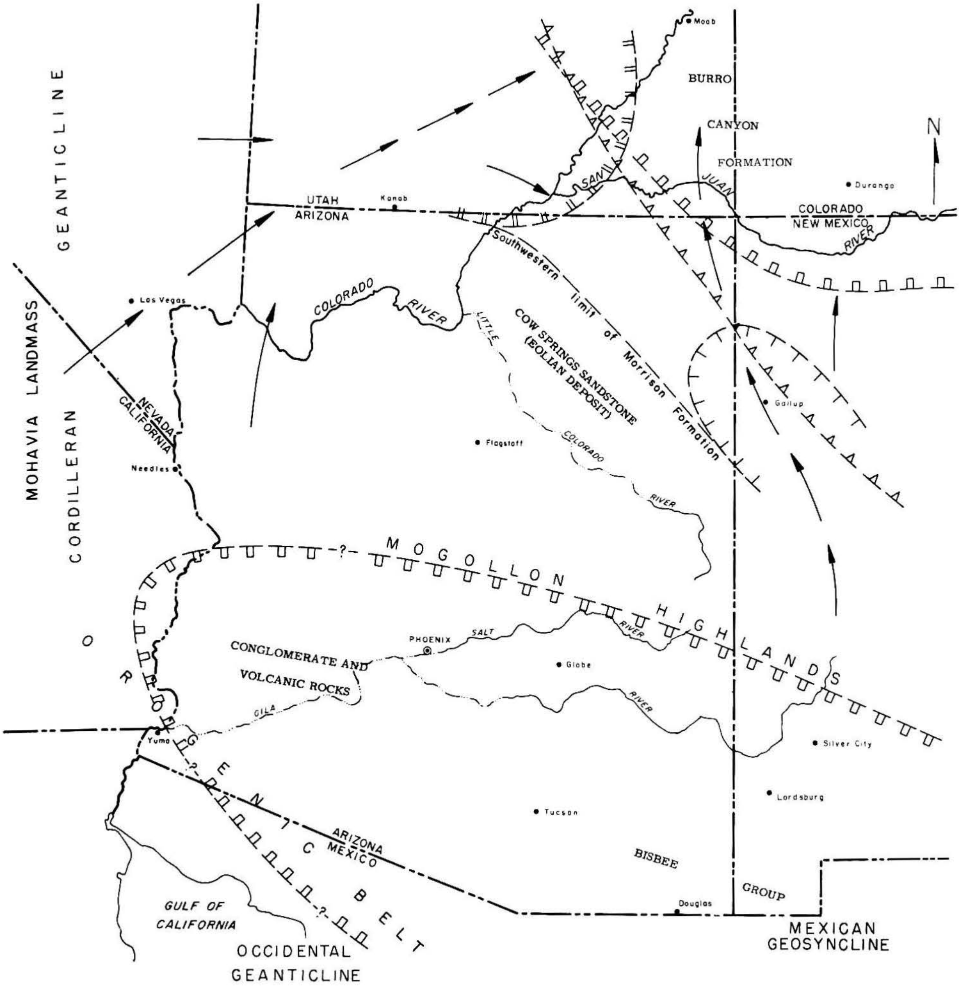
EXPLANATION

Area where marine sediments were deposited (Carmel Formation, Entrada Sandstone, and Summerville Formation in northeastern Arizona and southern Utah; Summerville Formation and Todilto Limestone in northwestern New Mexico)

Approximate limit of Jurassic sediments in Mexican geosyncline

Direction of streams which deposited the fluvial part of the San Rafael Group and fluvial Jurassic sediments in the Mexican geosyncline

Figure 5.--Map showing drainage and geologic features during deposition of the San Rafael Group, Late Jurassic time.



EXPLANATION

Approximate southwestern limit of the Brushy Basin Member of the Morrision Formation

Approximate area where Recapture and Westwater Canyon Members of the Morrison Formation contain arkosic sandstone

Approximate area where Salt Wash Member of the Morrison Formation contains conglomerate

Direction of streams which deposited the Morrison Formation

Limit of Lower Cretaceous deposits

Figure 6.--Map showing drainage and geologic features during deposition of the Morrison Formation, in Late Jurassic time and during Early Cretaceous time.

tributary drainages existed during this time (Craig and others, 1955, figs. 21 and 22). One drainage, probably with its source in Mohavia, deposited the conglomeratic sand of the Salt Wash Member in northern Arizona and southern Utah. Pebbles within the Salt Wash Member are dominantly white chert and cherty limestone derived from the Kaibab Limestone, which, therefore, must have been the dominant rock unit exposed at that time in Mohavia. Streams of the other drainage, originating in the Mogollon Highlands, deposited the somewhat arkosic Recapture and Westwater Canyon Members. The uppermost Jurassic Brushy Basin Member of the Morrison was laid down on a gigantic flood plain by sluggish streams that may have flowed generally northeastward into the Colorado Plateau area from the southwestern highlands, which at this time were subdued.

Cretaceous Period

The Mogollon Highlands were restricted at the beginning of Cretaceous time by the northwestward extension of the Cretaceous Mexican (Sonoran) geosyncline into Arizona (fig. 6). Throughout Cretaceous time the highlands were connected with the ancient Mohavia landmass of the Cretaceous Cordilleran geanticline. Uplift appears to have tilted the Mogollon Highlands as a block to the northeast, forming a broad structural slope that extended into the Colorado Plateau. The southern edge of the tilted highland block must have been outlined sharply and had considerable relief; it trended generally west-northwestward across central Arizona and west-central New Mexico and was nearly coincident with the present southern boundary of the Central Mountains province.

Rocks of Early Cretaceous age within the Mexican geosyncline are more than 20,000 feet thick in the central, Douglas-Lordsburg part of the geosyncline, and they thin abruptly along the southern front of the Mogollon Highlands (McKee, 1951, pl. 3A). These deposits, for the most part, are mudstone, arkosic conglomerate, and sandstone, broken by several prominent local unconformities. Other clastic and limestone deposits containing marine invertebrate fossils intertongue with the arkosic material. North of the Mogollon Highlands Lower Cretaceous sedimentation is represented by the Burro Canyon Formation. The Burro Canyon and rocks of equivalent age consist of mudstone, siltstone, and sandstone deposited in a fluvial and lacustrine environment.

Widespread planation followed regional elevation of the Mogollon Highlands area prior to deposition of the Dakota Sandstone. The Dakota and undifferentiated rocks of the Mesaverde Group transect Triassic and Permian strata near Show Low, but near the San Juan River the Dakota rests disconformably on the Morrison and Burro Canyon Formations. Conglomerate containing chert, jasper, and quartzite pebbles was laid down along the main stems of drainages that deposited the fluvial part of the Dakota Sandstone in southern Utah and west-central New Mexico. In general, the Dakota drainage system was similar to that which deposited the Morrison Formation.

The Dakota Sandstone was deposited along the edges of the transgressing Cretaceous seas, which covered much of middle North America and connected the Rocky Mountain geosyncline with the Mexican geosyncline. Regional downwarping was of sufficient magnitude to allow a thick overlap of Upper Cretaceous rocks on the New Mexico and east-central Arizona parts of the Mogollon Highlands (fig. 7). These seas may have extended into central Arizona, perhaps during deposition of the lower part of the Mancos Shale, as indicated by marine

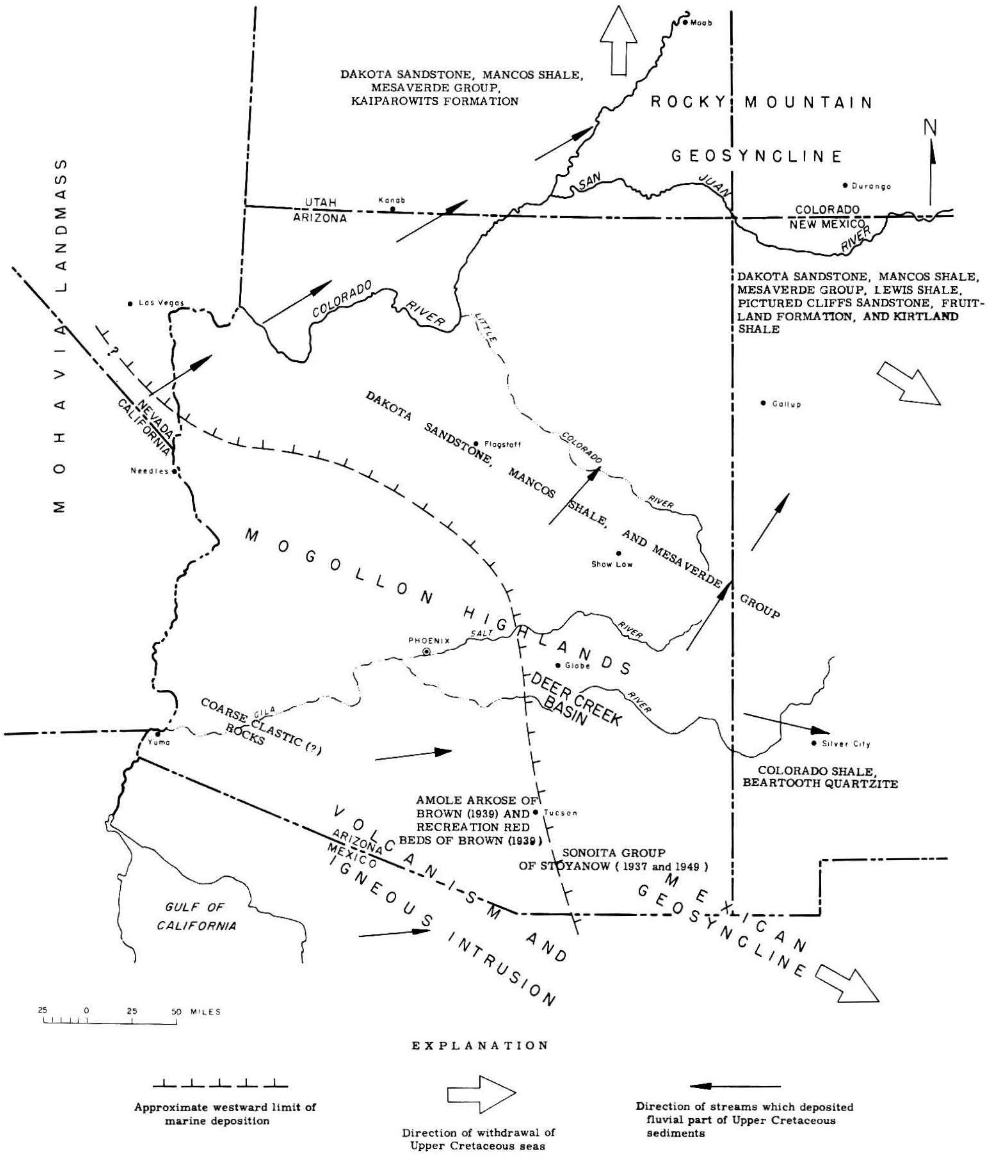


Figure 7. --Map showing the drainage and geologic features during Late Cretaceous time.

fossils found a short distance south of the Colorado Plateau near Show Low. Deposition probably was continuous in all eastern Arizona, and deposits typical of the Colorado Plateau intertongue with those typical of southeastern Arizona. Some evidence of this intertonguing is present in the Deer Creek basin near Globe (Ross, 1925, p. 25-28). During the slow withdrawal of the Upper Cretaceous seas, many transgressions and regressions occurred. These oscillations of the shoreline resulted in complex intertonguing of the continental and near-shore marine Mesaverde Group and the marine Mancos and Lewis Shales (Sears, Hunt, and Hendricks, 1941; Pike, 1947; Repenning and Page, 1956). The widespread distribution of thin sandstone and coal units of the Mesaverde Group and the lack of extensive planation or deep channeling indicate that the Upper Cretaceous sedimentation in northeastern Arizona and northwestern New Mexico was controlled chiefly by continuous but variable regional warping.

Upper Cretaceous sediments in southeastern Arizona and nearby areas, in contrast with correlative sediments to the north, were deposited near their source and were markedly affected by local structural movement and volcanic activity (McKee, 1951, p. 496; Wilson and Moore, 1959, p. 96). The rocks are chiefly continental in origin and consist of sandstone and conglomerate intercalated with marine beds and possibly some volcanic rocks. Rocks in southern Arizona assigned a Late Cretaceous age are the Sonoita Group of Stoyanow (1937 and 1949), Recreation Red Beds of Brown (1939), most of the Amole Arkose of Brown (1939), and scattered remnants of clastic rocks and interbedded flows and tuffs in southwestern Arizona. However, because southwestern Arizona may have been a positive area in much of Late Cretaceous time, Wilson and Moore (1959, p. 94-96) suggested the scattered remnants may be either early Tertiary or Early Cretaceous and older Mesozoic in age.

CENOZOIC GEOLOGY

Renewed regional upwarping and differential uplift of the Mogollon Highlands and adjoining parts of the Colorado Plateau and Basin and Range provinces, now restricted essentially to the Central Mountains province, modified the drainage system which was established near the end of the Cretaceous Period. The Mogollon Highlands were continuous with the Mohavia landmass, forming, during much of Tertiary time, a drainage divide between the Colorado Plateau area and the Basin and Range province. In late Cenozoic time block faulting and later diastrophic movement, centered largely in the Gulf of California region, influenced the development of the lower Colorado River and the Gila River drainages.

The age and correlation of the Cenozoic geologic events in Arizona are dependent to a large extent upon structural, lithologic, and distributary characteristics of the rocks involved, because of the general scarcity of datable fossils in sedimentary deposits. Thus, lithologic similarity or dissimilarity of deposits, amount and type of deformation, association with volcanic rocks, and correlation with the present physiography become critical factors in unraveling the geologic history.

Volcanic rocks form a vital part of the Cenozoic stratigraphic succession in the Mogollon Highlands and nearby regions because of the similar composition and texture of these rocks over wide areas. Volcanic rocks are dated in some places through their association with fossil-bearing sediments; stratigraphic correlation from place to place is based largely on tracing types or groups of similar volcanic rocks, and the following general breakdown of these rocks is used by many workers in the Basin and Range province. Volcanic rocks of Late Cretaceous and early Tertiary age are dominantly andesitic flows and agglomerate and silicic pyroclastic rocks; those of early and middle Tertiary age are composed of andesite, rhyolite, and dacite flows, tuff, and agglomerate; and the late Tertiary and Quaternary volcanic rocks are principally basalt and olivine basalt flows and intrusive rocks (table 1). Therefore, the composition of volcanic layers and of volcanic cobbles and pebbles in sedimentary deposits has a bearing on the stratigraphic position of the deposit. In like manner, the degree and the type of deformation of a deposit are used as an age criterion. Late Cretaceous and early Tertiary rocks are involved in thrust faults and are mildly to moderately metamorphosed in some places. A greenish cast produced by chlorite and epidote is one of the helpful diagnostic features of the typical andesite of the Silver Bell Formation (Richard and Courtright, 1960), and is especially useful for purposes of identification where this rock type is present as cobbles or pebbles in younger sediments.

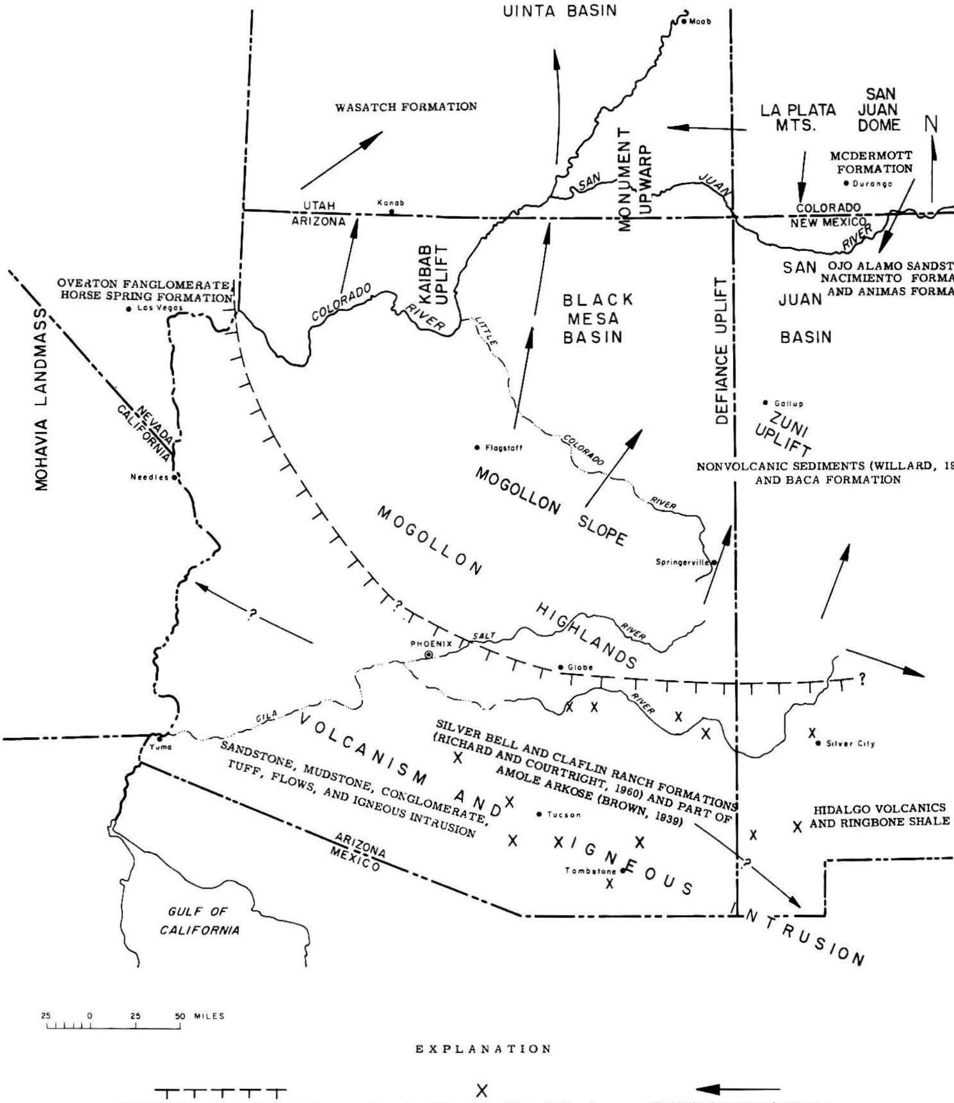
Early and middle Tertiary volcanic and sedimentary deposits are not noticeably metamorphosed, and they are involved in thrust faulting and other compressional features less severe than the faulting affecting the earliest Tertiary rocks. Late Tertiary rocks are involved only in normal faulting and associated tilting, commonly referred to as "block faulting," and displacement along some of these faults is more than 1,000 feet. Deposits of Quaternary age are nearly flat lying and display only moderate tilting accompanied by small-scale normal faults.

Erosional cycles beginning during the latter part of Miocene time are related to the development of the Colorado River system on the Colorado Plateau and in parts of the Mogollon Highlands, but in other parts of the highlands, late Quaternary sediments are the only deposits related to present drainage systems. Table 1 summarizes the erosional, depositional, volcanic, and structural episodes during Cenozoic time in the Mogollon Highlands and nearby areas.

Pre-Colorado River System

The effects of regional upwarping became increasingly prominent during the Late Cretaceous Period and resulted in a complete withdrawal of the seas by the end of the period. The seas in the Rocky Mountain geosyncline withdrew northward into Utah and eastward and southeastward through northern Mexico. Differential uplift and subsidence divided the region into local highs and basinlike structures or troughs in which coarse detrital material accumulated (fig. 8). Basinlike structures may have been present as early as Early Cretaceous time in southern Arizona, but folding that produced basins and uplifts on the Colorado Plateau did not begin until late in the Cretaceous Period and was not completed until about the end of Eocene time.

The earliest rocks of Late Cretaceous and possibly Cenozoic age—comprising arkosic sediments, epidotic and chloritic andesite flows and mudflows, and chaotic breccias—crop out beneath younger lavas and sediments in the southern part of the Mogollon Highlands and to the south. These rocks are grouped in the Silver Bell and Claflin Ranch Formations (Richard and Courtright, 1960) and their equivalents. These units are locally more than 5,000 feet thick and have been proposed as general equivalents of the Hidalgo Volcanics and Ringbone Shale of the Bisbee Group of southwestern New Mexico, the lower unit of the Bronco Volcanics near Tombstone, and the Tucson Mountain Chaos (Richard and



EXPLANATION

Approximate northward extent of rocks of the Silver Bell and Claflin Ranch Formations	X Some localities where Silver Bell and Claflin Ranch Formations of Richard and Courtright (1960), and equivalent rocks are exposed	Probable direction of streams

Figure 8.--Map showing drainage and geologic features during Late Cretaceous and early Tertiary (Paleocene and Eocene) time.

Table 1.--Summary of geological events in the Mogollon Highlands and nearby regions during Cenozoic time.

Age				Erosional and depositional events			Volcanism	Structure
				Colorado Plateau	Mogollon Highlands	Basin and Range province		
QUATERNARY	PLEISTOCENE	MIDDLE AND LATE	Events related to Colorado River	Downcutting and terracing	Downcutting and terracing	Downcutting, terracing, or alluvial deposition	Chiefly basalt	Warping and some movement along normal faults
QUATERNARY	PLEISTOCENE	EARLY	Events related to Colorado River	Downcutting and terracing	Downcutting, terracing, and deposition of basin-fill sediments	Deposition of the basin-fill sediments and formation of pediments		
TERTIARY, LATE	PLIOCENE	LATE	Events related to Colorado River	Formation of Zuni surface and deposition of the upper member of the Bidahochi Formation	Canyon cutting and deposition of sediments containing Pliocene fossils and the deformed gravel	Channel erosion, formation of pediments, and deposition of the deformed gravel, locally may be gradational with sediments above and below		Accelerated upwarping and large-scale normal faulting, formation of many basin and range structures
TERTIARY, LATE	PLIOCENE	EARLY	Events related to Colorado River	Formation of Hopi Buttes surface and deposition of the lower member of the Bidahochi Formation				Regional and local uplift; some normal faulting
TERTIARY, LATE	MIOCENE		Events related to Colorado River	Formation of the Valencia surfacc	Formation of Valencia surface, valley erosion, and deposition of the deformed gravel			
TERTIARY, MIDDLE	MIOCENE / OLIGOCENE		Events not related to Colorado River	Deposition of upper sedimentary unit of Wrucke (1961)	Erosion, deposition of Datil Formation, upper sedimentary unit of Wrucke (1961), and sediments similar to the Helmet Fanglomerate	Erosion, deposition of Helmet Fanglomerate and similar (Pantano Formation of Brennan 1957 sedimentary rocks	Chiefly rhyolite, dacite, and andesite	Thrust faulting and local folding
LATE CRETACEOUS AND EARLY TERTIARY (PALEOCENE AND EOCENE)			Events not related to Colorado River	Deposition in structural basins, including the nonvolcanic sediments of Willard (1959)		Erosion and deposition of Silver Bell and Claflin Ranch Formations of Richard and Courtright (1960) Hidalgo Volcanics and equivalents , formation of Tucson surface	Chiefly andesite some silicic pyroclastic rocks	Formation of uplifts and basins on Colorado Plateau, uplift with thrust faulting in Basin and Range province. Rocks mildly metamorphosed (chlorite, epidote)

Courtright, 1960, p. 2-6) near Tucson. All these rocks overlie the Tucson surface, a prominent erosion surface cut on rocks of Cretaceous and older ages (Kinnison, 1959, p. 50). The relief of the area was apparently irregular and locally fairly rugged, resulting in a rather widespread distribution of the chaotic breccias.

The northern part of the Mogollon Highlands was a gentle plain which sloped northward into the Colorado Plateau area. Sedimentation on the Colorado Plateau in early Tertiary time was centered in the San Juan basin of New Mexico and in the Uinta basin of Utah where several thousands of feet of sediments were deposited, in part by northward- and northeastward-flowing streams that drained the Mogollon and Mohavia Highlands (fig. 8). Evidence that the Mogollon Highlands furnished part of these early Tertiary sediments is contained in the nonvolcanic sediments of Willard (1959, p. 92-95) and in the correlative Baca Formation of probable Eocene age. The nonvolcanic sediments were folded by the same forces that caused the monoclinal structures on the plateau (Akers, 1961, p. 56). Near Springerville, coarse crossbedded conglomerate beds within the nonvolcanic sediments contain pebbles to small boulders of quartzite, granite, fossiliferous limestone, and volcanic pebbles of andesite similar to the andesite of the Silver Bell Formation. All these lithologic types are derived from outcrops which are present only in the Mogollon Highlands. The presence of typical Silver Bell andesite cobbles indicates that some parts of the nonvolcanic sediments are somewhat younger than the Silver Bell types.

Mid-Tertiary geology is dominated by extensive deposits of volcanic rocks of silicic to intermediate composition. One of the largest eruptive centers was in west-central New Mexico and east-central Arizona, where flows, tuffs, and clastic sediments of the Datil Formation formed a volcanic pile more than 3,000 feet thick (fig. 9). This volcanic accumulation formed a drainage barrier in the area east of the Pinaleno Mountains, dividing that which flowed northward into the Colorado Plateau from that which flowed southeastward in southeastern Arizona and southwestern New Mexico. Gravel within the Datil Formation is composed chiefly of fragments eroded from the volcanic units of the formation, but some fragments are quartzitic and igneous types derived from bedrock exposures. Other volcanic sequences were laid down on the southern and western border of the Mogollon Highlands and in the area to the south and west. Clastic sediments were laid down mainly in the areas adjoining the centers of volcanism in irregular troughlike depressions in southern Arizona and along the Arizona-New Mexico State line in the eastern part and north of the Mogollon Highlands.

In southern Arizona the Helmet Fanglomerate (Cooper, 1960, p. 77-89) probably is correlative with the Pantano Formation of Brennan (1957) and with part of the mid-Tertiary Mineta Formation of Chew (1952). Other sediments similar to the Helmet Fanglomerate crop out at several places along the southwestern flank of the Mogollon Highlands and in isolated exposures along mountain fronts elsewhere in southern Arizona. The Helmet Fanglomerate is thrust over other rocks in southeastern Arizona (Cooper, 1961, p. 95), and, as summarized by Heindl (1958, p. 170-172), sediments typical of the Pantano Formation and Helmet Fanglomerate have been affected similarly by thrusting, tilting, and large-scale normal faulting. The Whitetail Conglomerate (Ransome, 1904) near Ray is included with sediments typical of the Helmet Fanglomerate, owing to the relation of the conglomerate with an overlying dacite flow and the lack of basaltic gravel in the conglomerate, as reported by Heindl (1958, p. 101). Cooper (1961, p. 17-33) suggests equivalence between the Helmet and the series of andesite flows and intermediate to silicic tuffs of early and middle Tertiary

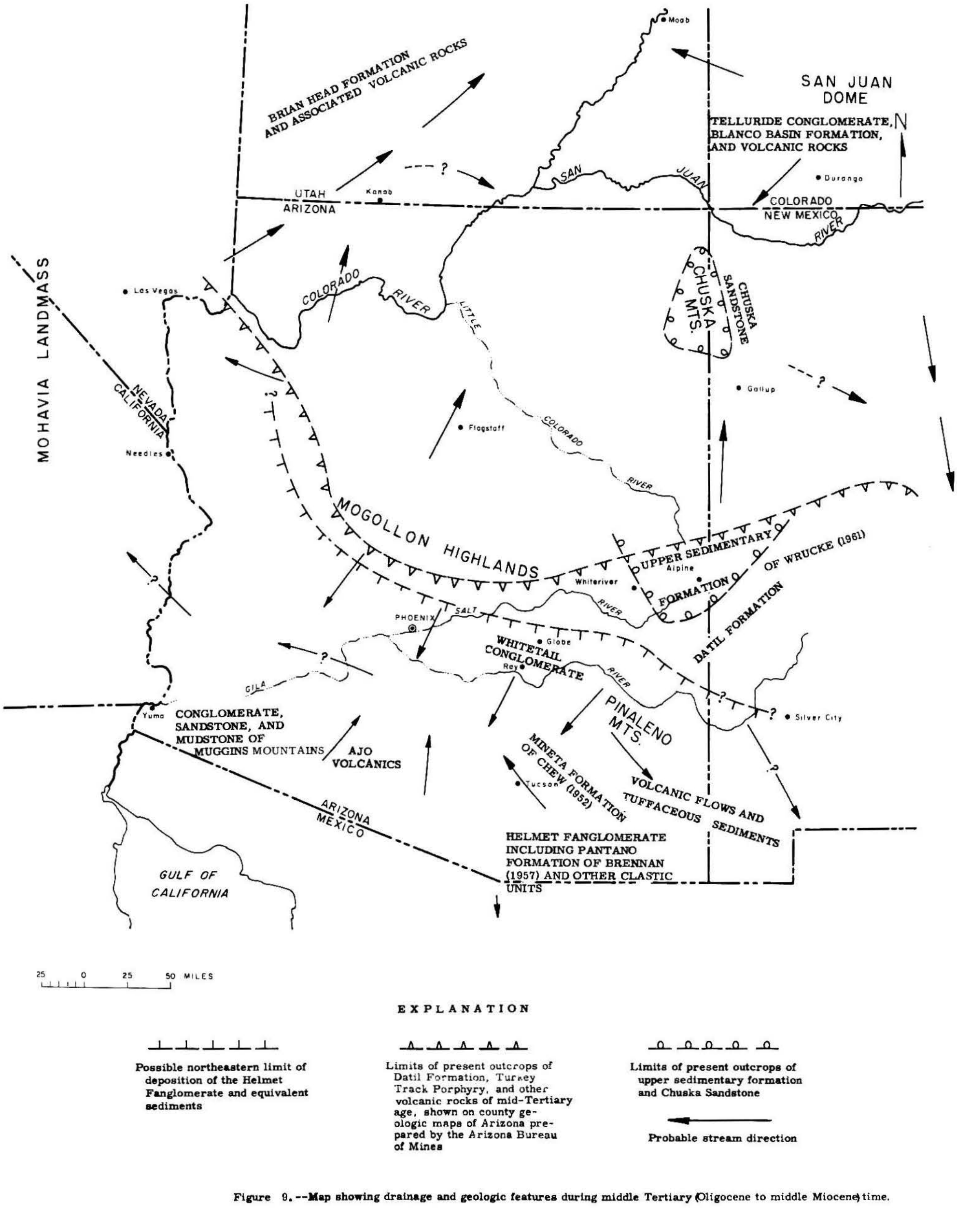


Figure 9.--Map showing drainage and geologic features during middle Tertiary (Oligocene to middle Miocene) time.

age because of the inclusion in all these units of an unusual series of porphyritic andesite flows termed the "turkey-track porphyry." The upper part of the Baca Formation and nonvolcanic sediments may be equivalent to the lower parts of these rocks.

In the eastern part of the Mogollon Highlands, at least 1,200 feet of light-colored large-scale crossbedded sandstone and thin-bedded siltstone and tuff was deposited in the Alpine-Whiteriver area and to the east in New Mexico (fig. 9). Near Alpine these sediments overlie the Datil Formation and were called informally the "upper sedimentary formation" by Wrucke (1961, p. 15-23), but in New Mexico they were included in the Datil Formation (Willard and Weber, 1958).

Near Whiteriver light-colored sediments lighologically similar to the upper sedimentary formation rest on rocks of Permian age and underlie basalt flows and tuffaceous sediments of the White Mountains volcanic field. Conglomerate at the base of the light-colored sediments consists of rounded pebbles to small boulders composed chiefly of limestone, volcanic rocks from the Datil Formation, quartzite, and fine-grained siliceous igneous rocks.

Lithologic similarities, particularly heulandite cement, and the eolian and fluvial structure of the upper sedimentary formation suggest a correlation between it and the Chuska Sandstone to the north in the Chuska Mountains (Wrucke, 1961, p. 20-21). The Chuska Sandstone, more than 1,500 feet thick, consists of an upper crossbedded sandstone unit of probable eolian origin and a lower silty sandstone and siltstone unit (Deza Formation of Wright, 1956) of fluvial origin (Repenning and Irwin, 1954, p. 1821-1826; Wright, 1956, p. 418-419). The Datil Formation, Chuska Sandstone, and other sedimentary and volcanic rocks of this general age must have formed a thick mantle, largely removed by later erosion, over much of the Colorado Plateau. The upper surfaces formed on these deposits at altitudes between 7,000 and 9,000 feet predate the Colorado River drainage system, and may well represent the "Miocene surface" of Gregory (1947, p. 704).

Colorado River System

Major changes occurred during the late part of mid-Tertiary (Miocene) time, and accelerated regional upwarping resulted in the development of the ancestral stages of the Colorado River system and in the outlining of the physiographic provinces of the Southwest. The renewed rising of the Mogollon Highlands and the formation of some of the basin-and-range features accompanied the upwarping, but there is no evidence of strong differential structural movement in the Colorado Plateau during this time. Mid-Tertiary thrust faulting has been noted in southeastern Arizona and in west-central Arizona near the Colorado River (Wilson and Moore, 1959, fig. 12). No notable thrusting took place within the Mogollon Highlands, but early movement along some of the large normal faults and some folding along the western edge of the Colorado Plateau may date from this period. In the nearby part of southern California, deformation and volcanism during the late part of Miocene and during Pliocene time caused the formation of local, interior-drained basins in the Mohavia Highlands (Reed, 1933). Thus, there was general widespread upwarping within the Mogollon Highlands and Colorado Plateau regions of Arizona and New Mexico, and intense deformation in many parts of the Basin and Range province.

Early Stages

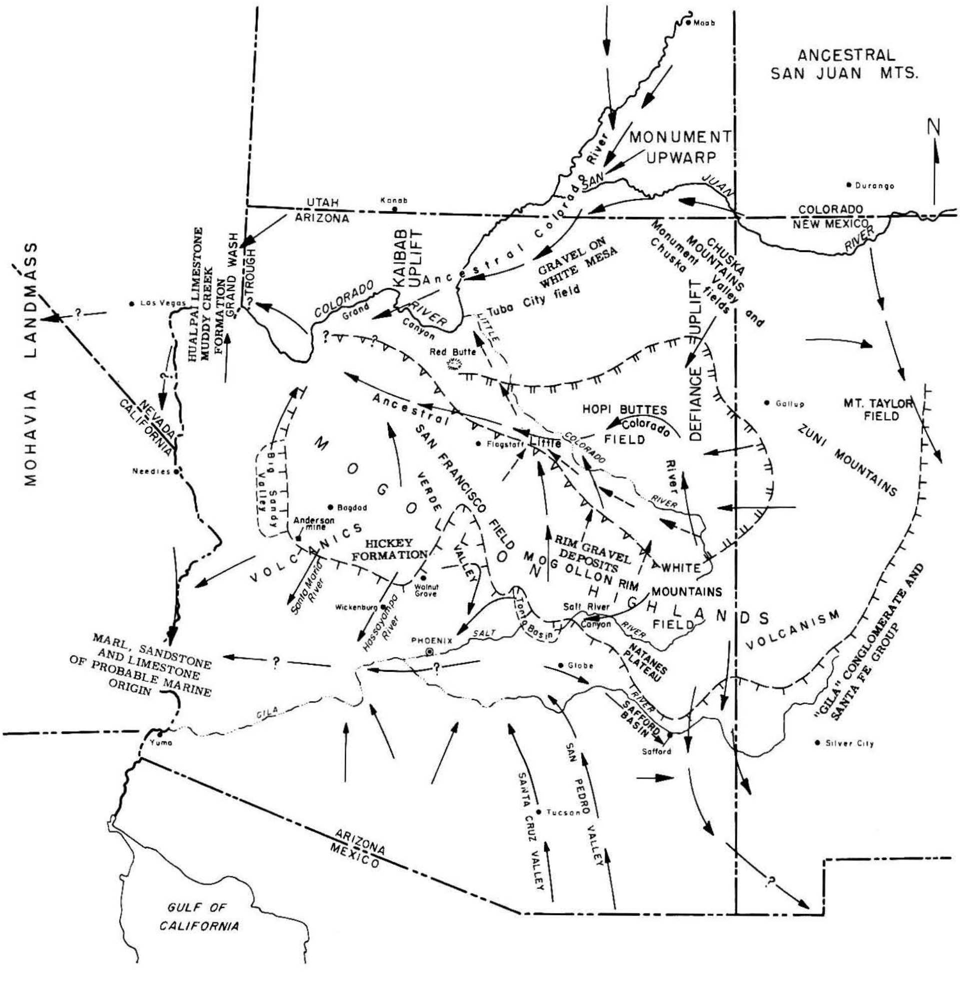
The initial stage of the Colorado River system is represented by the Valencia surface, whose remnants are present in the southern part of the Colorado Plateau (Cooley and Akers, 1961, p. 244-245). Differential uplift of the Mogollon Highlands and of the Zuni-Defiance-Monument uplift area, accompanied by early basaltic eruptions in some of the volcanic fields, restricted the ancestral systems of the Colorado and Little Colorado Rivers approximately to their present positions. The Valencia surface is present at altitudes of more than 7,500 feet beneath basalt flows capping Red Butte near the Grand Canyon and on other buttes and small mesas in the White Mountains volcanic field. The general trend of the drainage on the Valencia surface was west-northwest in the Little Colorado River area and southwestward in the Colorado River area, as reconstructed from the remnants of the surface and from the stream patterns on the following Hopi Buttes and Zuni surfaces (fig. 10). The eastern and northern parts of the Mogollon Highlands were then drained to the Colorado, and a volcanic pile formed by the Datil Formation maintained a drainage divide near the Arizona-New Mexico State line.

The Valencia surface predates the cutting of the Mogollon Rim, Grand Canyon, Verde Valley, Tonto basin, and Salt River Canyon. Stripping during its formation removed as much as 2,000 feet of the previously deposited Tertiary sediments and a considerable amount of the Mesozoic rocks on the Colorado Plateau and in the Mogollon Highlands.

Accelerated downcutting formed the Hopi Buttes (Gregory, 1917, p. 121-122) and Zuni (McCann, 1938, p. 260-279) surfaces in late Miocene and Pliocene time and entrenched the ancestral Colorado system to an average depth of about 1,200 feet below the level of the Valencia surface. However, cutting was interrupted temporarily in the ancestral valley of the Little Colorado River by the deposition of the Bidahochi Formation (fig. 10). The Bidahochi Formation was divided into a lacustrine and fluvial lower member, a volcanic middle member, and a fluvial upper member (Repenning and Irwin, 1954, p. 1821-1826). Fine-grained sediments which are lithologically similar to the lower member of the Bidahochi in the Hopi Buttes area crop out beneath basalt flows near Flagstaff in the structural saddle between the Kaibab uplift and the Mogollon Highlands.

Contours drawn on the base of the Bidahochi Formation and lateral equivalents indicate that the Defiance uplift-Chuska Mountains-Zuni Mountains area formed a divide between the ancestral Little Colorado system and the drainage in the San Juan Mountains area (Cooley and Akers, 1961, fig. 237.3). The Little Colorado may not have been connected with the Colorado River in the area upstream from the Grand Canyon until about late Pliocene time, during the formation of the Zuni erosion surface. The contours indicate also that part of the "rim gravel" near the Mogollon Rim and some of the volcanic rocks and clastic sediments in the San Francisco volcanic field are a lateral equivalent of the Bidahochi Formation. The rim gravel was derived from the south (McKee, 1951, p. 498) and is composed of coarse debris eroded from the Precambrian and Paleozoic rocks in the central part of the Mogollon Highlands.

During late Pliocene time, eruptions of the Hopi Buttes volcanic field (middle volcanic member of the Bidahochi Formation) formed a dam across the ancestral valley of the Little Colorado River. Upstream from this volcanic barrier the upper member of the Bidahochi Formation was deposited. The



EXPLANATION

Approximate area where deformed gravel deposits are present in the Basin and Range province and in the Mogollon Highlands; locally includes fine-grained deposits

Approximate northward and eastward distribution of the Bidahochi Formation

Approximate northward distribution of the rim gravel deposits

Direction of stream during early part of Hopi Buttes-Zuni cycle

Direction of stream during late part of Hopi Buttes-Zuni cycle in Little Colorado River area

Figure 10.--Map showing drainage and geologic features during late Tertiary (late Miocene and Pliocene) time.

volcanism also diverted the ancestral Little Colorado River southward around the Hopi Buttes field to nearly its present position. In places, the upper member of the Bidahochi filled the old valley and overlapped for short distances on broad terraces which represented the level of the Valencia surface.

Along the southern border of the Mogollon Highlands and in southern Arizona, generally coarse-grained gravel, tilted and moderately deformed by normal faulting, is exposed along the flanks of the various mountain ranges. This gravel, informally termed "deformed conglomerate or gravel" by Davidson (1961, p. 151) for exposures in the Safford basin, was deposited during the general time represented by the Valencia, Hopi Buttes, and Zuni surfaces on the Colorado Plateau and indicates a major stage in Cenozoic deposition in Arizona. The deformed gravel occurs at the top of a thick section of basalt flows of mid-Tertiary age, and in the Safford area and elsewhere the flows and gravel are interbedded. This gravel overlies the early and mid-Tertiary andesitic flows, tuffs, and correlative deformed deposits similar to the Helmet Fanglomerate and underlies the relatively undeformed basin-fill sediments. The gravel is part of the type section of the Gila Conglomerate of Gilbert (1875); it is generally equivalent to the Mimbres Conglomerate of Hernon, Jones, and Moore (1953) and to part of the Santa Fe Formation in New Mexico. Thick sections of the deformed gravel are exposed in the Safford basin, in the Aravaipa, San Pedro, and upper Santa Cruz Valleys, in the Big Sandy Valley, and near Wickenburg between the Gila River and the Mogollon Highlands. In southwestern Arizona, where dissection has not been so severe, the gravel is covered generally by younger-fill materials. In the Mogollon Highlands gravel similarly deformed as that in the Basin and Range province is exposed near Silver City, Globe, and south of Bagdad. Dips in the gravel beds are usually away from the larger mountain masses, and in most exposures their composition is reflective of the rocks of the nearby highlands.

Sediments correlative with the deformed gravel and the Bidahochi Formation were deposited in valleys throughout the Mogollon Highlands. These deposits and associated basalt flows crop out in about one-fourth of the highland area, and, judging from their association with widely scattered fossil localities, are of Pliocene age. The oldest dated deposit is near Walnut Grove and "***contains diagnostic fossils of lower Pliocene age" (Lance, 1960, p. 156). Other deposits containing fossils of Pliocene age are in the Tonto basin, Big Sandy Valley, and near Anderson mine (Lance, 1960, p. 156).

Basaltic volcanism was active throughout the Mogollon Highlands and formed barriers that blocked drainages and allowed local accumulations of sediments which generally are tuffaceous. In many places, sequences of interbedded tuff and basalt flows are more than 1,000 feet thick. Locally, gravel beds composed of granite, schist, gneiss, and quartzite underlie and are interbedded with the volcanic rocks. These deposits include the Hickey Formation (Anderson and Creasey, 1958, p. 56-59) to the west of the Verde Valley, the Dry Beaver Creek rocks of Twenter (1961, p. 153-155) in the Verde Valley area, and many unnamed deposits throughout the area. Many deposits have been preserved in the ancestral Salt River drainage in the reach above Salt River Canyon. All these deposits contain basaltic gravel, underlie basalt flows, and are associated directly or indirectly with the thick basaltic sequence that forms prominent escarpments between the White Mountains and the Natanes Plateau.

As regional structural movement elevated the area of the Mogollon Highlands as a unit, the uplift produced irregular structural disturbances in the highlands and in the adjoining Basin and Range province. Normal faulting, aided in places by differential downwarping and upwarping, formed zones of weakness along which stream erosion excavated the main valleys. These include the Grand Wash trough, Big Sandy Valley, Verde Valley-Tonto basin-Safford basin, and other valleys. A major pulse in the structural movements must have occurred during the late part of the Pliocene Epoch, as indicated by the faulted Pliocene fossil-bearing beds, basaltic rocks, the deformed gravel, and the small folds in the Bidahochi Formation. These movements were virtually completed by Pleistocene time and are often referred to as the basin-and-range block-fault structures. The younger basin-fill and terrace deposits containing fossils of Pleistocene age are essentially undisturbed.

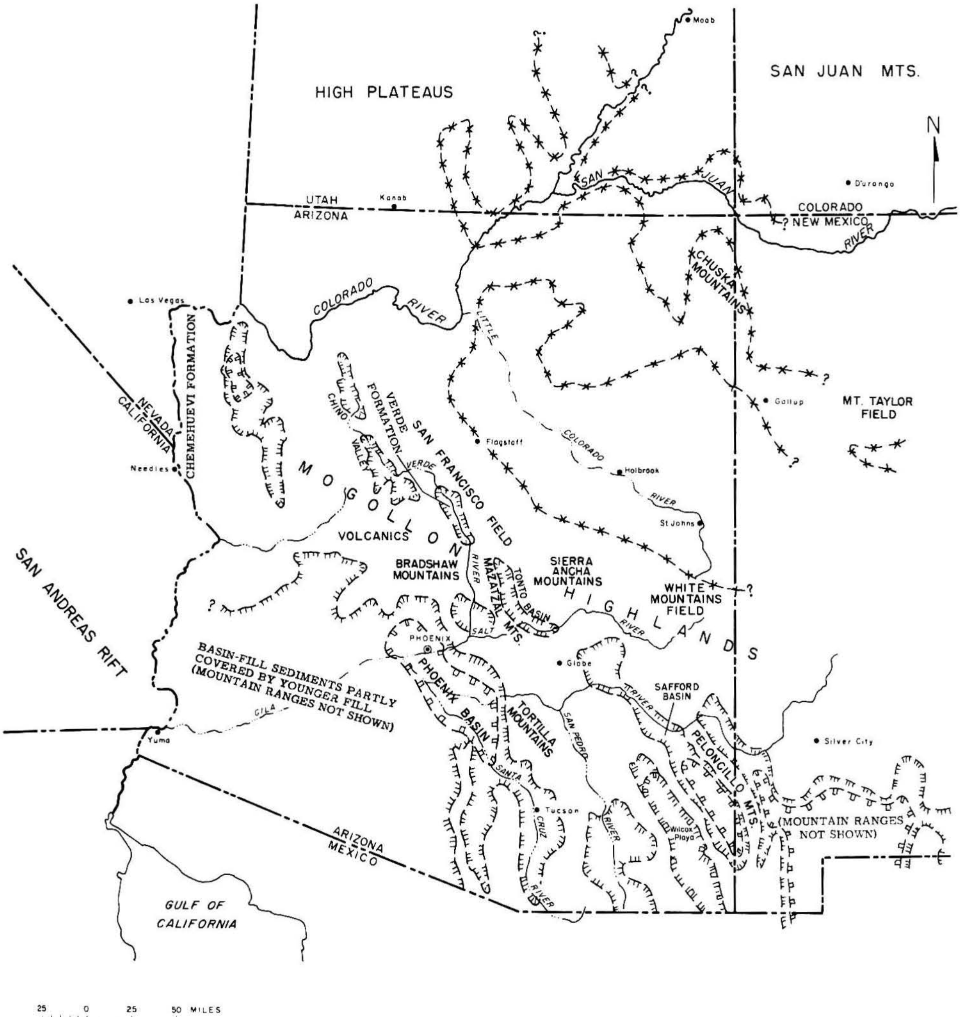
Throughout the early stages of the Colorado River system, the Mogollon Highlands stood as a barrier between the ancestral Little Colorado and the Salt-Gila drainages. During the formation of the Valencia and Hopi Buttes surfaces, the Little Colorado River drained most of the Mogollon Highlands, but progressively the Salt and Gila Rivers, by headward cutting and capture, diverted nearly all this drainage southward. The Mogollon Highlands furnished sediments to all the deposits laid down around its flanks on the Colorado Plateau and in the Basin and Range province. These deposits may have formed a nearly continuous alluvial apron around the mountains before incisement of the canyons and deep valleys. During the formation of the Zuni surface (late Pliocene) on the Colorado Plateau, the streams were entrenched in the Grand Canyon, Verde Valley, Tonto basin, and Salt River Canyon, and the Mogollon Rim was outlined in its present physiographic form. In southern Arizona, deep trenching that accompanied the faulting excavated valleys, which then were partly filled with younger sediments.

What happened to the ancestral Colorado River downstream from the Colorado Plateau is an open question. The river may have drained southward approximating its present course, drained westward, or may have been imponded northeast of the Mogollon-Mohavia Highlands area. Limestone and clastic sediments containing fossils of brackish-water marine origin (Ross, 1922, p. 189-195) crop out at altitudes of 600 to 800 feet near the Colorado River in southwestern Arizona and eastern California and may have been deposited in an embayment connected with the Gulf of California (Wilson, 1933, p. 31-32; Hamilton, 1960, p. 276-277). This marine embayment may have influenced erosion and sedimentation along the southwestern flank of the Mogollon Highlands and in the lower reaches of the ancestral Colorado and Gila Rivers.

Late Stages

By the beginning of Quaternary time, all drainages of the Colorado Plateau and Mogollon Highlands were established in their present courses. Headward-cutting tributaries from the south had completely isolated the Colorado Plateau drainage from the central part of the Mogollon Highlands, and the Mogollon Rim extended uninterrupted from the White Mountains to beyond the Verde Valley (fig. 11). From this time on, structural movements in the Mogollon Highlands had little effect on erosion and sedimentation in the Little Colorado River area.

Quaternary time on the Colorado Plateau is represented by as many as seven terraces along the Colorado River and in the lower reaches of the Little Colorado River. Terrace deposits overlie the Black Point surfaces (Gregory, 1917, p. 120) of early Pleistocene age and the Wupatki surfaces (Childs, 1948,



EXPLANATION

Main areas of basin-fill sediments and equivalent sediments of early Pleistocene age

Area where gravelly deposits overlie the Black Point and Wupatki surfaces, and their lateral equivalents on the Colorado Plateau

Main areas of alluvium of late Pleistocene age

Figure 11.-- Map showing drainage and geologic features during Quaternary time.

p. 379-381) of middle and late Pleistocene age. Mapping of the terraces over an area of about 35,000 square miles has shown that their formation was controlled by regional events. The terrace deposits are as much as 200 feet thick and are composed of gravelly sediments derived from the sedimentary bedrock, volcanic rocks, and the reworking of older gravel. Near Holbrook the present valley of the Little Colorado River was excavated about 800 feet below the base of the Bidahochi Formation (Hopi Buttes surface). Downstream the cutting was more severe, but upstream from St. Johns it was less than 200 feet.

Large-scale and local structural movements of the Mogollon Highlands and surrounding regions during Quaternary time also controlled sedimentation and erosion in the Salt-Gila River system, and in general, uplift in southern Arizona and New Mexico did not keep pace with uplift of the Mogollon Highlands. Differential movement is indicated by a general depression of the area centering in Phoenix, which is structurally lower than the surrounding regions. Much of the structural movements in southwestern Arizona in Quaternary time may be associated with downfaulting in the Gulf of California area (Eardley, 1951, p. 460-473) and with the formation of the San Andres rift.

In early Quaternary time, thick accumulations of generally fine-grained alluvium were laid down in most of the valleys of the Basin and Range province and along the southwestern flank of the Mogollon Highlands. This alluvium, often called erroneously "lake-bed" deposits, is referred to informally as basin fill. The basin-fill sediments are more than 1,500 feet thick and constitute the bulk of the valley fill exposed in the Basin and Range province. Most of the sediments are derived locally and consist of stream-deposited gravel, sand, and clay interbedded with lesser amounts of lacustrine clay and limestone. Probably correlative with the basin fill is the Chemehuevi Formation, which filled canyons along the Colorado River (Longwell, 1960, p. 16-17).

Reconstruction of drainage patterns from the terrace levels, the types of deposition, and the association with basaltic volcanism suggest that in the reaches upstream from Phoenix, the ancestral drainage of the Salt River predates that of the Gila River. By late Pliocene time the Verde River seems to have been a south-flowing tributary to the Salt River in the Verde Valley area. The headward extension of the Salt River east of Tonto basin essentially was completed by Quaternary time. The upper part of the Gila River system, however, seems to have developed later, and, based on the variation in the erosion and alluviation within the several valleys, its development was by headward capture and diversion of drainages that previously flowed southward and southeastward from the Mogollon Highlands. The amount of erosion along the Gila River and lower reaches of tributary valleys is greater in the area between the Tortilla and Peloncillo Mountains, where downcutting has been more than 1,000 feet. It seems likely that the Santa Cruz and San Pedro Rivers were integrated as part of the Gila system during early Pleistocene time or before, but the Safford basin and upstream areas were not connected with the Gila until the early part of middle Pleistocene time. This diversion of the drainage in the Safford basin terminated the deposition of the basin-fill sediments, which contain vertebrate fossils of early and early-middle Pleistocene age (Wood, 1960, p. 141-143). At the present time, north-flowing tributary streams of the Gila River are eroding headward and dissecting the northern part of the broad alluvial valleys east of the San Pedro River in Arizona and New Mexico.

Erosional-depositional conditions of early Quaternary time, owing to faulting and to volcanic damming of drainage courses, were extremely variable within the Mogollon Highlands. As a result, fine sediments (Verde Formation) were laid down in the Verde Valley, and gravelly sediments were deposited in the Tonto basin and in places in the Chino Valley area. Erosion was predominant in the area above Salt River Canyon and in most of the headwater reaches of streams elsewhere. However, terrace deposits in these reaches are more than 100 feet thick.

In the Basin and Range province, alluvial deposition during middle and late Quaternary time was concentrated chiefly in the troughlike depression in the Phoenix basin, in a considerable part of southwestern New Mexico, and in isolated basins elsewhere in Arizona (fig. 11). In the Mogollon Highlands and in the more rugged parts of the Basin and Range province, prominent terraces were formed along the Santa Cruz, San Pedro, Verde, Salt, and Gila Rivers and other streams. The episode of terracing exhumed many large pediments overlain by the basin-fill sediments and the deformed gravel. In southeastern Arizona and southwestern New Mexico, cutting and the formation of terraces have not been extended far upstream from the main stem of the Gila River, except along the San Pedro and Santa Cruz Rivers. Alluviation and only slight terracing occurred in the valleys of southwestern Arizona.

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