ROCKY MOUNTAIN SECTION - S.E.P.M.
CENOZOIC PALEOGEOGRAPHY OF WEST-CENTRAL UNITED STATES
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CENOZOIC PALEOGEOGRAPHY OF ARIZONA

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ABSTRACT

The Cenozoic paleogeography of Arizona is interpreted from the sedimentary and volcanic strata throughout the state. Paleogeographic features such as mountains, plateaus, depositional basins, and drainage systems are interpreted within the constraints of known structural features of Laramide age, and in some places, the depth of erosion into the pre-Cenozoic basement rocks. The absence of Paleocene sediments and the pronounced unconformity beneath Cenozoic rocks attests to an epeirogenic uplift of the region during the Laramide orogeny. This uplift was most pronounced in central and western Arizona. The resultant erosion produced a beveled surface that cut deeply into Precambrian rocks of central Arizona and removed much of the Mesozoic cover of the future Colorado Plateau. Paleocene drainage systems transported the sediments of that age northward to the Uinta basin of Utah and eastward to the San Juan basin of New Mexico, along the downwarped Coconino and Baca-Eager basins that were formed as a synclinal trend adjacent to the Mogollon Highlands. The northward regional drainage was controlled by the Sevier foreland basin in Utah.

During the Paleocene and Eocene, compressional deformation of the Laramide orogeny uplifted the Rocky Mountains, which interrupted eastward drainages and converted the Colorado Plateau to a very large internally drained basin during the Eocene. It was bounded on the west by the Sevier thrust belt, on the north by the Uinta uplift, on the south by the Mogollon Highlands and by the Rocky Mountains to the east. That same deformation created numerous north-trending anticlinal and synclinal folds, thereby converting the Colorado Plateau into a synclinorium. These interior folds controlled the development of drainage patterns throughout the remainder of the Tertiary.

Eocene strata on the southern Colorado Plateau are typically coarse-grained, well-sorted conglomerates, with clasts of Precambrian igneous and metamorphic rock whose provenance was the Mogollon Highlands of central and southern Arizona. These strata were deposited in elongate synclinal and erosional valleys north of the Mogollon Highlands by streams that flowed northward into the early Tertiary Coconino and Baca-Eager basins on the southern margin of the Colorado Plateau. The coarse clastics were deposited at the southern margins, and fine-grained clastic and carbonate sediments accumulated in the more distal, northern parts of the basins. Drainage patterns were controlled by Laramide anticlinal uplifts and synclines.

In southern and western Arizona, Paleocene volcanic rocks are common, but no sediments of Paleocene or Eocene age are known. Eocene volcanic rocks are rare in Arizona. Oligocene sediments and volcanics occur in uplifted fault blocks of present-day mountain ranges and in the subsurface of several sedimentary basins. These sedimentary rocks include coarse-grained, angular, poorly-sorted redbeds that were deposited as fanglomerates adjacent to local highs that were formed by Laramide and middle Tertiary orogenesis. Fine-grained clastic, carbonate, and evaporite sediments are intercalated with those basin margin fanglomerates in some areas, suggesting deposition in the center of closed basins. Late Oligocene-Early Miocene strata include fanglomerates and fine-grained fluvial and lacustrine sediments with clasts and flows of silicic to intermediate volcanic rocks reflecting the onset of extensive volcanism and structural warping of the mid-Tertiary orogeny. Middle Miocene sediments and volcanics were affected by low-angle normal faulting, subsequent folding, and unroofing of metamorphic core complexes.

Late Miocene-Pleistocene sedimentary and volcanic rocks are generally confined to basins that coincide with modern valleys throughout the state. Late Miocene to Holocene strata in the Basin and Range Province were deposited in normal-fault bounded extensional basins initiated by the Basin and Range disturbance. In southern Arizona basin deposits typically exhibit gradation from marginal fanglomerates to fine-grained clastic, carbonate, and evaporite sediments in the centers of closed basins. By late Miocene time, the integrated drainage system of the Gila, Salt, Verde and other tributaries to the lower Colorado River had developed, and dissection of the higher basins (e.g., Chino Valley, Verde, Tonto, and Safford basins) had begun in response to the lowered base level established by the opening of the Gulf of California in the late Miocene. The Pliocene-Pleistocene paleogeography of Arizona was similar to present topography except for a few Holocene volcanic mountains and increased dissection of eroded stream valleys.

INTRODUCTION

Nature of the Stratigraphic Record

Locations of sedimentary basins, drainage systems, and source areas shown on the maps (Figs. 2-7) in this paper have been interpreted from scattered occurrences of Tertiary marine, lacustrine, and fluvial sediments and their relationships to Laramide and subsequent structural and topographic features. The record varies from sparse occurrences of Eocene and Oligocene sedimentary rocks to common and well-preserved Miocene and Pliocene deposits. Chronological control is also quite variable and is based on isotopic dating of intercalated volcanics and paleontological correlations (Fig. 1).

The areal extent of Paleogene basins and drainage systems is highly interpretive because the deposits have been subsequently deformed by middle Miocene tectonic events and by younger Basin and Range extensional tectonics. They also have been largely removed by erosion or covered by younger deposits. The Paleogene deposits of southern and western Arizona are found only in exposed fault blocks of present-day mountain ranges or in deeper portions of wells drilled beneath the Neogene sedimentary and volcanic fill of modern basins. Some Paleogene units are precisely dated by isotopic ages on interbedded volcanics or by mammal fossils. The ages of other Paleogene rocks are loosely constrained by the unconformable relationships with older rocks and by degree of structural deformation.

Source areas for Paleogene strata are poorly known because outcrops are limited and because very few detailed measured sections, facies analyses, or paleogeographic analyses have been done. The coarse-grained fluvial strata were probably derived from adjacent highlands that are not clearly definable because they were subsequently disrupted by middle and late Tertiary tectonic events. Many of the Tertiary units, particularly those of Paleogene age, consist of texturally immature alluvial fan deposits that accumulated adjacent to active fault scarps or near elevated areas that were formed by volcanism, plutonism, or tectonism. Fine-grained clastic and chemical deposits are also present, although facies relationships are difficult to analyze because of the small lateral extent of preserved outcrops.

Source areas for Neogene strata are more obvious because the facies relationships are consistent with present topography. Fine-grained clastic, biogenic, and/or chemical strata typically occur in the central parts of the basins and grade laterally to fanglomerates at the basin margins. Most of the fine-grained materials of the basin-center facies are typically buried beneath younger basin fill sediments and are not commonly exposed. Some basins have been dissected by Quaternary erosion, thus exposing the earlier basin-center facies. A few closed basins remain undissected.

Regional Setting

Arizona is divided into two distinct structural-physiographic provinces--the Colorado Plateau Province to the north and the Basin and Range Province to the south, with a narrow Transition Zone in between. While the whole state was affected by epeirogenic uplift in late Cretaceous time, these two regions responded differently to Laramide and Tertiary tectonism, presumably due to differences in thickness and composition of the crust, which resulted in different types of Laramide structural features and Cenozoic sedimentary basins.

The Laramide structures on the relatively stable Colorado Plateau were formed by subtle structural warping or monocline growth, which controlled the development of drainage systems and subsequent erosion. Laramide uplifts disrupted the pre-Laramide regional drainage patterns that flowed eastward from the Sevier thrust belt in Nevada and northward from the Mogollon Highlands of central Arizona (Cooley and Davidson, 1963), into the coastal plain and the Cretaceous Western Interior Seaway that occupied northern Arizona. Structural features in the Transition Zone and Basin and Range Province of southern and western Arizona were formed by more intense structural deformation. There, Cenozoic deformation began with Laramide regional uplift, plutonism, volcanism and thrusting; continued with mid-Tertiary folding, faulting and volcanism; and culminated with late-Tertiary extensional tectonics. As a result of these differences in structural deformation, only a few Cenozoic sedimentary basins were formed on the Colorado Plateau, while numerous Cenozoic basins were formed in the Transition Zone and southern and western Arizona.

The locations of Cenozoic sedimentary deposits (some with intercalated volcanics) are shown on a series of paleogeographic maps (Figs. 2-7) that depict successive time intervals. The precise ages of many of these units are not known, and many of them span more than one Tertiary epoch. The sedimentary basins were formed and defined by episodes of crustal deformation and erosion, including the Laramide orogeny (Late Cretaceous to late Eocene); mid-Tertiary orogeny (late Eocene to middle Miocene); and the Basin and Range disturbance (middle Miocene the present).

The stratigraphic units that were deposited in basins formed by these tectonic events tend to span the times of deformation, and are not limited to the epochs of the standard Cenozoic time scale. For this reason, the mapped intervals used herein reflect the times of basin formation, i.e., Paleocene-middle Eocene (Fig. 3), late Eocene-middle Oligocene (Fig. 4), late Oligocene-middle Miocene (Fig. 5), late Miocene to early Pliocene (Fig. 6) and late Pliocene-Recent (Fig. 7) rather than epoch boundaries. Volcanic rocks from many stratigraphic units have been dated and their age is used to relate the stratigraphic units to epoch subdivisions of the standard Cenozoic time scale of Palmer (1983) (Fig. 1).

Age of Sedimentary Rocks

Isotopic dating of intercalated volcanic rocks is the most useful technique for dating Cenozoic sedimentary rocks. Numerous dates published during the past few years, have provided the chronologic control necessary for our interpretation of the

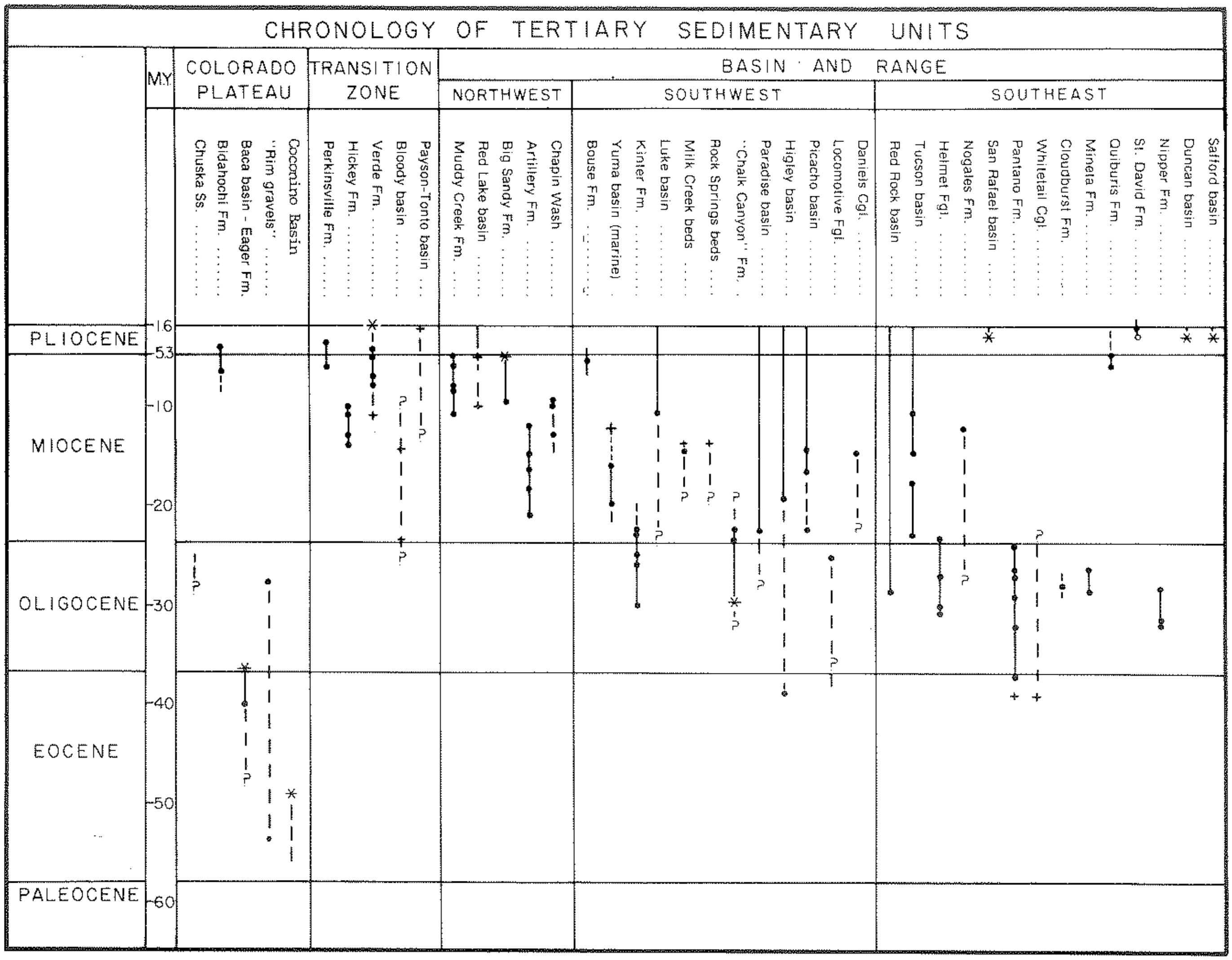
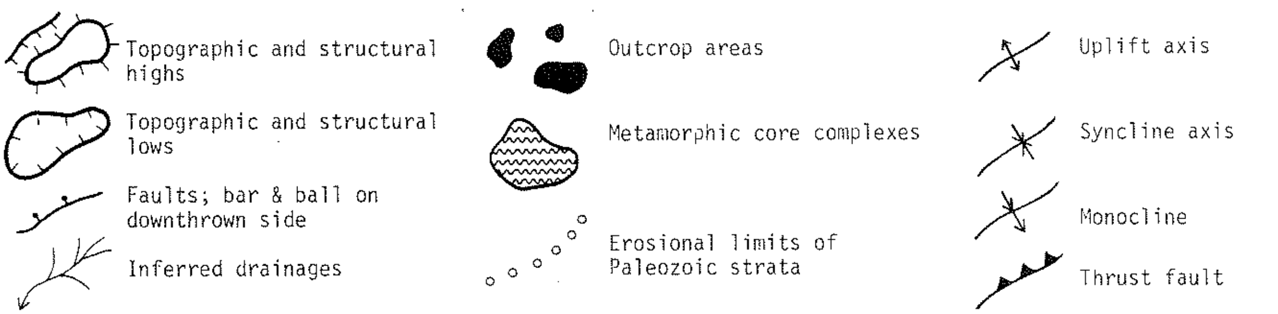


Figure 1: Correlation of selected Tertiary stratigraphic units and basin-fill sequences in Arizona. The shifting of depocenters through the Tertiary is illustrated by Eocene deposition in the Colorado Plateau area, Oligocene deposition in southern Arizona and late Miocene-Pliocene deposition across the state (modified from Nations and others, 1982).

o - isotopic date; * - paleontological age; + - lithologic correlation.

EXPLANATION OF SYMBOLS ON MAPS 2 - 6



Uplifts: D=Defiance; M=Monument; K=Kaibab; CC=Circle Cliffs; Z=Zuni; S=Sedona arch; CM=Chuska Mts.

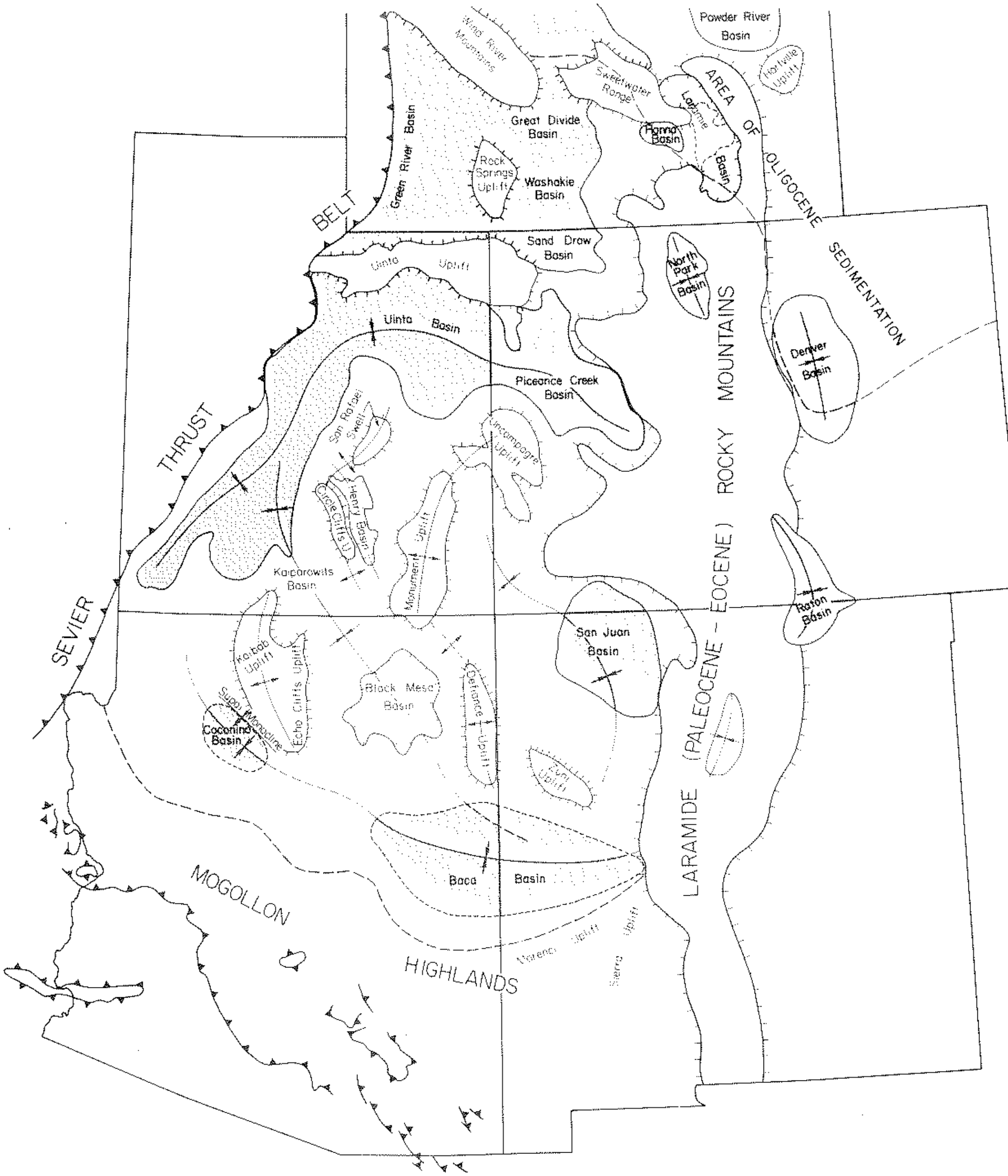


Figure 2: Late Cretaceous to Eocene tectonic features of the Colorado Plateau synclinorium. The peripheral uplifts (Sevier thrust belt, Mogollon Highlands, Rocky Mountains and the Uinta uplift), were formed by thrusting and/or vertical uplift by compression from the west and south. Foreland downwarping occurred in a concentric pattern, inside the uplifted periphery. The northeasterly compression warped the interior of the area into several large northwest-southeast anticlines and synclines, that constrained the development of drainage patterns throughout the Cenozoic. Eocene depositional basins are indicated by the shaded pattern and are restricted to the peripheral downwarps. Oligocene sediments are absent from the synclinorium, probably indicating uplift at that time with drainage towards the Oligocene depositional area east of the Rocky Mtns. in Colorado, Wyoming and Nebraska.

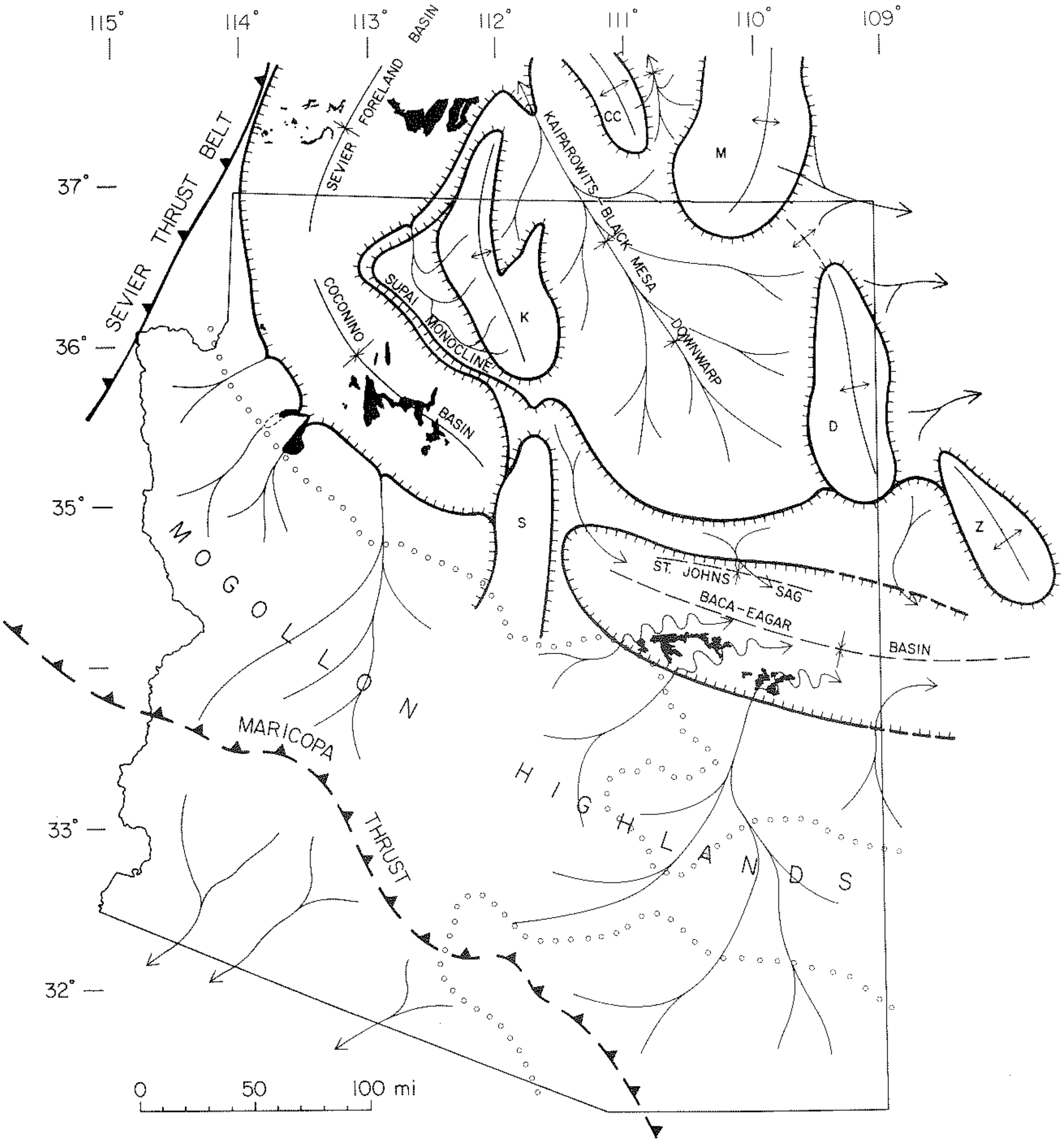


Figure 3: Paleocene to Middle Eocene Paleogeography of Arizona. The dominant physiographic features at this time are the Mogollon Highlands and the Sevier thrust belt. These areas were broadly uplifted and being eroded during the Paleocene. The Colorado Plateau area was raised slightly above sea level, tilted to the northeast and eroded to a beveled pediment surface by streams flowing into the Sevier foreland basin and the St. Johns Sag to the Uinta basin and the San Juan basin. By Eocene time, continued warping of the crust created interruptions of the regional drainage and additional ponding of drainage in the Coconino and Baca-Eagar basins, and deposition of coarse materials ("Rim gravels") on the pediment surface nearer the rising Mogollon Highlands. The absence of Paleocene or Eocene sediments from southern and central Arizona indicates that those areas were high enough to cause erosion and no deposition. Other features shown include the "Rim gravels," Laramide monoclines and uplifts, and various drainages inferred in northwestern Arizona.

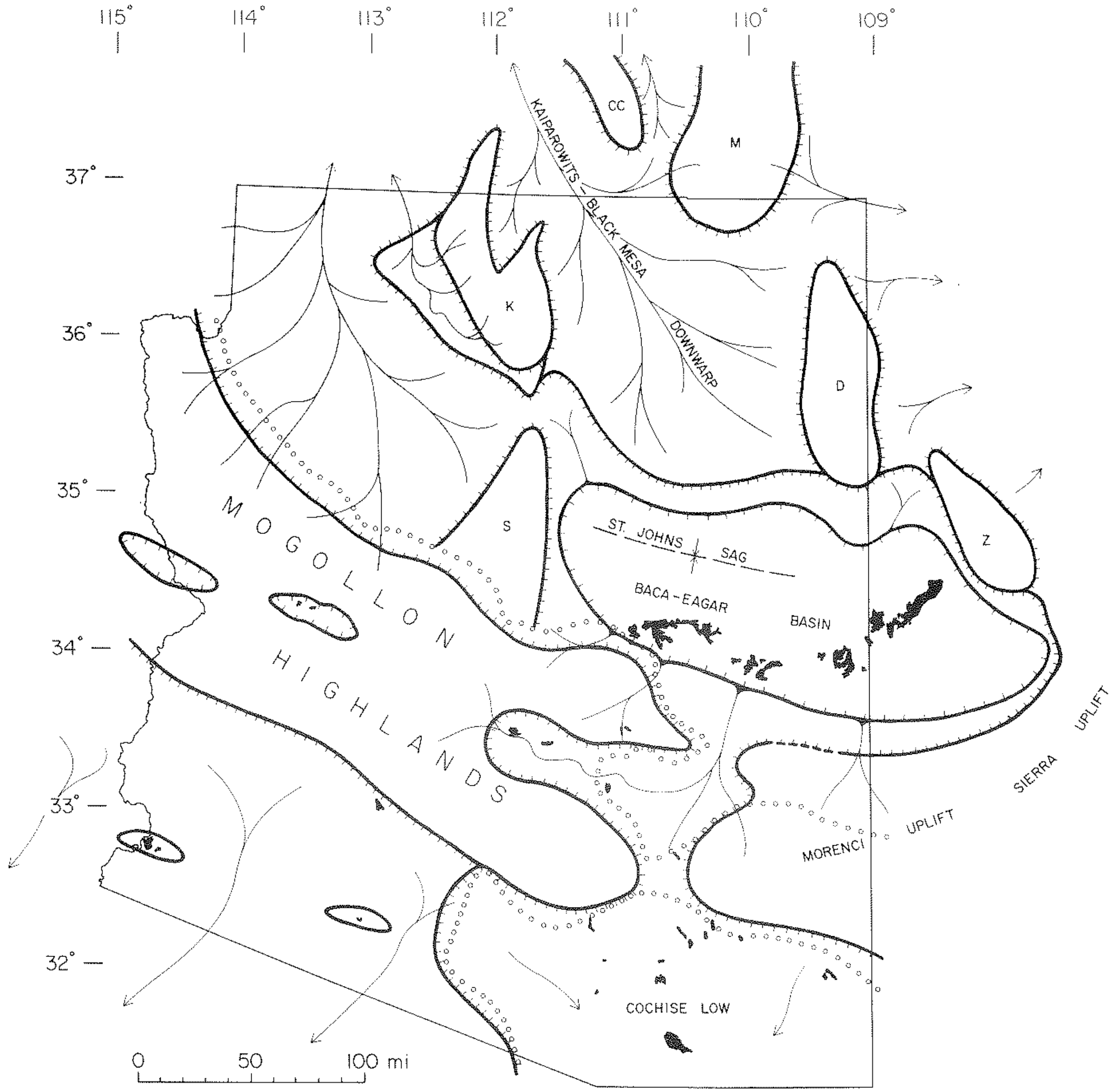


Figure 4: Late Eocene to middle Oligocene Paleogeography. By late Eocene, continued uplift had raised the Colorado Plateau synclinorium enough to initiate drainage and erosion of the Coconino basin and cause the depocenter of the Uinta basin to shift northward. The Baca-Eager basin was not drained because it was contained by the Sedona arch, Kaibab uplift, Sierra uplift and the cuesta of Mesozoic strata to the north. During this time the whole Colorado Plateau was uplifted to approximately 1000 m (3000 feet) and eroded, with sediments transported predominantly northward. In southern Arizona, sediments of this age began to accumulate in northwest-trending depocenters in broad downwarped basins that were separated by elongate upwarps.

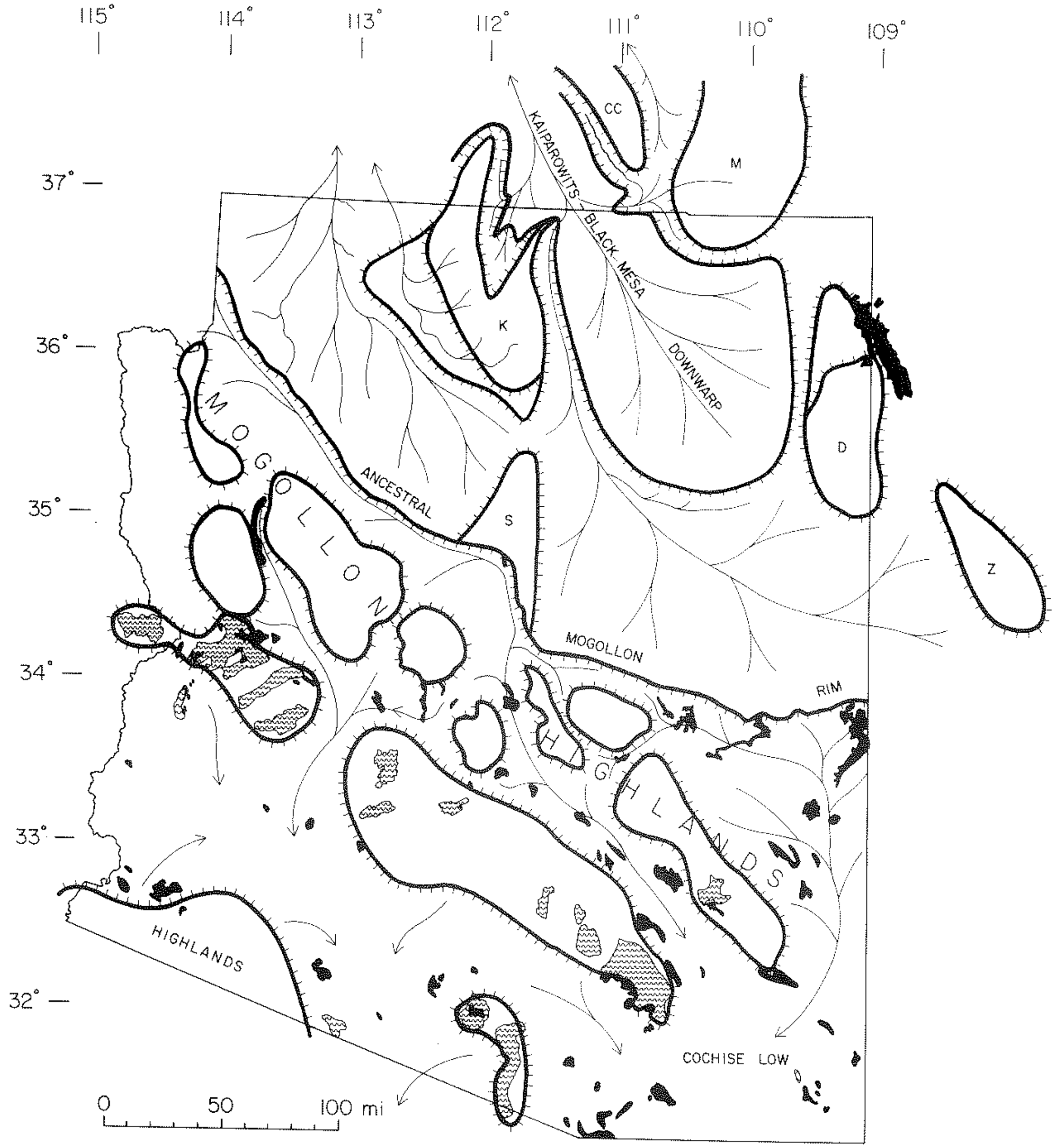


Figure 5: Late Oligocene to Middle Miocene Paleogeography. Continued uplift and erosion of the Colorado Plateau occurred with drainage centered in the Kaiparowits-Black Mesa downwarp and the Sevier foreland basin, and northeastward through the Uinta-Green River basins. Eocene sediments were eroded from the Coconino and Baca-Eager basins. The ancestral Little Colorado River erodes the ancestral Bidahochi basin by down-dip retreat of escarpment around the Black Mesa downwarp. The ancestral Mogollon Rim is formed by scarp retreat, down-dip from the Mogollon Highlands, with reworked "Rim gravels" and other coarse sediments accumulating along its base. Depocenters in southern Arizona expanding due to continued warping, with accumulation of coarse sediments derived from Mogollon Highlands and unroofing of rising metamorphic core complexes.

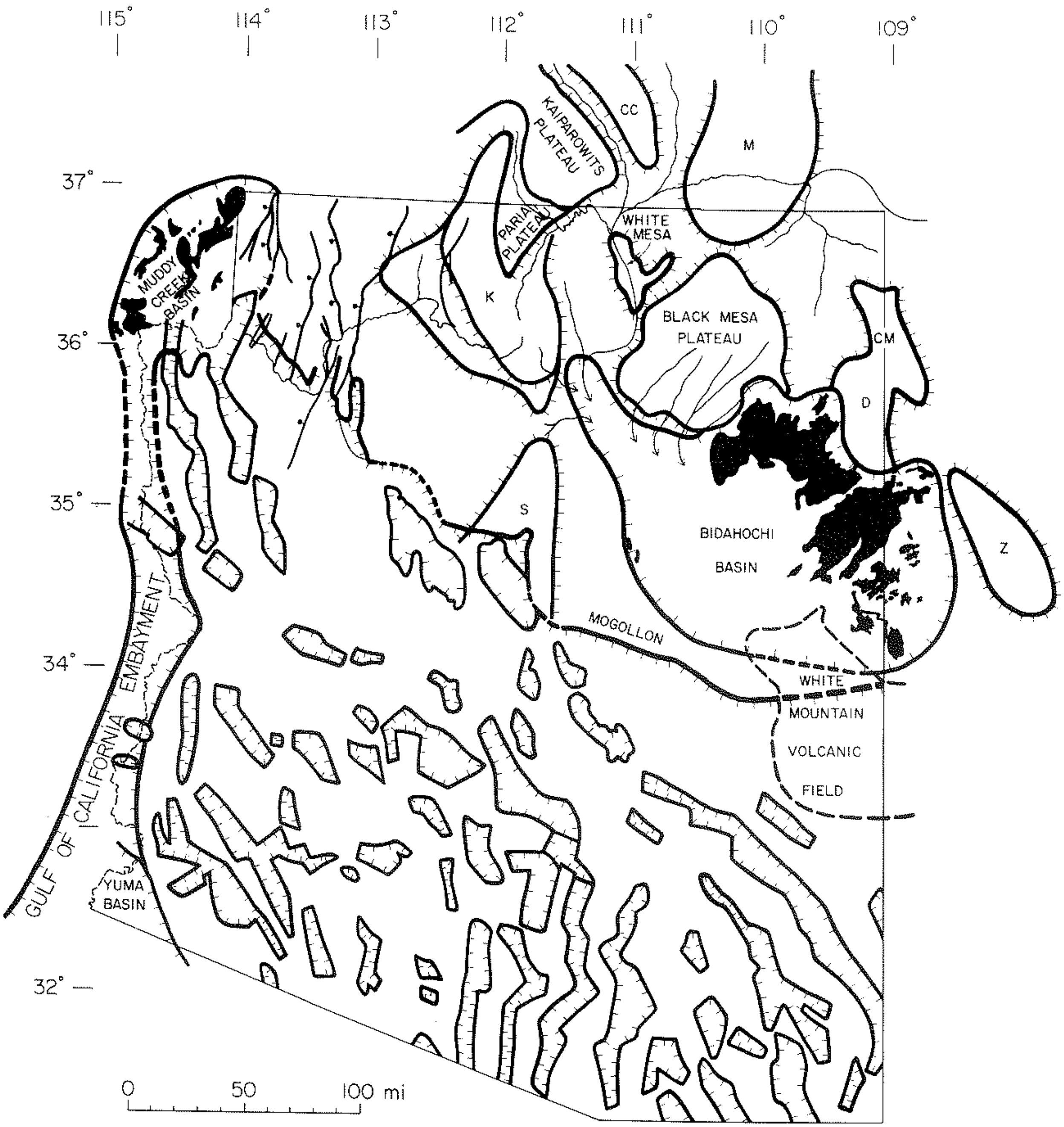


Figure 6: Late Miocene to Middle Pliocene Paleogeography. Drainage reversals on the Colorado Plateau were caused by southward tilting, with depocenters shifting to the Bidahochi and the Muddy Creek basins. The northeastward drainage from the Kaibab uplift and the Paria Plateau and other, previously northward flowing streams, were deflected southward along the Kaiparowits-Black Mesa downwarp, into the Bidahochi basin. The previously northward flowing stream west of the Kaibab uplift was reversed and flowed southwestward into the Muddy Creek basin that was formed by down-to-the-west normal faults. By middle Pliocene the lower Colorado River eroded its channel across the Kaibab uplift, captured the Bidahochi basin drainages and completed the modern integrated Colorado River drainage system. The onset of Basin and Range faulting at 13-12 Ma, created numerous graben-type basins throughout the Basin and Range Province of Arizona. Drainage systems were disrupted and created many restricted basins where fluvial, volcanic, and lacustrine sediments were deposited. By late Miocene the marine Gulf of California embayment extended northward, to or near the Muddy Creek basin.

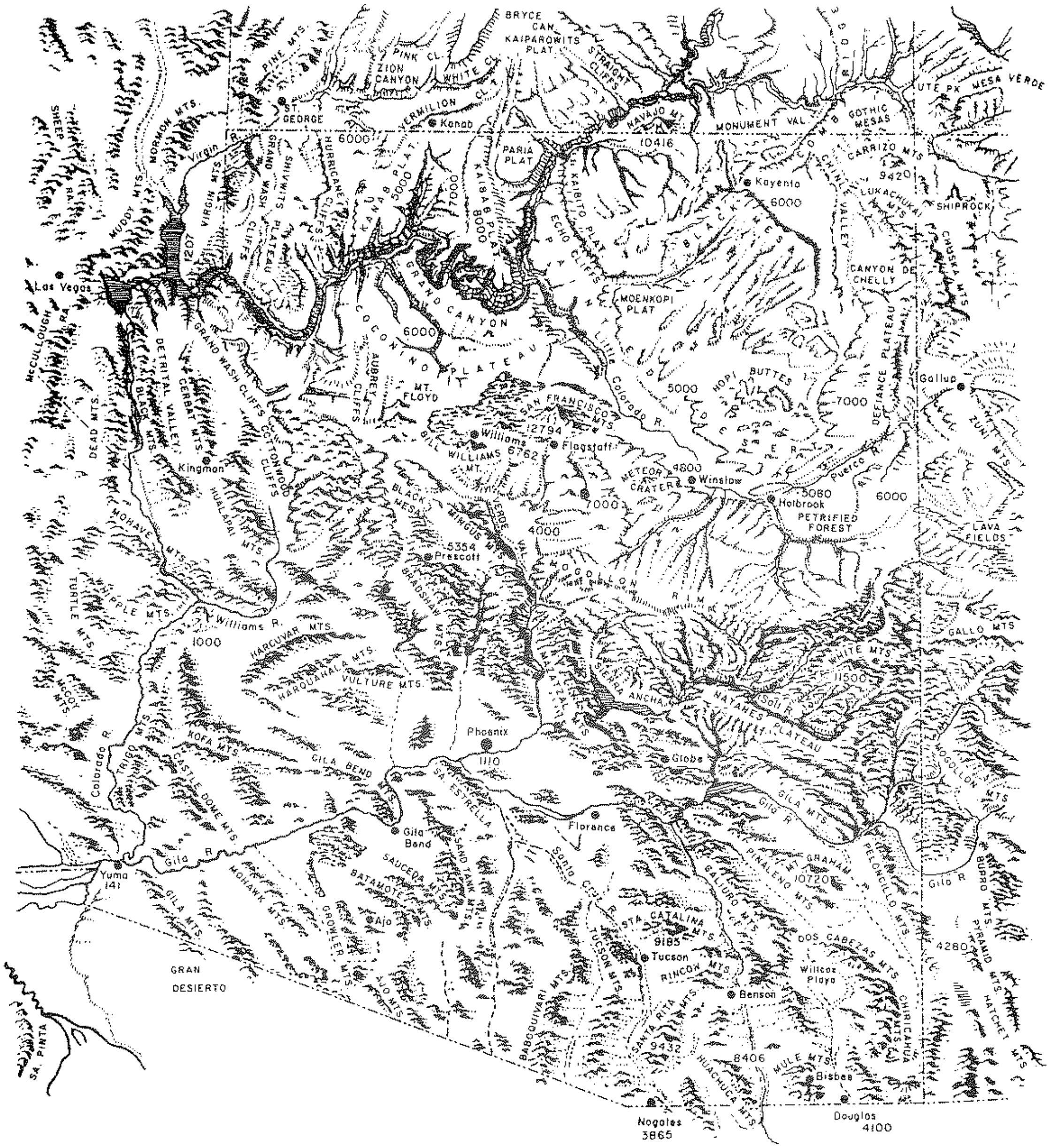


Figure 7: Late Pliocene to Recent. Physiographic diagram with recent topographic features, major drainages and major cities (from Smiley and others, 1984).

Cenozoic paleogeography of Arizona. Because Cenozoic volcanism and tectonism is discussed by several other authors cited in this paper, the obviously important volcanic stratigraphy is not summarized here. Many of the dates on these volcanic rocks were published and/or summarized by Keith (1977); Eberly and Stanley (1978); Marvin and others (1978); Peirce and others (1979); Shafiqullah and others (1978, 1980); Wilt and Scarborough (1981); and Otton (1982). Paleontologic and magnetic-reversal chronologies have been used to supplement isotopic dates (Lindsay and Tessman, 1974; Lindsay, 1978; Lindsay and others, 1984; Nations and Landye, 1984) (Fig. 1).

TECTONIC SETTING

The Tertiary history of Arizona was dominated by three major tectonic events: the Laramide orogeny, mid-Tertiary orogeny and Basin and Range disturbance. General age ranges of Late Cretaceous - middle Eocene (Laramide orogeny), late Eocene - middle Miocene (mid-Tertiary orogeny), and middle Miocene-present (Basin and Range disturbance) are commonly used. However, the exact beginning and ending age dates vary from place to place because these orogenies were time-transgressive. In general, the time interval for the Laramide orogeny was earlier in the west and later in the east (Coney and Reynolds, 1977). The time interval for the mid-Tertiary orogeny was earlier in the southeast and later in the northwest (Wilt and Scarborough, 1981). Therefore, the age ranges used in this paper are general ranges rather than absolute ages.

The Laramide orogeny of Coney (1972) lasted from about 85 Ma (middle Late Cretaceous) to about 43 Ma (late middle Eocene) and resulted in a broad epeirogenic uplift of the entire state. The southern and central parts of the state were subjected to compressional stresses, resulting in extensive thrust faulting, silicic plutonism and volcanism, and uplift. The Colorado Plateau area was raised to a lesser degree as part of the epeirogenic uplift and became an eroded pediment surface, gently sloping northward toward the early Tertiary lake basins of Utah, New Mexico, and Colorado (Shafiqullah and others, 1980; Epis and Chapin, 1975). The Plateau was bounded by highlands around its periphery, including the Sevier thrust belt to the west, the Mogollon Highlands to the south, the Rocky Mountains to the east, and the Uinta uplift to the north which converted it into a broad interiorly-drained basin. The Coconino and Baca-Eager basins were formed by downwarping and erosion along the southern margin of the interior basin and adjacent to the Mogollon Highlands. These basins were filled with fluvial and lacustrine sediments during the Eocene, most of which were later removed by erosion during the Oligocene. The interior of the Plateau was warped into several dominantly north-trending anticlines and synclines that influenced the subsequent development of drainage patterns within the Plateau (Fig. 2).

The second event, the mid-Tertiary orogeny of Eberly and Stanley (1978) lasted from about 38 Ma (latest Eocene), through the Oligocene, to about 13 Ma (middle Miocene) in southern and western Arizona. During the mid-Tertiary orogeny crustal heating, metamorphism, melting, and tectonism resulted in the formation of granitic plutons, associated intermediate to silicic volcanic rocks, and uplift of metamorphic core complexes. The resulting crustal disturbances created local elevated areas and adjacent basins in southern Arizona that were filled with predominantly coarse continental sediments. The sizes and shapes of these basins have been obscured by later events, but their distribution and the presence of intercalated fine-grained sediments suggests that there were interconnected areas of internal-drainage (Wilt and Scarborough, 1981; Peirce, 1984b). Chaotic breccias, fanglomerates and low-angle detachment faults are common in areas adjacent to the metamorphic core complexes, suggesting a process of unroofing by erosion and gravity gliding into adjacent low areas. The absence of Oligocene sediments and retreat northward of middle and late Eocene deposits in the Uinta basin suggests that the Plateau was also uplifted enough during the Oligocene to create external drainage through the Uinta-Green River and Washakie basins, through the Rocky Mountains to the Denver basin and Great Plains where extensive deposits of Oligocene sediments are found (Fig. 2).

The third event, the Basin and Range disturbance of Scarborough and Peirce (1978) lasted from 13 Ma (middle Miocene) to the present, although active tectonism was probably confined to the first few million years of that period in southern Arizona (Menges and McFadden, 1981). This event was characterized by crustal extension, basaltic volcanism, and high-angle normal faulting, that resulted in the formation of numerous grabens with internal drainage. For a more detailed discussion and documentation of Tertiary tectonic events, see Eberly and Stanley (1978); Shafiqullah and others, 1980; Damon and others (1984).

PALEOBIOGEOGRAPHY

The Tertiary basins of Arizona and adjoining areas contain a variety of plant and animal fossils. Comparison of these fossils to their nearest living equivalents in modern communities permits uniformitarian reconstruction of Tertiary paleoenvironments, including inferences of climate, elevation, and drainage patterns. The Paleogene portion of this reconstruction must be based on data from adjacent areas since there is very little fossil data from rocks of that age in Arizona. The Neogene fossil record is quite good, with numerous occurrences of fossil plants, invertebrates and vertebrates known across the state (Nations and Landye, 1984).

Paleobotany and Paleogeography

The fossil record of Cenozoic plants indicates that many modern families and genera of angiosperms and gymnosperms have stratigraphic ranges that extend back to the early Cenozoic, permitting interpretations of paleoenvironments. There is increasing similarity of these floras to modern communities, from early Cenozoic to the present.

Modern plant communities are limited to narrow climatic ranges that are largely controlled by elevation above sea level. The composition of plant communities of the past are known from fossil records of pollen or other plant remains, and the climatic conditions that existed at the time and location of their deposition can be inferred. The variation of fossil plant communities that are preserved in rocks of the same age in adjoining locations, can be interpreted as indicating differences in paleoclimates and/or elevations of the depositional sites. Based on the interpretation of uniform Neogene climate (Wolfe, 1978), the occurrence of plant communities with different temperature tolerances in sediments of different ages in the same area, are believed to indicate changing elevations of the depositional basin (Axelrod and Bailey, 1976). This makes the fossil plant record a valuable tool for interpreting paleoclimates and related elevation changes through the Cenozoic.

LARAMIDE (85-43 Ma) PALEOGEOGRAPHY

Paleocene (66.4-57.8 Ma)

The shallow Cretaceous seas which had previously occupied the northeastern and southeastern portions of Arizona and adjacent areas (Enos, 1983; Molenaar, 1983) had receded by early Tertiary time as a result of the epeirogenic uplift of the region during the Laramide orogeny (Dickinson, 1981; Haxel and others, 1984). The tectonically stable Mogollon Highlands of central and northwestern Arizona was broadly uplifted and the Paleozoic and Mesozoic strata of northern Arizona were tilted gently to the north. The previously established northward flowing streams beveled the strata to a gently sloping pediment and began transporting debris from the exposed Precambrian and Paleozoic rocks across the beveled surface. The southern edge of the mountainous region south of the Mogollon Highlands formed as a result of compressive deformation, plutonism and volcanism, in a thrust-faulted terrain called the Maricopa thrust belt. In the southeastern portion of the state, silicic plutonic and volcanic rocks of Paleocene age include the Gringo Gulch volcanics (60.4 Ma), Beehive Peak rhyolite (60.5 Ma), Ruby Star granodiorite (67-53 Ma) and Patagonia granodiorite (64-58 Ma) (Keith, 1977). No Paleocene age sedimentary rocks are known in southern Arizona, which also suggests that the area was elevated and undergoing erosion, with no low areas in which deposition could occur.

In the northern portion of the state and adjacent parts of the Plateau, faulting and folding of the Laramide orogeny produced broad downwarps such as the Sevier foreland basin, Uinta basin, San Juan basin (Hamilton, 1978), and the Baca-Eager basin (Chapin and Cather, 1981), in which early Tertiary sediments accumulated. An additional basin herein named the Coconino basin is defined as the downwarped portion of the Coconino Plateau in which early Eocene fluvial and lacustrine sediments were deposited (Young, 1982; Young and Hartman, 1984). They were formed adjacent to the large scale or regional uplifts (Sevier, Mogollon, San Juan, Sierra, etc.) that bounded the Colorado Plateau synclinorium (Fig. 2). Other downwarps were formed in the central part of the future Plateau, e.g., Kaiparowits, Black Mesa, and Henry basins. These subordinate basins were adjacent to uplifts such as the Kaibab, Echo Cliffs, Monument and Defiance uplifts (Hunt, 1956; Kelley, 1959; Chapin and Cather, 1981) (Fig. 1). No sedimentary units of Paleocene age have been definitely identified in northern Arizona. The absence of Paleocene sediments on the Colorado Plateau of northern Arizona suggests that the area was being eroded with the derived sediments being transported into the Paleocene basins of Lake Flagstaff in southwestern Utah and the San Juan basin of northwestern New Mexico (Hunt, 1956). It is probable that the removal of all Mesozoic strata from the Coconino Plateau, where early Eocene sediments were deposited, (Young, 1982) and the erosion of post-Triassic sediments from the Eocene-Oligocene Baca basin area (Chapin and Cather, 1981), was accomplished by this Paleocene erosion. The drainage courses probably followed the synclinal axes or strike valleys that were developed parallel to the uplifted Sevier thrust belt to the west and the Mogollon Highlands to the south (Figs. 2 and 3).

Paleocene Paleobiogeography

At the beginning of the Laramide orogeny in late Cretaceous time, much of Arizona was near or below sea level (Enos, 1983; Molenaar, 1983). As the area was elevated above sea level, it was colonized by humid, warm-temperate to subtropical mesophytic forests. Palynological studies of the Paleocene Ojo Alamo and Nacimiento formations of the San Juan basin by Anderson (1960) documented a diverse assemblage of spores and pollen of taxa whose modern phytogeography permits interpretations of the adjacent Paleocene topography. Fossil pollen of the gymnosperms Podocarpus and Taxodium in those formations, indicate significant topographic relief in the source areas of those sediments. Podocarpus lives today in upland areas of southern Mexico and Central America, while Taxodium is typically found in wet, coastal lowlands of Mexico and the southeastern United States. Angiosperm pollen reported by Anderson (1960) includes subtropical taxa such as the Bombacaceae and Sapindaceae, which probably grew in low-lying areas near the basin margin; but also includes more temperate taxa such as maple (Acer), alder (Alnus), willow (Salix), oak (Quercus) elm (Ulmus), tupelo (Nyssa) and basswood (Tilia), that must have grown in the adjacent San Juan Mountains, and other structurally and topographically high areas such as the Monument, Defiance and Zuni uplifts where more temperate climates existed (Fig. 2).

The similarity of the Paleocene flora in the San Juan basin to that in the Paleocene Silverado Formation of southwestern California (Axelrod, 1979; Gaponoff, 1984) suggests that the former was also deposited very near sea level and that the Plateau area was not very high above sea level during the Paleocene. The forests of gymnosperms and both evergreen and deciduous angiosperms persisted through the Paleocene into the Eocene (Axelrod and Bailey, 1976; Leopold and MacGinitie, 1972).

Eocene (57.8-36.6 Ma)

Northern Arizona

Eocene "Rim gravels" of Peirce and others (1979) crop out at several places along the Mogollon Rim and on the Coconino and Shivwits plateaus (Fig. 3, 7). These gravels are well-rounded, well-sorted, fluvial deposits that were transported from a southerly source and deposited on Cretaceous, Triassic or Permian rocks that were exposed on the Paleocene pediment, downslope from the Mogollon Highlands. They are now preserved at high elevations along the southern edge of the Plateau and are interpreted as remnants of a well-developed stream system that was flowing across the Paleocene pediment from central and northwestern Arizona northward toward the Eocene Coconino and Baca-Eager basins on the present southern edge of the Colorado Plateau (Fig. 3). They consist of clasts of Precambrian sedimentary, metamorphic and plutonic rocks and lower Paleozoic limestones and cherts that were derived from Precambrian and Paleozoic terranes in the Mogollon Highlands of central Arizona. The presence of the "Rim gravels" on the high plateaus indicates that the streams that carried these sediments predated the development of the Mogollon Rim that subsequently separated the drainages of the Colorado Plateau and the Transition Zone. The age of the "Rim gravels" has been bracketed in the Whiteriver area between 54.6 Ma and 28 Ma by Peirce and others (1979) with the maximum age determined by clasts in the gravels and the minimum age by the overlying volcanics (Figs. 3 and 4). The occurrence of widespread early Eocene fluvial and lacustrine sediments on the Coconino Plateau suggests an extensive drainage system flowed from west-central Arizona across the erosional surface that was cut down to the Kaibab Limestone during the late Cretaceous and Paleocene when it lay at a lower elevation (Young, 1979, 1982). These strata include Rim gravel-type sediments of Precambrian clasts derived from the south, and overlying lacustrine limestones dated as early Eocene by fossil snails (Young and Hartman, 1984). Young noted that the strata on the Coconino Plateau occur in a structural downwarp on top of the Kaibab Limestone (here called Coconino basin) and appear to have been deposited in a drainage system that was bounded on the north by the Laramide age Supai Monocline (Young, 1982) (Figs. 2 & 3). Similar gravels are present on the Triassic Moenkopi Formation, beneath Miocene (6-8 Ma) basalt flows on the Shivwits Plateau (Lucchitta, 1975), which could have been deposited in the margin of Coconino basin at that same time (Fig. 3).

The Eocene Eagar Formation crops out in the Springerville area (Fig. 4). It includes basal gravels and fine-grained sediments equivalent to the Eocene Datil Formation of southwestern New Mexico. These sediments were deposited in the Baca basin which was localized in a downwarped area the St. Johns Sag of Kelley (1955) and eroded down to Triassic strata during the late Cretaceous and Paleocene by an eastward flowing stream system. The initiation of sedimentation in the Baca Basin was caused by structural damming of the easterly paleodrainage by the Sierra uplift (Chapin and Cather, 1981). They appear to be the fine-grained equivalent of the "Rim gravels" of the Show Low area (Lucas and Ingersoll, 1981). The Coconino and Baca-Eager basins appear to have been separated in central Arizona, possibly by renewed uplift of the Sedona arch of Blakey (1980).

Southern Arizona

No records of Eocene age sediments have been described for southern Arizona.

Eocene Paleobiogeography

No Eocene pollen records are known in Arizona, but the Eocene Green River and associated formations of Utah and Colorado include sediments transported by streams flowing northward from Arizona. These formations contain pollen of plant taxa which live today in environments ranging from cool temperate uplands to subtropical lowlands (Newman, 1983). Eocene pollen indicative of warm temperate to subtropical lowland environments includes Cycadaceae, Taxodiaceae, Palmae, Rutaceae, Malvaceae, Euphorbiaceae, Bombacaceae, Sapindaceae and juglandaceous taxa such as *Engelhardtia*. Fossil pollen indicative of cooler, drier, temperate forests includes *Podocarpus*, *Ulmus-Zelkovia*, *Acer*, *Carpinus*, *Corylus*, *Salix*, *Populus*, *Castinopsis*, *Pinus* and such juglandaceous elements as *Carya* and *Pterocarya*. Joint occurrence of these taxa in those formations is indicative of a source area with an environmental gradient ranging from warm, moist lowlands to cooler, drier uplands. Modern analogs for such assemblages are found in the broadleaved evergreen forests of southern China and eastern Mexico (Axelrod and Bailey, 1976). These pollen records indicate that such environments existed in elevated regions around the Green River and Uinta basins, possibly including the Kaibab and Monument uplifts, and the Mogollon Highlands of northern and central Arizona (Fig. 2). Eocene pollen and macroscopic plant remains suggest that similar plant communities ranged over a wide area from Wyoming, California and New Mexico (Axelrod, 1966; Cushman, 1983; Leopold, 1983; Leopold and MacGintie, 1972). The only Eocene fossils reported from Arizona are viviparid gastropods snails in the limestone of Coconino basin (Young and Hartman, 1984) and charophytes (Lasky and Weber, 1949), and hydrobioid snails (Nations and Landye, 1984) from the Artillery Formation south of the Bill Williams River.

MID-TERTIARY (40-13 Ma) PALEOGEOGRAPHY

Oligocene (36.6-23.7 Ma)

Northern Arizona

No Oligocene sediments are known on the Colorado Plateau except the eolian Chuska Sandstone that crops out high on the eastern side of the Defiance uplift (Damon and Shafiqullah, 1981) (Fig. 5).

The absence of fluvial or lacustrine sediments on the Colorado Plateau is interpreted as indicating that the Plateau was uplifted enough during the Oligocene to cause erosion of the region by northward flowing drainage systems. These streams are believed to have followed the relatively low Uinta-Green River downwarps northeastward, between uplifts of the Wyoming Rockies, to the Oligocene depositional basins and Great Plains of northeastern Colorado, Wyoming, Montana and Nebraska (Fig. 1).

By late Oligocene the Mogollon Rim with up to 600 m relief was formed by scarp retreat caused by down-dip erosion of the northward dipping Mesozoic and Paleozoic strata. This minimum age of the Rim is defined by the presence of pre- 22 Ma gravels of probable Oligocene age which were deposited at the base of the eroded escarpment by streams flowing along its strike valley (Peirce and others, 1979). These gravels and other sediments south of the Mogollon Rim in the White River, Cibeque and Alpine areas, including the 25 Ma eolian sandstone of Escudilla Mountain (Damon and Shafiqullah, 1981), are believed to be the result of the reworking of "Rim gravels" and transport of fresh gravels by eastward flowing streams from the Mogollon Highlands, after the Mogollon Rim was formed (Fig. 5).

Southern Arizona

Stratigraphic units of Oligocene age are common in the southern part of Arizona, where they accumulated as predominantly coarse clastic sediments in local basins formed by crustal deformation during the mid-Oligocene (Figs. 4,5). The shape and size of these basins are interpreted in a very generalized way, but are based on the observed distribution of Cenozoic sediments in elongate patterns, which suggest that the southern Arizona crust was broadly warped. Drainage systems were probably localized by the continued development of broad scale folding (Fig. 5). The Oligocene strata occur as isolated exposures in uplifted fault blocks of present-day mountain ranges and in the lower portions of deep grabens that resulted from the disruption of Oligocene basins during subsequent Basin and Range faulting. The area of apparent concentration of early to middle Oligocene sediments in southeastern Arizona is believed to have been a local downwarped "sump" to which the Mogollon escarpment drainage flowed (Figs. 4, 5). Early Oligocene strata are dominantly fine-grained but the middle and late Oligocene strata are coarse-grained, reflecting the onset of the Mid-Tertiary orogeny.

Early Oligocene units in southeastern Arizona include the Locomotive fanglomerate, Helmet fanglomerate, Whitetail Conglomerate, Mineta Formation, and Pantano Formation (Shafiqullah and others, 1978, 1980; Wilt and Scarborough, 1981; Peirce, 1984b; Damon and others, 1984). They range widely in thickness and in lithology, but are typically coarse-grained and poorly sorted. They generally consist of reddish-brown conglomerate, either as alluvial-fan accumulations ranging from 2000 to 10,000 ft thick, or as relatively thin, basal conglomeratic units underlying ignimbritic volcanics of early to middle Oligocene age (Wilt and Scarborough, 1981). Because of this relationship to Oligocene ignimbrites, Wilt and Scarborough (1981) designated these as "pre-ignimbrite sediments". They occasionally contain fine-grained members consisting of light-colored to greenish mudstone, calcareous shale and limestone with some gypsiferous beds that are of probable lacustrine origin. The limestones are commonly fetid, indicating a high organic carbon content, and deposition in lacustrine environments. The presence of red fanglomerate and monolithologic megabreccia overlying or underlying fine-grained strata indicates that nearby areas had high relief (Wilt and Scarborough, 1981). These observations suggest that southern Arizona during the Oligocene was a mountainous region with local internal drainage systems in which lakes and playas were formed periodically (Fig. 5). The Oligocene-Miocene conglomerate and redbeds of the Yuma area (Olmstead and others, 1973) and several other fine to coarse-grained deposits such as the Sil Murk, Clanton Hills, and Gila Bend limestones and the Locomotive fanglomerate, indicate conditions in southwestern Arizona were similar to those in southeastern Arizona (Wilt and Scarborough, 1981). Oligocene and/or early Miocene isotopic dates of intercalated volcanics in cores from deep wells in the Paradise, Higley, Picacho and Red Rock basins (Fig. 1), indicate that the south Central Arizona (the Gila Low of Peirce, 1976) subsided during the mid-Tertiary orogeny, and has remained low ever since.

Volcanism was not common until middle Oligocene (30 Ma) when silicic volcanism termed the "ignimbrite flareup" by Coney (1976) began. Oligocene sediments intercalated with thick sections of volcanics in the "ignimbrite package" of Wilt and Scarborough (1981) include the Nipper Formation, Faraway Ranch Formation, Cloudburst Formation, Artillery Formation, upper Sil Murk Formation, Kinter Formation, and many others (Figs. 4,5). Many of these formations include relatively thin (compared to the volcanics) sections of mudstone, fetid and cherty limestone, and tuffaceous shale indicating probable deposition in lacustrine environments. These sections also commonly contain thick units of monolithologic breccia, indicating high basin-margin relief and deposition of landslide debris.

Sediments deposited after the bulk of ignimbrite volcanics were extruded were included in the "post-ignimbrite package" by Wilt and Scarborough (1981). These sediments are generally light-colored and contain thin, reworked tuffaceous material or proximal tuff deposits. One example is adequately. The areal extent of Bidahochi Formation outcrops has been mapped by Akers (1964), which provides a minimum area of the fluvial and lacustrine Bidahochi basin. Cooley (1962) suggested that calcareous sand and silt, that crops out between basalt and the Chinle Formation at Sunset Buttes, 30 km southwest of Winslow is similar to the upper Bidahochi Formation. Several other outcrops of Tertiary sediments along the Mogollon Slope and in the Little Colorado River valley (Ulrich and others, 1984) appear to be genetically related to the upper Bidahochi and are interpreted here as such. If those deposits were continuous with the Bidahochi Formation, then the fluvial sands of the Bidahochi basin probably extended as far west as the Kaibab Uplift (Figure 6). Lucchitta (1984) postulates a through-flowing, ancestral (pre-Basin and Range faulting) Little Colorado River approximately along its present course and in the same direction. This is logical because a long erosional event by a well established drainage system was necesssary to erode the topographic basin in which the Bidahochi Formation was deposited. We propose that this stream course was established in the strike valley of the Chinle Formation on the Mogollon Slope after headward erosion by a southeastward-flowing stream in the Baca-Eager basin intersected the northward-flowing regional drainage down the Kaiparowits-Black Mesa downwarp. The resulting stream capture created the northward-flowing ancestral Little Colorado River, and continued to erode the Little Colorado River valley between the Kaibab Uplift to the west and the Black Mesa plateau to the east (Figs. 4 and 5).

Bidahochi sedimentation may have begun in that erosional valley as early as 10-15 Ma (Lance, 1954). At that time, southward tilting of the Plateau, probably effected by subsidence in the adjoining Basin and Range Province, caused the reversal of drainage of the long established northward drainage system (Figs. 5 and 6). By that time, headward erosion by the ancestral Little Colorado and San Juan rivers had dissected the Cretaceous cliff-forming sandstones enough to allow the reversed drainage to abandon the previous regional drainage in the Kaiparowits-Black Mesa downwarp, and to flow into the ancestral Little Colorado River Valley possibly along the course of Moenkopi Wash (Fig. 6). That dissection effectively separated the Kaiparowits and Black Mesa plateaus. Sedimentological evidence of the early development of this drainage reversal may be found in the gravels containing lithologic clasts from the San Juan Mountains that are now located on White Mesa (Hunt, 1956). It is likely that the Marble Canyon portion of the Colorado River and the Paria River were entrenched during that drainage reversal into the Bidahochi basin (Fig. 6). The other streams of the upper Colorado River system were integrated into the reversed drainage system into the Bidahochi basin at that time, including the San Juan River which established its course across the Monument uplift by late Miocene time (Hunt, 1956; Huber, 1981).

The segment of the Colorado River which presently flows west of the Kaibab uplift, was flowing northward as part of the Sevier foreland basin drainage (Figs. 3,4,5) until the drainage reversal in late Miocene time. With the southward tilting, this river changed its course southwestward and flowed into the Muddy Creek basin (Fig. 6). By 5.5 Ma the Gulf of California had opened and the lower Colorado River segment was eroding its channel northward toward the Muddy Creek basin (Fig. 6). It cut its channel down into the 5.9 Ma Fortification Hill basalt of the Muddy Creek Formation and completed the lower Colorado River drainage, between 5.9 and 3.8 Ma (Shafiqullah and others, 1980). The lowered base level resulting from the opening of the Gulf of California increased headward erosion by the river, thereby capturing both the Marble Canyon segment of the Colorado River and the Little Colorado River completing the integration of the upper Colorado River system with the lower Colorado River to the Gulf of California (Figs. 6 and 7). Sedimentation continued in the ancestral Little Colorado River Valley until the Kaibab Uplift barrier was breached by headward erosion of the lower Colorado River at its present confluence with the Little Colorado River sometime after the middle member of the Bidahochi Formation was deposited 6.7 Ma (Scarborough and others, 1974). This breaching of the Kaibab Uplift and draining of the Bidahochi basin probably occurred primarily by headward erosion and stream capture by a short tributary to the lower Colorado River during the Pliocene. Since then the mouth of the Little Colorado River has been lowered to 900 m (2700 ft) above sea level, well below the 1970 m (5900 ft) lowest elevation of the base of the Bidahochi Formation. This lowering of local base level resulted in the removal of much of the Bidahochi Formation from a large portion of the ancestral Little Colorado River Valley (Fig. 6).

Incised meanders on the Doney Cliffs Monocline (Breed, 1969), easterly flowing drainage channels on Gray Mountain (Barnes, 1985, pers. comm.), and barbed drainages of the Little Colorado River were probably developed during the deposition of the Bidahochi Formation, prior to its dissection by the integrated Colorado River system.

Pliocene (5.3-1.6 Ma)

Basins that continued to accumulate sediments through upper Miocene and into the Pliocene include the Gulf of California embayment (Bouse Fm.), Muddy Creek basin, Bidahochi basin, Verde basin, Safford Basin(?), Big Sandy basin, San Pedro basin, Perkinsville basin, San Raphael basin, Duncan basin, and the Safford basin. They all are partially or entirely Pliocene in age, but appear to have been drained at different times during the Pliocene as headward erosion of the developing integrated stream system reached them and breached their margins.

Miocene-Pliocene Paleobiogeography

Neogene plant and animal fossils are relatively common in Arizona. The locations and taxonomic composition of the Cenozoic fossil localities of Arizona were summarized by Nations and Landye (1984) and Lindsay (1984).

Aquatic plants, invertebrates and vertebrates have been used to interpret intrabasin environments of deposition in the Bouse Formation (Smith, 1970), Muddy Creek basin (Blair and others, 1979; Cornell, 1979), Verde basin (Nations and others, 1981) and in the Bidahochi basin (Taylor, 1957; Baskin, 1975). Former drainage patterns have been inferred from the distribution of fossil and modern fish faunas (Uyeno and Miller, 1965; Smith, 1966; and Miller, 1981).

Terrestrial palynomorphs and macrofossils in Neogene sediments have been cited as evidence of elevation above sea level for several Miocene depositional basins. The occurrence of pine and other high altitude genera in the Nogales Formation (Damon and Miller, 1963), the Bidahochi basin (Anderson, 1962), and the Verde basin (Nations and others, 1982), indicates elevations above 1300 m (4000 ft). The absence of higher elevation (+2200 m) taxa such as Abies, Picea and Pseudotsuga in Miocene or older sediments of Arizona suggests that there was no topography of that elevation until the Pliocene, at which time those genera appear in the Safford basin (Martin and Gray, 1962). They become common in the Sulphur Springs Valley and in the lacustrine sediments of the Colorado Plateau during the Pleistocene (Nations and Landye, 1984).

The occurrence of fan palm (Washingtonia) in the Miocene Big Sandy basin (Axelrod, 1950; Worley, 1979) indicate warm climates and elevationsless than 1200 m (3500 ft). A similar interpretation is indicated for the Pliocene of the Yuma basin, based on the occurrence of paloverde (Cercidium or Parkinsonia) (Lee and Zavada, 1977).

Preliminary analysis of the distribution of mammal taxa in Tertiary deposits, suggests that they may also be useful indicators of paleoclimates and paleogeography during the Tertiary, including the development of physiographic barriers to dispersal.

Pleistocene (1.6 Ma - Present)

Other basins, generally in the low-lying areas of the Basin and Range (the Gila Low of Peirce, 1976), or areas not yet in the modern integrated drainage system, continued to accumulate sediments through the Pleistocene and Holocene. They include Red Lake, Luke, Paradise, Higley, Picacho, Red Rock and Tucson Basins (Figs. 1, 6, 7). As previously stated, these basins commonly contain sediments ranging from Oligocene to Recent because they are located in areas that have remained low since the end of Laramide time, and have remained near or below base level during the Tertiary tectonic events.

Pleistocene Paleobiogeography

Significant climatic change occurred during the Pleistocene resulting in drastically altered distributions of both plants and animals. The present distribution of taxa and the resulting composition of biotic communities has emerged only within the past 11,000 years (Axelrod, 1979). Associated with this development has been the extinction of many Plio-Pleistocene vertebrates. This subject has been thoroughly discussed in a recent symposium volume (Martin and Klein, 1984).

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The interpretations expressed in this paper are our own and will most certainly find disagreement in parts with any particular workers. We offer them as an attempt to pull together the diverse data relative to Cenozoic history and evolution of the state of Arizona, and as a challenge to those who will add more data and/or improve upon our interpretations.

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