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THE PLATE TECTONIC SETTING OF SOUTHEASTERN ARIZONA

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INTRODUCTION

The regional tectonic evolution of southwestern North America has been dominated by a succession of variable and rapidly changing plate tectonic settings since Paleozoic time. Although seemingly far removed from a plate margin, southeastern Arizona lies well within a broad belt which has experienced complex continental plate tectonic activity over the past 200 m.y.

This prolonged period of complex continental tectonics can be divided into six phases: a Paleozoic period of extended cratonic stability; a Late Triassic to Late Jurassic period of magmatic arc activity; a Cretaceous period during which the region was in an arc-rear setting; an intense period of compressive deformation and magmatic arc activity during Late Cretaceous to early Tertiary (Laramide) time; a middle Tertiary period of calderas and evolution of metamorphic core complexes; and finally, Late Tertiary Basin and Range rifting. Perhaps the most unique aspect of the tectonic evolution of this region was the complex interplay of plate tectonic events in two oceans—the Pacific Ocean to the southwest and the Gulf of Mexico to the southeast—and a very complex magmatic arc evolution during Mesozoic-Cenozoic time.

Paleozoic

The Paleozoic tectonic setting of southeastern Arizona was a relatively stable cratonic shelf (Peirce, 1976). Continental freeboard was very low, and during a period of over 300 m.y., only about 2 km of primarily carbonate shelf accumulation is recorded. Minor warping, faulting and eustatic changes in sea level notwithstanding, the era was one of relative tectonic stability compared to what was to follow.

This stability is of interest when viewed in a wider regional tectonic perspective. Two major Paleozoic orogenic belts were evolving on the margins of North America not too far apart (fig. 1). To the southeast, no more than 500 km distant, was the Appalachian-Ouachita-Marathon orogen (Graham and others, 1975) marking convergence and final collision between Africa-South America and North America, mainly during later Paleozoic time. Effects of this collision may be recorded in deformation and sedimentation of the ancestral Rockies north and east of the region with which we are here concerned. To the west, no more than 800 km distant, was the Cordilleran miogeocline (Stewart and Poole, 1974), and related Devonian-Mississippian and Permo-Triassic arc-continent collisions recorded as Antler and Sonoma orogenic events (Dickinson, 1977).

These two great orogenic belts, one to the southeast, the other to the west and southwest, must have joined in some presently obscure geometry southwest and south of Arizona-New Mexico, possibly as close as about 1,000 km. In summary, southeastern Arizona was in the midst of an irregularly shaped southwest-extending spur of the North American craton, and was bordered on the west, southwest and southeast sides by belts of plate convergence, arc-continent collisions and inter-continental collisions, particularly from Devonian into Triassic time.

Jurassic

Beginning some time between about 220 m.y. and 190 m.y. ago in latest Triassic to early Jurassic time, and extending to Late Jurassic time, a magmatic arc trended northwest-southeast across southwestern Arizona (figs. 1, 2). This magmatic arc stood on continental crust above sea level and was continuous with arc activity to the northwest in California and southward into central and southern Mexico. This magmatic arc has most of the essential characteristics resulting from plate convergence and subduction along the southwestern margin of North America during latest Triassic to Late Jurassic time.

The original width of this magmatic arc was probably over 200 km, but it seems not to have entered New Mexico. Nevertheless, it was a broad arc which extended much further inboard from the North American continental margin than the succeeding Cretaceous arc. The evidence for this arc (Armstrong and Suppe, 1973; Rangin, 1978; Hayes and others,

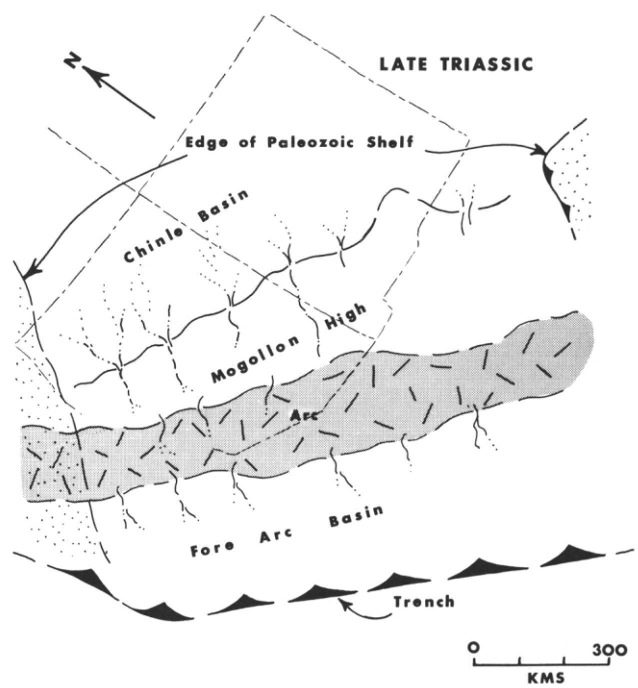

Figure 1. Late Triassic. Summary map showing major tectonic features of late Paleozoic and early Mesozoic time. Stippled pattern shows edge of Paleozoic cratonic shelf. Western pattern in Cordilleran Paleozoic miogeocline, southeastern pattern in Marathon region. On this and all other figures, outline of states is modified to account for middle to late Tertiary extension. North arrow on all figures is with respect to present day.

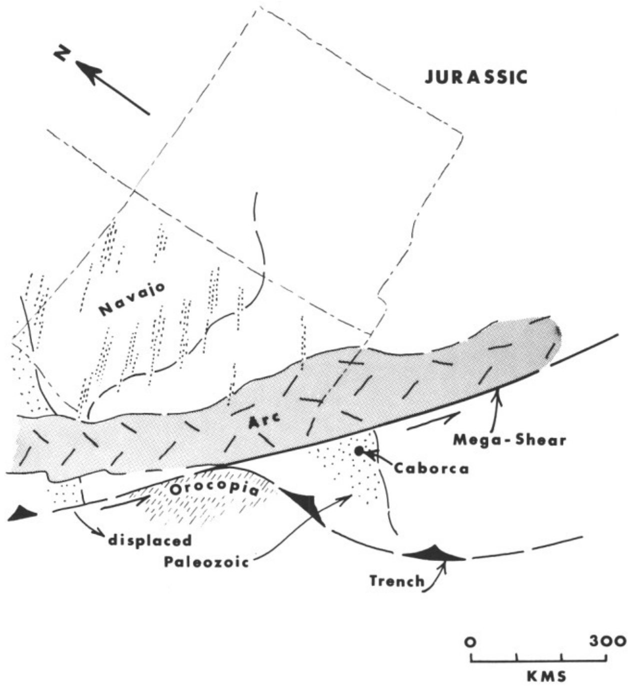

Figure 2. Jurassic. Major features of Jurassic arc (heavy dash-stipple pattern), including the Silver-Anderson mega-shear, and displaced Paleozoic (heavy stipple) and Orocopia (light dash) terranes.

1965; Drewes, 1971; Silver and Anderson, 1978) is scattered sequences of volcanic rocks and associated continental sedimentary rocks in southeastern California, southern Arizona and in western and central Sonora. The volcanic rocks are accompanied by granitic intrusions. The southwesternmost occurrences in Sonora (Rangin, 1978) have marine sequences interbedded with the volcanics, and Liasic and Oxfordian fossils have been found in these marine sequences. Elsewhere, scattered radiometric age dates using mostly plutons and some volcanics are consistent with the fossil ages.

The relationship of this arc terrane to classic Triassic-Jurassic sedimentary sequences on the Colorado Plateau (Stewart, 1969; Lewis and others, 1961) is of considerable paleogeographic interest. Correlation is made difficult by a general scarcity of fossils in both arc and plateau deposits, and also by certain problems of absolute chronology with respect to stratigraphy on the Colorado Plateau. Except for one or two possible exceptions (Miller and Carr, 1978), the two sequences are not in directly traceable contact, and the facies are very distinct. It may be possible that the ancestral Mogollon highland, exposing Precambrian basement along a belt just southwest of what is now the Mogollon rim in Arizona, may have stood as a low barrier between the alluvial systems and deserts of the Colorado Plateau and the Jurassic arc terrane to the southwest. In any event, the arc seems to have been in part a system of continental, perhaps fault-bound basins and of volcanoes whose deposits interfingered with marine deposits of a fore-arc basin along the arc's southwestern margin.

This paleogeographic setting was also influenced by events in the Gulf of Mexico. To the southeast, the Gulf of Mexico was presumably beginning to open as part of the opening of the Atlantic Ocean marking separation of Africa-South America from North America (Coney, 1978). This separation was probably underway by Middle to Late Jurassic time. There were two principal effects of the opening of the Gulf of Mexico: formation of the Silver-Anderson mega-shear, or continental transform fault, across northwestern and central Mexico, and initiation of marine transgressions, originating out of the Gulf of Mexico, which eventually covered much of interior North Ameica.

The Silver-Anderson mega-shear (Silver and Anderson, 1974, 1978) (fig. 2) apparently extended from southern California southeastward across Sonora to the opening Gulf of Mexico. This mega-shear was presumably a continental transform fault system connecting spreading centers in the Atlantic Ocean-Gulf of Mexico with the trench system along the southwestern margin of North America. The feature was active some time between Early Jurassic and Early Cretaceous time. The exact geometry is obscure, but the evidence for it is very compelling. Possible effects in southern Arizona-New Mexico are discontinuities and faults with a similar trend which were probably active during this time (Titley, 1976).

The most important effects of the Silver-Anderson mega-shear, however, are seen on a much larger scale. Since it was a left-separation transform fault system, reversal of the assumed 600 to 800 km offset brings all of Mexico southwest of the fault back to the northwest. This restoration, with other adjustments, essentially eliminates the embarrassing overlap of South America onto southern Mexico, which results from pre-drift reconstructions of the continents surrounding the Atlantic Ocean (Coney, 1978). Besides explaining offsets of Paleozoic facies similar to those of southern California-southern Nevada, exposed off-trend near Caborca, Sonora (fig. 2), and distribution of Precambrian age terranes which led to its discovery, the mega-shear might also explain other enigmatic terranes in southern California. If the fault system extended into southern California on or near the present trend of the San Andreas fault, movement on the mega-shear would have produced a newly embayed continental margin in southern California. This movement could either have brought in, or have allowed later emplacement of oceanic crust that could now be the Orocopia schist (Ehlig, 1968). Later draping of the Peninsular batholith arc outboard of this margin during Cretaceous time would have trapped inboard the oceanic facies which were to be over-ridden and deformed by telescoping in later Cretaceous time (Haxel and Dillon, 1978).

Another effect of the opening of the Gulf of Mexico and the separation of South America from North America was the initiation of a marine transgression out of the growing Gulf of Mexico, starting with pre-Oxfordian salt and extending into the middle Cretaceous Chihuahua-Bisbee embayment and the more extensive Rocky Mountain-Colorado seaway. The Bisbee embayment had a particular influence on the tectonics of southeastern Arizona.

Cretaceous

In late Jurassic time, magmatic activity waned, then flared up again in Early Cretaceous time far to the southwest along the extreme southwestern margin of North America (fig. 3). This new magmatic activity produced volcanic and volcaniclastic deposits and an enormous plutonic complex along what is now the Peninsular batholith terrane of southern California and Baja California (Gastil, 1975; Silver and others, 1975).

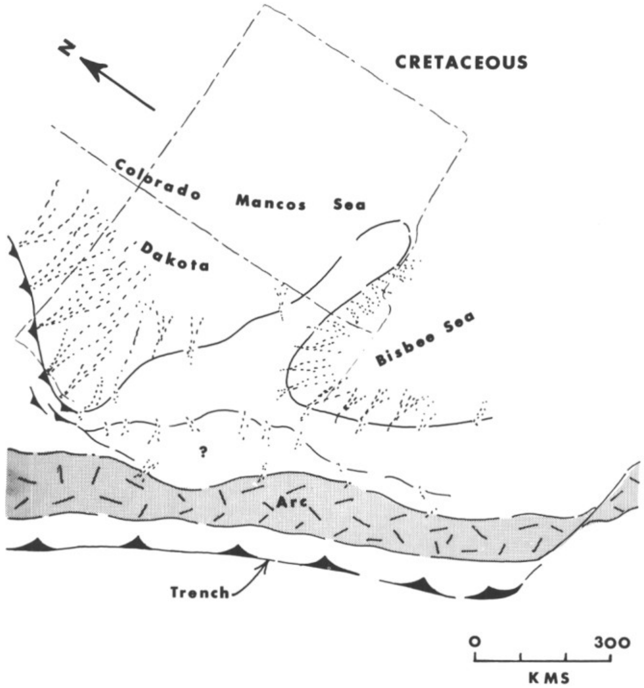

Figure 3. Cretaceous. Major features of mid-Cretaceous Peninsular batholith arc (heavy dash-stipple patterns) and Cretaceous interior seas. Sevier thrust belts shown by smaller barbed lines along far northwestern margin.

Much of this arc seems to have been off-shore, since marine rocks are involved.

To the northeast of this marginal arc in the arc-rear area of Sonora, Arizona and New Mexico, the paleogeography is complex and still not entirely clear. We know that compressive arc-rear thrusting was taking place in Nevada-Utah west of the Wasatch line, shedding debris eastward into the expanding Rocky Mountain foreland interior sea (Armstrong, 1968). This sea lapped southward onto the ancestral Mogollon highland, but it apparently did not cross the highland. South of this highland, extending from the southeast out of the Gulf of Mexico, was the Bisbee sea (Hayes, 1970; Rangin, 1978) (fig. 3). This embayment must have merged with the Rocky Mountain seaway somewhere to the east, but the peninsular-like Mogollon highland seems to have separated the two in Arizona-New Mexico.

The Bisbee sea lapped across the Jurassic arc terrane in Sonora and southernmost Arizona, and across a varied Precambrian-Paleozoic terrane northward. Its inception during latest J urassic(?)-Early Cretaceous Glance conglomerate time (Bilodeau, 1978, this guidebook) was accompanied by faulting, perhaps a waning phase of the mega-shear, and other effects presumably related to the opening of the Gulf of Mexico. A barrier, presumably low, separated this embayment from the middle Cretaceous marine arc on Baja California (Rangin, 1978).

This period of arc-rear setting was apparently accompanied by or ended by folding, thrust faulting and some metamorphism. This belt of deformation seems to have extended across southwesternmost Arizona and into Sonora, and to have shed Late Cretaceous debris (Fort Crittenden-Ringbone-Cabullona formations) into local basins and northeastward into southeastern Arizona-southwestern New Mexico (Hayes, 1970) and northeastern Sonora (Rangin, 1978). Whether this compressional event is related to collision and collapse of marginal arc terranes in central Baja California (Rangin, 1978) or to early phases of mainly later Laramide deformation is unclear. This deformation was quite intense and important in southwestern Arizona. It seems to pre-date very early Laramide plutons (Rehrig and Reynolds, 1977), and it certainly post-dates very thick sequences of detrital sedimentary rocks (Harding, 1978) of almost certain Mesozoic age and possible Late Jurassic to Cretaceous age. It also clearly post-dates thick sequences of volcanic rocks (Miller, 1970) of probable Jurassic age which are part of the Jurassic arc terrane.

Late Cretaceous-Early Tertiary Laramide Orogeny

During Late Cretaceous-early Tertiary time (fig. 4), southeastern Arizona was gripped by uplift, volcanism, intense compressive deformation and plutonism—in that order. This activity swept southwest to northeast across the region and produced what has been termed the Laramide orogeny (Coney, 1976; Drewes, 1972; Damon and Mauger, 1966). Whether it simply grew out of earlier Cretaceous deformation to the southwest, or marks a separate event, is still not clear. Analysis of the magmatic history suggests a continuous northeastward magmatic sweep which started from the mid-Cretaceous Peninsular batholith and extended to central New

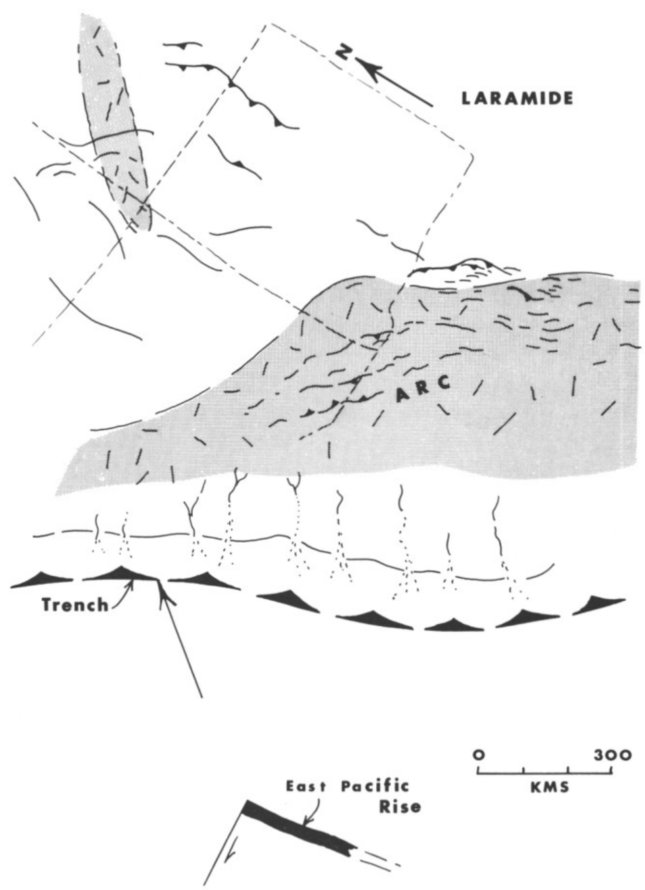

Figure 4. Laramide. Major features of Laramide deformation and magmatic activity. Position of East Pacific Rise approximate for end of Laramide time about 40 m.y. ago. Arrow on trench is direction of Farallon/North America convergence.

Mexico and west Texas by Eocene time. This sweep has been interpreted as due to progressive flattening of a Benioff zone (Coney and Reynolds, 1977).

There are scattered early Laramide volcanic and sedimentary rocks, but important thick and widespread sediments of Laramide age are not abundant within the main deformation belt in southern Arizona. Outside the belt, Laramide-age deposits accumulated in basins between Laramide uplifts on the Colorado Plateau and in the southern Rocky Mountains (Tweto, 1975). The only other abundant deposits of this age are fluvial and near-shore deposits shed from the east across the beveled Peninsular batholith in coastal southern California and northern Baja California (Gastil and others, 1975). The Laramide orogen in southern Arizona was apparently uplifted, though not greatly, or at least eroded as fast as it was uplifted, and shed debris southwestward into a wide fore-arc basin. It also shed debris into local basins, and possibly northeastward into large intra-Laramide basins. The orogen was a very complex arc terrane where surface volcanism, thrust faulting and intrusion followed one another, usually in that order, in rapid succession. For some reason, many of the plutons of this period acquired significant copper concentrations (Titley and Hicks, 1966).

There has been much debate about the geometry of Laramide deformation in southeastern Arizona and southwestern New Mexico (Drewes, 1978; Davis, in press; Jones, 1963). Faults of all types occur, some of which are reactivated from earlier periods of deformation, and thrust faults vary from very steep-dipping to locally sub-horizontal. The thrust faults dip both southwest and northeast (Davis, in press). Many of the thrust faults appear to bound basement blocks, and considering the relatively thin Phanerozoic cover, appear to be deep-seated rather than thin-skinned (Davis, in press). Southeastward in New Mexico and Mexico, the Phanerozoic section thickens, mainly by Cretaceous marine sequences, and familiar foreland folds and low-angle thrust faults evolved (Corbitt and Woodward, 1970). It is to be remembered that Laramide deformation in southeastern Arizona and adjacent New Mexico is not linked either in space or in time with low-angle thrusts of Sevier (pre-Laramide Cretaceous) age in Nevada-Utah (Armstrong, 1968). It is linked in space and in time, and in part by deformational style, with classic Laramide deformation (Coney, 1976) on the Colorado Plateau (Kelley, 1955) and the Rocky Mountains (Berg, 1962; Tweto, 1975). It is also continuous in space and in time with the great belt of Laramide thin-skinned deformation across northeastern and eastern Mexico in the Sierra Madre Oriental. Above all, the Laramide orogeny was a profound compressional event (Coney, 1976). The entire crust was folded and broken by very deep-seated thrust faults.

Middle Tertiary

The mid-Tertiary (fig. 5) was certainly the most bizarre and varied period of tectonic activity in the entire history of the region. Its full significance is only recently emerging and is still not fully understood. This was the time of vast calderas (Elston and Northrop, 1976; Damon and Mauger, 1966) and related ignimbrite eruptions on a scale rarely seen anywhere on the planet. It was also a time of widespread shallow cataclastic metamorphism and related deformation in a belt of metamorphic core complexes over 1,000 km long extending from western Arizona to central Sonora.

The period began by the waning stages of widespread erosion of Laramide landscapes (Epis and Chapin, 1975). This produced a major erosional surface, apparently of little relief, which extended far beyond the region concerned here. Broad basins formed, in which rather thick, now largely red, continental deposits accumulated. Locally, there are lacustrine and evaporite deposits. By the late Eocene, Laramide magmatism had swept northeastward into central-southern New Mexico and west Texas. It then began a rapid retrograde sweep back across the beveled Laramide terrane toward the continental margin (Coney and Reynolds, 1977). This magmatic arc had an explosive intensity unparalleled in Cordilleran tectonic history and is directly linked to a Cordillera-wide sequence of volcanism extending from the Pacific northwest (Armstrong, 1974) (Challis-Absaroka) to southern Mexico (Sierra Madre Occidental). This rapid retrograde sweep, actually a magmatic flash, reached the continental margin about 20 m.y. ago, leaving a landscape buried in ash flows and punctured by calderas.

During the outburst, which has most of the characteristics of a magmatic arc relating to subduction, very large extensional terranes formed. These terranes, in part basins, were floored by cataclastically deforming basement gneiss, middle Tertiary plutons and attenuating Phanerozoic rocks. The basins were filled with red-bed deposits and distal volcanic outfall. These terranes eventually domed and arched, causing late sliding and denudation of the extended cover off the rising and still hot metamorphic basement below. A belt of over 15

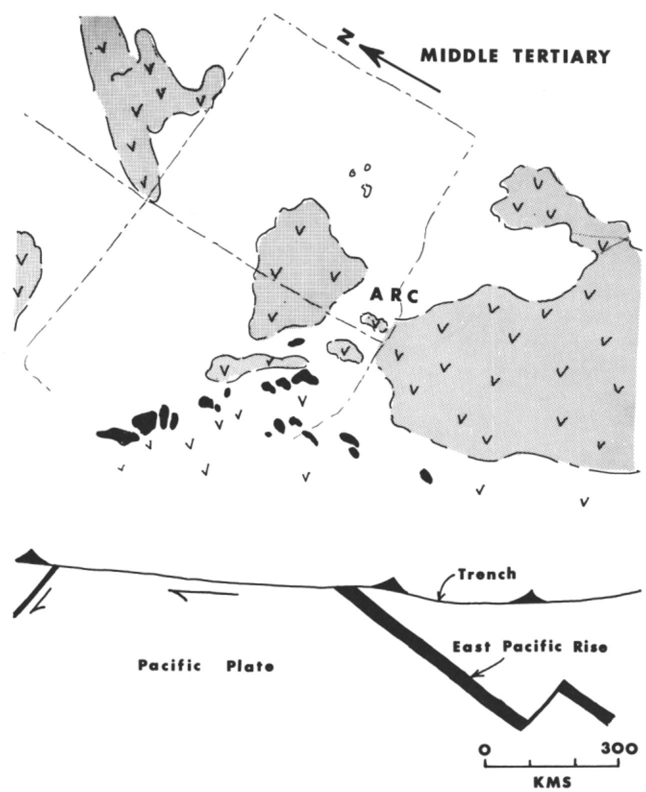

Figure 5. Middle Tertiary. Major features of middle Tertiary magmatism and development of metamorphic core complexes. Larger caldera complexes outlined by V-stipple pattern. Location of presently identified domal uplifts of Tertiary cataclastic gneiss in core complexes shown by solid black. Position of East Pacific Rise approximate at about 20 m.y. ago.

Tertiary metamorphic domed complexes was produced, stretching from the Colorado River near Kingman in western Arizona southeast to Tucson, then southward to Hermosillo, Sonora (Davis, 1977; Rehrig and Reynolds, 1977; Anderson and others, 1977). The belt takes on the character of an enormous zone of pull-apart terrane. The direction of extension (Davis, 1977), recorded in the direction of lineation in the cataclastic gneiss, was within 10° of N. 55° E. over most of the entire belt. As far as is known, none of these evolved in New Mexico. The belt continues, however, into Nevada, Idaho and Washington (Crittenden and others, 1978).

Much of this middle Tertiary history certainly evolved before even initial contact of the East Pacific rise with the trench along southwestern North America, thus during final stages of subduction of Farallon plate (Atwater, 1970). What caused the ignimbrite flare-up and the massive extension is not clear. It is, however, coeval with, and presumably related to, the retrograde sweep of a magmatic arc terrane. This return sweep has been interpreted as due to massive collapse of a flattened Laramide Benioff zone beneath the entire southern Cordillera (Coney and Reynolds, 1977), and all the thermal instability in the upper mantle that such a collapse implies. The period ended, through a period of transition (Eberly and Stanley, 1978; Shafiqullah and others, 1976), with initiation of Basin and Range block-faulting as the Pacific plate came in contact with North America along the growing transform margin.

Late Tertiary

By 15 m.y. ago, the Pacific plate was in contact with North America off Baja California and southern California, and by 6 m.y. ago, the transform boundary had jumped inboard to rift open the Gulf of California and to initiate the San Andreas transform fault system (Atwater, 1970; Atwater and Molnar, 1973). These events correlate in time and in space with widespread block-faulting and with the mainly basaltic volcanism which produced the Basin and Range province and the Rio Grande rift. This period of rifting and extension is clearly superimposed on, and younger than, the volcanic-extensional events of the middle Tertiary.

The faulting appears to be quite steep (Eberly and Stanley, 1978), and often produced narrow graben and wider horsts. The present mountain uplifts have been considerably narrowed by subsequent pedimentation. Most of the major faulting seemed to avoid large caldera-plutonic complexes as well as the Colorado Plateau. The relationship to the Colorado Plateau is of considerable geotectonic significance, and it is important to determine if the Basin and Range collapsed around an already uplifted plateau or if the plateau uplifted in the midst of a foundered Basin and Range province. Certain floral evidence (Axelrod and Bailey, 1976) can suggest the latter, but much additional work needs to be done. Most recent rifting seems to be concentrated in parts of the Rio Grande rift and in a belt extending northward out of eastern Sonora into southeasternmost Arizona, thence arcing northeastward along the mountain province south of the Mogollon Rim.

All of the late Tertiary Basin and Range block-faulting probably produced no more than 15 to 20 percent regional extension, based on reconstructions of faulted margins of uplifts (Coney and others, 1976). Reassembly of the faulted mosaic in southeastern Arizona suggests that the original extension was largely by movements in mostly east-west directions. The amount of additional extension which occurred in northeast-southwest direction during middle Tertiary time is as yet unclear, but local extension in and adjacent to the core complexes may have exceeded 100 percent.

The causes for this late Tertiary extension and rifting have been much debated. The best explanation still seems to be that it is related to evolution of the San Andreas transform system and eventual opening of the Gulf of California. The western margin of North America became a broad zone of simple right shear between a Pacific plate moving northwesterly relative to North America (Atwater, 1970). There is much subtle and complex interplay of collapse and regional uplift during late Cenozoic time. The interplay is probably due to an effect of subsidence, which is caused by attenuation and thinning of lighter upper crustal rocks because of the rifting, and of uplift, presumably slightly later, due to the rise of isotherms from tectonic thinning of the lithosphere.

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