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ABSTRACT OF THE DISSERTATION

Cenozoic Evolution of the Mojave Block and Adjacent Areas

by

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Doctor of Philosophy in Geology
University of California, Los Angeles, 1981
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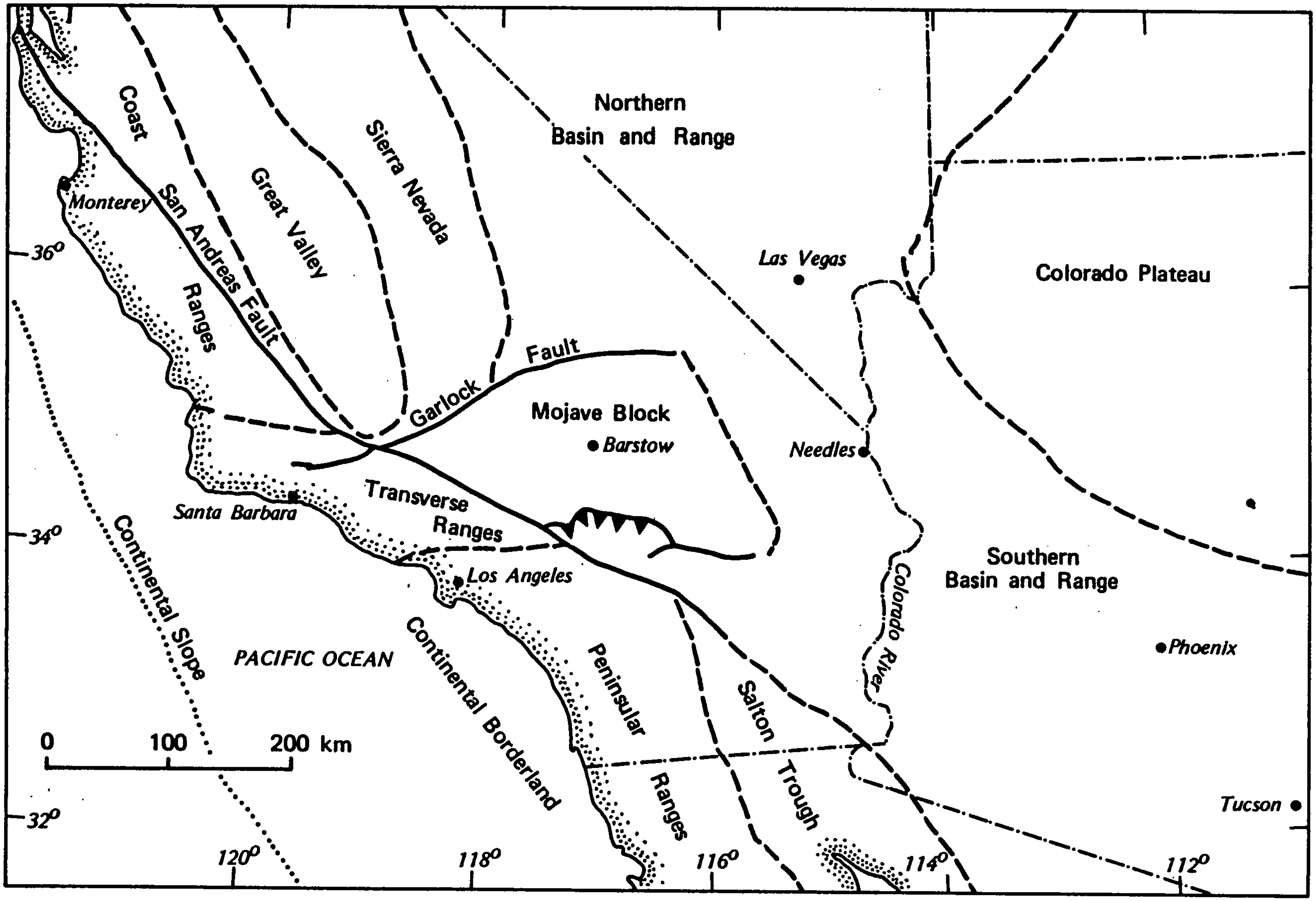
Recent studies of Tertiary terranes in the southwestern United States show that volcanism and faulting occurred during a short time interval (1-3 m.y.) during the mid to late Tertiary. This period of magmatism and deformation, known as the mid-Tertiary orogeny, resulted in rapid extrusion and faulting of thick volcanic sequences. Many of the terranes exhibit low-angle normal (detachment) faults, and lie above metamorphic core complexes. A compilation of fault and volcanic-rock ages shows that the orogeny moved northwest with time, occurring about 25 m.y. ago near Tucson and 5-10 m.y.

ago in Death Valley. Plate reconstructions show that the orogeny occurred when the subducted Mendocino fracture zone (MFZ) passed under each terrane.

The MFZ was a major east-west discontinuity in the subducted Farallon plate, because it juxtaposed very young lithosphere on the south against old lithosphere on the north. The continental plate flexed in response to this density contrast in the subducted plate, producing a regional, monoclinal, north-facing slope that moved northward at a few cm/year, leaving the ground in its wake about 1 km higher than before it passed. Faulting and volcanism were probably triggered by stresses induced in the continental plate by passage of the subducted MFZ. Studies of sedimentary basins and drainage patterns in the Southwest support the theory of a regional, north-facing, north-moving slope in late-Oligocene--Miocene time, and suggest that east-west faults in the Transverse Ranges formed as the crust failed above the subducted fracture zone.

Detailed mapping in the southeastern Cady Mountains shows how the orogeny affected the Mojave block. About 20 m.y. ago, over 3 km of volcanic rocks were extruded and cut by low-angle normal faults within a 1- to 2-m.y. period. The stratigraphic sequence comprises, from old to young, 1) andesite, 2) bimodal basalt-silicic tuff, 3) dacite, 4) lacustrine sediments. Correlation with the rest of the Mojave


Northern
Basin and Range
Colorado Plateau
Coast
Monterey
San Andreas Fault
Great Valley
Sierra Nevada
Las Vegas
36°
Ranges
Garlock
Fault
Mojave Block
Barstow
Needles
Transverse
Ranges
Santa Barbara
34°
Los Angeles
Southern
Basin and Range
Colorado River
Continental Slope
PACIFIC OCEAN
Continental Borderland
Peninsular
Ranges
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0
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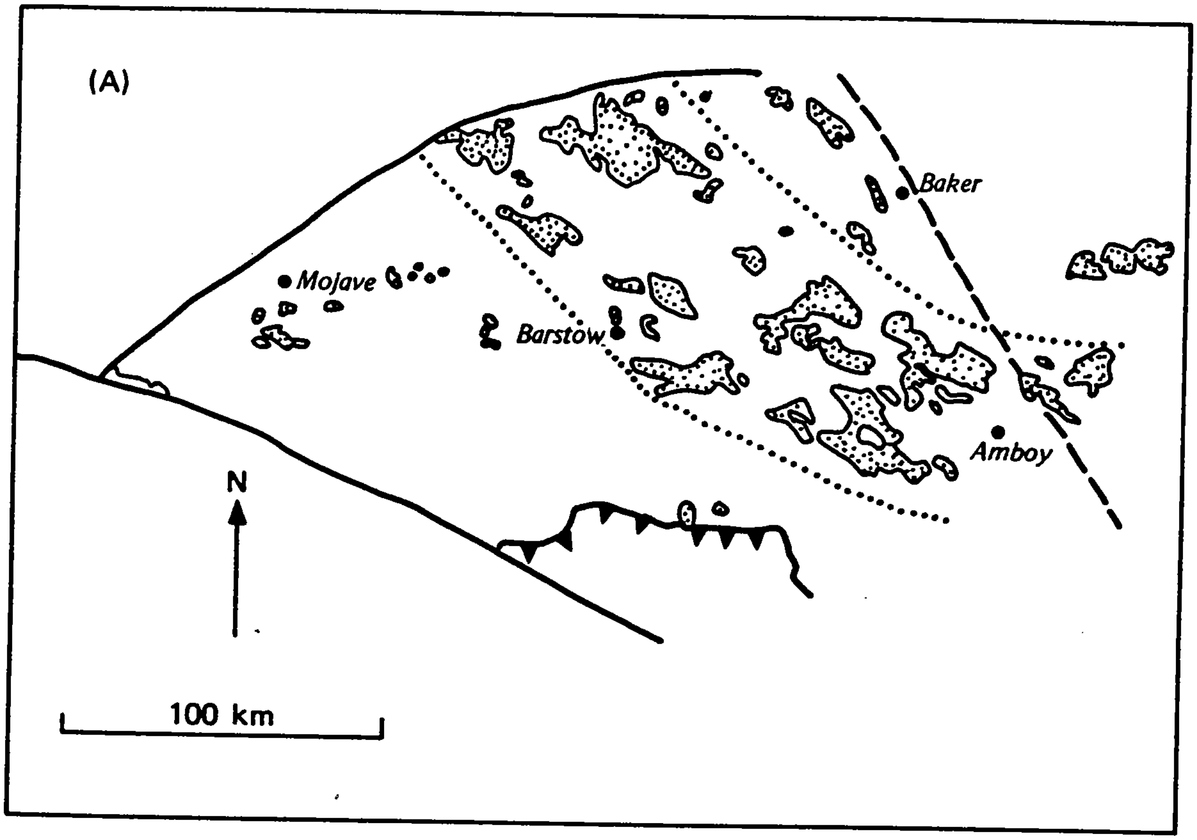
(A)
Baker
Mojave
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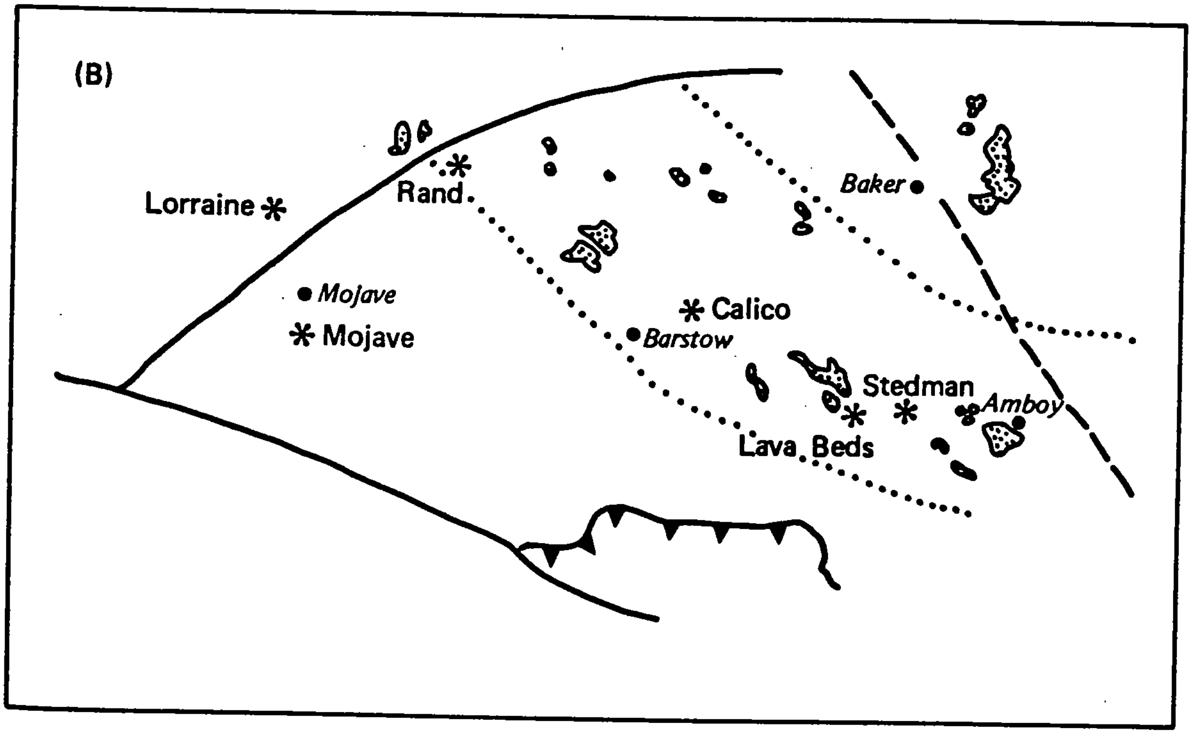
(B)
Lorraine
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Baker
Mojave
Mojave
Calico
Barstow
Stedman
Amboy
Lava Beds

2.2 CENOZOIC HISTORY OF THE MOJAVE BLOCK

2.2.1 Pre-Tertiary

There are few detailed studies of the pre-Tertiary history of the Mojave block. Current knowledge is summarized in Burchfiel and Davis (1981) and Dibblee (1980). Briefly, the region was characterized by sedimentation during the Precambrian and Paleozoic, and by Andean-type magmatism during the Mesozoic. These events produced a varied pre-Tertiary basement, consisting largely of Mesozoic granitoids with pendants of Mesozoic metavolcanics and older metasediments.

2.2.2 Paleogene

There are no known Paleogene rocks in the Mojave block, so the history of this period is obscure. Paleogene rocks are present north of the Garlock fault, in the El Paso Mountains (Eocene Goler Formation) and Death Valley area (Oligocene Titus Canyon beds), but none have been identified within the block. Armstrong and Suppe (1973) failed to find any Tertiary plutonic rocks in the Mojave region. In addition, Precambrian and Paleozoic rocks, which are thick and abundant in areas surrounding the block, are thin and scattered within it. This is shown strikingly by Figure 9-2 of Burchfiel and Davis (1981).

By inference, then, the Mojave block was undergoing great erosion with external drainage during at least the late Paleogene (Hewett, 1954; Nilsen, 1977). Hewett estimated uplift of 4.5-6 km during this period, based on a comparison of the thickness of pre-Mesozoic units within and outside the block. During this time, the Mojave shed vast quantities of sediment westward to coastal basins in California. Paleogeographic reconstructions (Nilsen and McKee, 1979) show that the ancestral Colorado River had developed by the Oligocene, so much of the debris could have been carried eastward as well. Reed (1933) called this highland, together with the Sierra Nevada to the north, "Mohavia." He concluded that it must have risen quite rapidly, because Paleogene coastal sediments are feldspathic. This uplift coincided with an Oligocene marine regression (Reed, 1933; Ingle et al., 1976).

2.2.3 Miocene

The tectonic character of the Mojave block changed abruptly in the early Miocene, when widespread volcanism began and the Barstow-Bristol trough developed. Isotopic dates indicate that volcanism began abruptly across the block about 22-20 m.y.b.p. (Chapter 3; Armstrong and Higgins, 1973; Woodburne et al., 1974; Nason, 1978; Miller, 1978; Moseley, 1978; Dokka, 1980). The onset of volcanism apparently coincided closely with inception of basin development, because early volcanic rocks are interbedded with coarse clastic sediments in some areas.

Early volcanism was most voluminous in the central Mojave, between the Newberry and Bristol Mountains. Here, thick volcanic piles accumulated along the axis of the Barstow-Bristol trough. The southwestern limit of volcanism was very sharp, and essentially no rocks were erupted or intruded southwest of this boundary (Figure 4).

The most voluminous volcanism during this early period was bimodal, consisting of high-Ti mafic flows interbedded with silicic tuffs. This bimodal assemblage forms thick basal units in the Newberry Mountains (Dokka, 1980; Nason, 1978) and Bullion Mountains (Bassett and Kupfer, 1964). However, in the southeastern Cady Mountains, the bimodal series is underlain by a thick series of andesite flows and tuffs that bear a close resemblance in chemistry, petrography, and mode of eruption to lavas from the Cascades (Chapter 3). These rocks may represent a localized early phase of intermediate, subduction-related volcanism that predated the bimodal sequence, in keeping with the LPC model.

After the major pulse of volcanism, voluminous sedimentation began in parts of the Mojave. These early sediments are represented by the Hector Formation in the Cady Mountains (Woodburne et al., 1974; Miller, 1978; Moseley, 1978), the Tropico Group in the western Mojave (Dibblee, 1967a), the Spanish Canyon Formation in the Alvord Mountains (Byers, 1960), and by several local units in the Newberry Mountains (Dokka, 1980). Dates on intercalated volcanics indicate that these sediments accumulated over a period of several million years, beginning about 22 m.y.b.p. The sediments are varied, and represent alluvial, fluvial, and lacustrine facies of evolving lake basins. The persistence of these basins indicates that they were tectonic in origin, rather than ephemeral basins formed when volcanoes dammed existing drainage.

The boundaries of the Barstow-Bristol trough were actively developing during the early Miocene. The best-studied example is in the Newberry Mountains. Dibblee (1971, 1981) interpreted the Tertiary-basement contact there as a great buttress unconformity, but Dokka (1976, 1980) reinterpreted it as a low-angle detachment fault. In Dokka's model, the boundary developed as Tertiary rocks tilted and moved northeastward along listric normal faults. Thick wedges of coarse clastic sediments accumulated in the gap between allochthonous upper plate and autochthonous basement. The time of movement is bracketed between 23 and 21 m.y.b.p., based on two isotopic dates. However, if the Cady Mountains are part of the same terrane, as Dokka (1980) has suggested, then movement must have occurred after 20 m.y. ago, because units in the Cady Mountains dated at 20 m.y. are steeply tilted (Chapter 3; Plates 1 and 2). Dokka's date of 21 m.y. changes to 17.6 m.y. if the more recent decay constant of Galliker et al. (1970) is used; this constant is preferred (Wagner et al., 1975)[#]. Unfortunately, the Tertiary-basement nonconformity is not exposed in the Newberry Mountains, so the original configuration of the contact is unknown.

In the northern Cady Mountains, Miller (1978) and Moseley (1978) determined that the Hector Formation was deposited in an elongate, east-west-trending basin, with a granitic source to the north and a volcanic source to the south. Transport was dominantly to the north. They found no evidence that the contact and basin were modified by detachment faulting. In the western Mojave, early Miocene, borate-bearing sediments of the Tropico group were laid down in an east-west basin that was bounded on the south by a normal fault (Siefke, 1980).

Lake sedimentation continued at least into the middle Miocene in several areas, with the accumulation of great thicknesses of Barstow Formation sediments (Dibblee, 1968; Byers, 1960; Link, 1980). These sediments contain scattered

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[#] Low values of the decay constant for spontaneous fission of U-238, such as that used by Dokka, are apparently biased low because of track fading. However, some authors maintain that the old value shows better agreement with the K-Ar method (e.g., Izett and Naeser, 1976). For a review, see Faure (1977, p. 269).

volcanic units belonging to the bimodal sequence, and they were generally deposited in downwarping basins that were elongate east-west or northwest-southeast. Like earlier basins, these were concentrated along the Barstow-Bristol trough. Byers (1960), in his study of the Alvord Mountains quadrangle, concluded that the Barstow Formation was deposited in a westnorthwest-trending basin or chain of basins; Link (1980) reached similar conclusions. The nature of the basin margin is speculative. The great thicknesses of sediments deposited in areally restricted basins suggest that high-angle faulting was responsible. This is supported by the occurrence, in most sections, of abundant alluvial units and landslide breccias derived from nearby highlands.

At most of the Miocene volcanic centers, the last eruptions were dacitic or andesitic, and their compositions fall within the compositional gap of earlier bimodal eruptions. Eruption of these intermediate rocks occurred at different times at different centers, occurring earlier in the center of the Barstow-Bristol trough than in areas to the north. In the Newberry Mountains, a thick section of dacites, bracketed by Dokka (1980) and Nason (1978) between 23 and 21 m.y. old, caps the bimodal (dominantly basaltic) section. Similar dacites cap the bimodal sequence in the southeastern Cady Mountains (20.2 ± 1.3 m.y.; see Chapter 3) and Bullion Mountains (Bassett and Kupfer, 1964). In the area north and northeast of Barstow, pods of dacite and andesite intrude and overlie the middle Miocene Barstow Formation (Dibblee, 1968; Byers, 1960), and one has been dated at 13.5 m.y.b.p. (unpublished data by Hillhouse et al., cited in Link, 1980). In the Lava Mountains, near the Garlock fault, dacite flows overlie sediments that are dated by fossils as late Miocene (mid-Hemphillian; Smith, 1964, and C.A. Repenning and G.I. Smith, personal communications, 1981).

Sedimentation and volcanism were minor in the Mojave block in the late Miocene and Pliocene. The only known or suspected sediments of this age, aside from the Lava Mountains, occur in a few isolated exposures in the western Mojave block (Dibblee, 1967). Deposition of the Barstow Formation probably ceased in the middle Miocene (about 13 m.y.b.p.), although younger sediments may have been deposited in the basin of the Barstow Formation, and later eroded (Link, 1980). Sediments in some of the deeper playa basins may be Pliocene.

2.2.4 Pliocene and Quaternary

After middle Miocene bimodal and dacitic volcanism waned, alkali basalts were erupted from cinder cones scattered along the Barstow-Bristol trough. These lavas, which range from subalkaline basalts to basanites (Wise, 1969), were erupted from vents not directly associated with earlier Miocene volcanic centers. The major vents, such as Amboy Crater, Pisgah Crater, and Black Mountain, lie in a narrow band along the axis of the trough (Figure 4). These rocks are equivalent to widespread late Cenozoic alkali basalts of the Basin and Range (Leeman and Rogers, 1970; Best and Brimhall, 1974). Most of the basalts are considered to be Quaternary, although unpublished data of Hillhouse et al. (cited by Link, 1980) dates the Black Mountain basalt near Barstow at 2.5 m.y., and Katz and Boettcher (1980) report that the Cima field, outside the Mojave block, ranges in age from 10 million to 400 years.

The Quaternary brought a renewal of lacustrine sedimentation in the Mojave, after the late-Miocene-Pliocene lull. The deepest basins developed along the Barstow-Bristol trough, and are now expressed by playas such as Lavic, Bristol, and Cadiz Lakes. Sediments in these lakes extend at least several hundred feet below sea level (Darton et al., 1915, p. 157; Thompson, 1929, p. 696-699; Bassett et al., 1959; Madsen, 1970), so the basins are obviously of tectonic origin.

2.2.5 Summary

The short history given above shows that the Mojave block was affected by a brief but intense episode of volcanism and tectonism in the early Miocene, after a long period of quiet uplift. This history is outlined below.

1) During the Paleogene, pre-Tertiary basement of the Mojave block was uplifted and eroded, with external drainage. No Paleogene rocks are known from within the block.

2) In the early Miocene, about 22 m.y.b.p., widespread volcanism began, and the Barstow-Bristol trough developed as a volcano-bearing graben. Early volcanic rocks were dominantly bimodal assemblages of high-Ti basalts and silicic tuffs, like post-subduction assemblages of the Basin and Range. The Cady Mountains, and possibly a few other areas (Chapter 3), show an earlier assemblage of low-K, Cascade-type andesitic volcanism.

3) At most of the volcanic centers, the latest eruptions were of dacites whose compositions fall in the compositional gap of the earlier bimodal eruptions. The change to dacites was time-transgressive, moving from the center of the block in the early Miocene to the northern edge in the Pliocene.

4) Voluminous sedimentation began shortly after intense volcanism ceased, in a chain of basins along the Barstow-Bristol trough. Basins continually shifted throughout the Cenozoic; early Miocene, middle Miocene, Pliocene, and Quaternary sediments are separated from one another and rarely occupy the same basin. Many of the basins were elongate east-west.

5) In the early Miocene, during or shortly after the main pulse of volcanism, much of the central-Mojave volcanic terrane was involved in a brief episode of detachment faulting. Transport of the upper plates was to the northeast.

6) Sedimentation continued through the middle Miocene with deposition of terrestrial sediments of the Barstow Formation. These sediments contain minor beds of basalt and tuff, and they are locally overlain by dacite.

7) Sedimentation and volcanism had largely ceased by the end of Barstovian time, about 13 m.y. ago. The late Miocene was a quiet time in the Mojave block.

8) The Pliocene or early Quaternary brought a renewal of volcanism and sedimentation, when alkali basalts were erupted and deep playa basins formed. The deepest basins and most of the cinder cones developed in the Barstow-Bristol trough. Continued downwarping of these basins is responsible for maintenance of the trough as a topographic form.

2.3 TECTONIC HISTORY OF THE MOJAVE BLOCK

2.3.1 Previous reconstructions

The Cenozoic tectonic evolution of the Mojave block and surrounding areas is tied closely to plate-tectonic events that occurred off the California coast. Early reconstructions, based on magnetic anomalies in the Pacific ocean, proposed that most of the Farallon plate was subducted under the west coast of North America during the late Mesozoic and early Tertiary (Vine, 1966; McKenzie and Morgan, 1969; Atwater, 1970). Subduction of the Farallon plate stopped when the spreading ridge, which was moving toward the continent, met the trench; motion between the Pacific and North American plates then occurred by strike-slip faulting. The Juan de Fuca-Gorda and Cocos-Rivera plates are remnants of the Farallon plate. These early reconstructions indicate that first contact between the Pacific and North American plates occurred in the Oligocene.

More detailed reconstructions can be developed by looking at relative movements between plates. The "global plate-circuit" method (Atwater and Molnar, 1973; Pilger and Henyey, 1979; Molnar and Stock, 1981) calculates relative motions at collisional boundaries by summing plate motions at spreading centers. The "hot-spot" method (Coney, 1978; Engebretson and Ben-Avraham, 1981) calculates movements of plates over hot spots that are assumed to be fixed relative to one another. In this paper, the plate-circuit reconstruction of Pilger and Henyey (1979) is used. Molnar and Stock (1981) discussed the uncertainties in such reconstructions.

Figure 5 is a series of reconstructions showing the relative positions of the Pacific, Farallon, and North American plates at 38, 29, 21, and 10 m.y.b.p. In this reconstruction, subduction occurred along the entire coast of western North America throughout the early Tertiary, as the Pacific-Farallon ridge steadily moved toward the trench. Initial contact between the Pacific and North American plates occurred about 30 m.y. ago, west of northern Mexico. Subduction of the Farallon subplate between the Mendocino and Pioneer fracture zones continued under the Mojave for another 8 m.y. or so, until that segment of ridge reached the trench. From that time (22-20 m.y.b.p.) to the present, the Pacific-North American plate boundary in southern California has been characterized by strike-slip movement.

Evidence presented earlier shows that volcanism did not begin in the Mojave until about 22 m.y.b.p., and Armstrong and Higgins (1973), Snyder et al. (1976), and Cross and Pilger (1978) showed that volcanism in much of the Southwest did not begin until this time. Thus, the hiatus in magmatism was of regional extent, even though the area was above an active subduction zone. Volcanism began when the ridge neared the trench, and when the Mendocino and Pioneer fracture zones passed under the southwestern United States. This suggests a connection between volcanism and subduction of young crust and fracture zones.

2.3.2 Second-order effects of subduction

2.3.2.1 Subduction of young crust

In most of the classic areas of subduction, such as the Aleutians and western-Pacific island arcs, the crust being subducted is relatively old (50-100 m.y.). There are only a few areas, such as the Juan de Fuca-Gorda and Cocos-Rivera plates, where very young crust is being subducted. These areas are characterized by slow convergence rates and poorly-defined or absent Benioff zones and trenches. Figure 5 shows that when volcanism began in the Mojave block, very young crust was being subducted. Therefore, the plate-tectonic setting of the block was similar to that of the southern Cascades or Trans-Mexican volcanic belt, and unlike the Andes.

Young and old lithosphere behave differently because young lithosphere is thinner, and therefore stands higher. As newly created lithosphere cools, it becomes denser, sinks, and moves away from the spreading ridge. The relationship between the depth and age of ocean crust was quantified by Sclater et al. (1971), who showed that depth increases as the square root of age. Ridges stand about 3 km above the level of old (100 m.y.) ocean floor.

If the crust being subducted becomes progressively younger with time, as depicted in Figure 5, then the overlying plate will undergo uplift in an attempt to maintain isostatic equilibrium (Damon, 1979; DeLong and Fox, 1977). The amount of uplift is about 70 percent of the change in elevation of the crust being subducted. In Figure 5, the oceanic plates are contoured for depth, using the depth-age relationship of Sclater et al. (1971) and assuming a spreading half-rate of 4.4 cm/year, derived from the data of Atwater and Menard (1970) and the time scale of Heirtzler et al. (1968). The contours show that uplift of the area south of the Sierra Nevada should have totaled over 2 km during the early Tertiary, with the maximum uplift rate occurring just before subduction stopped, in the middle or late Oligocene.

The force driving young oceanic plates down the subduction zone is weaker than the force driving old plates. Calculations by Forsyth and Uyeda (1975) indicate that the slab-pull force, caused by cool, dense lithosphere sinking into the mantle, is far and away the strongest force driving the downgoing slab. Because young plates are pulled by thinner lithosphere than old plates, their slab-pull force is weaker and they descend more slowly. This is exhibited today by the young Rivera and Gorda plates, both of which are converging very slowly with North America, after earlier episodes of rapid convergence. Below, it is shown that the Farallon plate also slowed as the ridge approached the trench in the Oligocene.

Subduction of young crust produces magmatism of characteristic location and type. Because young lithosphere is thinner than old, H2O (as pore fluid and in hydrous minerals) and basaltic (eclogitic) crust carried down the subduction zone reach high temperatures at shallower depths, and the locus of magmatism shifts seaward. Pilger and Henyey (1979) invoked this effect in their explanation of coastal volcanism in California, and Cross and Pilger (1978) used it to explain the divergent trend between the Trans-Mexican volcanic belt and the Middle America trench, above the Cocos plate. Hurst (1978) noted that the anomalously low potassium contents of volcanic rocks in coastal southern California are consistent with shallow melting caused by proximity of a spreading ridge.

2.3.2.2 Subduction of fracture zones

Because of the differences between young and old crust, subduction of fracture zones can have important consequences in the overlying plate. The crust on one side of a fracture zone is older and lies at a lower elevation than crust opposite it across the fracture zone. As the ridge approaches the trench, relief on the downgoing fracture zone increases rapidly. Because of the difference in elevation, the overlying plate, above the fracture zone, will be stressed as it tries to isostatically adjust. Trench-pull on the young subplate will be less than that on the old, so the two subplates may separate along the fracture zone and descend at different rates, moving past one another with strike-slip motion that may be communicated to the overlying plate. Figure 6 illustrates the effect of subduction of a fracture zone on the overlying continental plate.

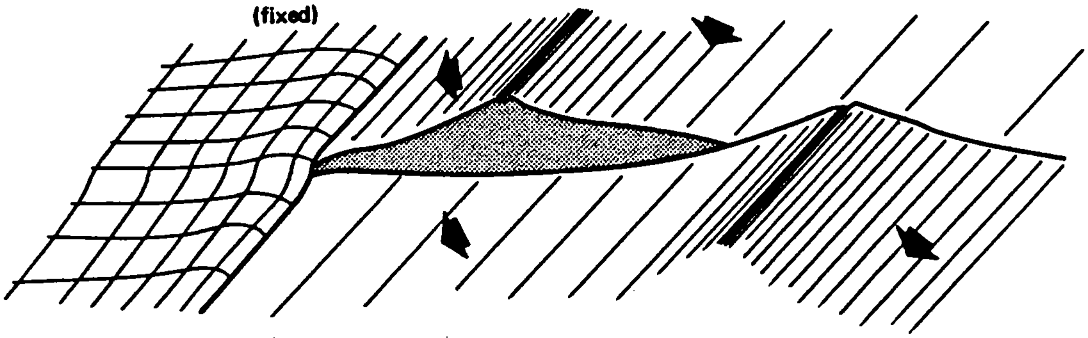

Figure 6: Subduction of a fracture zone

The importance of bending effects in the upper plate caused by subduction of a fracture zone can be estimated by treating the plate as an elastic slab overlying fluids of different densities. The model is illustrated in Figure 7a, and details of the calculation are in Appendix 1. For a given flexural rigidity (which depends on Young's modulus and Poisson's ratio), the width of the bent zone is a function of the mechanical thickness of the plate. Turcotte et al. (1978) derived plate-thickness values of 20-30 km in solution of the problem of bending of the downgoing slab at a trench, a problem which is similar in strain rate to the one considered here. Figure 7b gives the calculated profile of the overlying plate for thicknesses of 20 and 30 km.

causing upwelling of hot underlying asthenosphere along a narrow zone. The Pioneer fracture zone apparently spread in this manner about 30 m.y. ago (see below).

The Juan de Fuca and Gorda plates present present-day examples of oblique subduction of young lithosphere. These young plates are steadily shrinking as the ridge moves toward the trench. Vine (1966) showed that the spreading rate decreased suddenly about 5 m.y. ago. According to the discussion above, this decrease is a result of reduced trench-pull on the thinning plate. Magnetic anomalies younger than 5 m.y. are rotated clockwise relative to older anomalies (Raff and Mason, 1961; Atwater and Menard, 1970), perhaps because the spreading direction rotated in response to slower convergence and increased coupling with the North American plate. Anomalies in the Gorda plate, the youngest of the subplates, are conspicuously bent and have rotated about 45 degrees relative to the ridge. Silver (1971) gave evidence that the thin, weak Gorda plate is underthrusting the Pacific plate along the Mendocino escarpment.

2.3.3 Plate-tectonic evolution of the Mojave block

In summary of the above discussion, oblique subduction of young crust and fracture zones can produce several effects that are not seen with subduction of old crust. The most important effects are: 1) slowing of spreading rate, 2) uplift of overlying plate, 3) rotation of young subplate, with concomitant opening of fracture zones and upwelling of asthenosphere, and 4) shifts in loci and character of magmatism. With these concepts and Figures 5 and 6 in mind, we can interpret the plate-tectonic history of the Mojave block.

2.3.3.1 Pre-Miocene

In the early Tertiary, the Mojave block was avolcanic even though it was above an active subduction zone. This lull in volcanism encompassed the entire southwestern United States (Armstrong and Higgins, 1973; Snyder et al., 1976; Cross and Pilger, 1978). Although the reason for this is unclear, Snyder et al. (1976) invoked a proto-San Andreas fault, whereas Coney and Reynolds (1977) and Keith (1978) related the quiet time to shallow dip of the subduction zone, with analogy to present-day avolcanic sections of the Andes (Barazangi and Isacks, 1976). Presumably, the Southwest was undergoing slow uplift during this time, owing to subduction of progressively younger crust (Damon, 1979).

By the middle Oligocene, the ridge was quite close to the trench (Figure 5b). Offset on the Pioneer fracture zone at the trench was about 600 m. About 30 m.y. ago, the Pioneer-Murray subplate of the Farallon plate broke up and rotated clockwise (Figure 5b). Spreading slowed abruptly at this time (Atwater, 1970, Figure 11), because of the difficulty of subducting young, broken crust.

When the subplate rotated, the Pioneer fracture zone opened up (Figure 5b). This process is similar to that discussed by Menard and Atwater (1968), who showed that changes in spreading direction result in secondary spreading along transform faults. Secondary spreading caused by rotation of the Pioneer-Murray subplate is expressed in magnetic anomaly data as northwest-trending anomalies that formed normal to the ridge (Mason and Raff, 1961, summarized in Figure 11 of Atwater, 1970; Theberge, 1971). Upwelling of hot asthenosphere along the fracture zone should have caused noticeable effects in the overlying plate. It is intriguing to note that the postulated zone of upwelling roughly corresponds to the southern limit of the Basin and Range province, and that upwelling coincided with development of basin-range structure in this area (Stewart, 1978). Perhaps upwelling produced a thermally weakened zone in the upper plate, which developed basin-range structure when subduction ceased and extension began. Upwelling could also have initiated delamination of the continental lithosphere, as described by Bird (1979), resulting in uplift and thinning of the lithosphere.

The history of the Pioneer-Murray subplate after anomaly 8 (29 m.y.b.p.) is sketchy, because younger anomalies are not clearly defined. Presumably, transform motion began near the trench when the Pacific and North American plates came in contact.[#] The Pioneer-Murray subplate may have descended with the rest of the Farallon plate, forming a "slab window" as postulated by Stewart (1978) and Best and Hamblin (1978). This window inadequately explains the development of the southern Basin and Range, as proposed by Dickinson and Snyder (1979b), because it does not clarify the timing of the structures. Alternatively, the subplate may have broken up and acted independently of the rest of the Farallon plate; its lesser density contrast with the surrounding asthenosphere would probably have resulted in a shallower angle of descent. In any case, it quickly lost its identity in the mantle, because it was young, thin, and nearly thermally equilibrated when it began descent.

2.3.3.2 Late Oligocene-Miocene passage of the Mendocino fracture zone

Strong Oligocene uplift of the Mojave block occurred because high-standing, young lithosphere south of the Mendocino fracture zone moved under the block. About 29 m.y. ago, the Mendocino fracture zone was under the south end of the Mojave area, moving north at about 3.5 cm/year (Figure 5b). Relief on the fracture zone was about 1 km at the trench,

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[#] This simple model assumes that the trench is roughly parallel to the vector of relative motion between the two plates. Complications can arise if this is not true (Dickinson and Snyder, 1979a).

and steadily increasing. Thus, the step in the overlying plate swept north like a wave across the Mojave, causing uplift totalling 0.5-1 km within about 5 m.y.

As the Mendocino fracture zone scraped along the base of the North American plate it may have opened, as the Pioneer did. However, the youngest identifiable anomaly on the Mendocino-Pioneer subplate is anomaly 8, 29 m.y.b.p. (Atwater, 1970), so more recent history is unclear. Magnetic surveys (Mason and Raff, 1961; Theberge, 1971) show a few northwest-trending anomalies on the young side of anomaly 8. These probably represent spreading of the fracture zone.

Figure 5 shows that the Mendocino fracture zone passed under the central Mojave block in the early Miocene. Subduction stopped at about the same time, because the ridge met the trench. In the formerly quiet Mojave block, the Barstow-Bristol trough developed, volcanism and sedimentation began, and detachment faulting occurred. All these phenomena may be related to disruptions in the overlying plate caused by passage of the fracture zone.

Volcanism. Volcanism requires both a magma source and a path to the surface. Perhaps passage of the fracture zone cracked the block, which had been stable until that time (Figure 8). Cracks allowed magma generated by the downgoing slab to reach the surface. Shortly after cracking occurred, subduction ceased and volcanism changed from intermediate to bimodal.

The distribution and age of Cenozoic volcanic rocks in the Southwest supports the idea that volcanism was triggered by passage of the fracture zone. Figure 9 shows the ages of volcanic rocks in several fields plotted against latitude. The path of the Mendocino fracture zone is superimposed (the fracture zone trended approximately east-west, so its latitude offshore was about the same as its latitude under the continent). Figure 9 shows correspondence between the inception of volcanism and passage of the fracture zone. In several widely spaced areas with brief but intense volcanism, the volcanic pulse coincided with passage of the fracture zone. These areas include the Mojave block, southeastern California (Crowe et al., 1979), southernmost Nevada (Anderson et al., 1972), and southwestern Arizona (Eberly and Stanley, 1978). Figure 9 suggests that there may be a correlation between the type of magma erupted and its relationship to passage of the fracture zone. Data that lie off the line to the right represent flat-lying, post-orogenic, bimodal basalt or basalt-rhyolite fields, whereas data that plot on the line reprsent fields characterized by intermediate composition, severe faulting and tilting, and associated coarse sedimentary breccias.

Figure 10, a plot of 198 K-Ar ages from southwestern Arizona, shows this correspondence in more detail. Most of the dates are on volcanic rocks, but a few are cooling ages on basement rocks. Much scatter is evident, but in general, volcanism began shortly after the fracture zone passed. Seven-tenths of the rocks were erupted within the time span from 1 m.y. before to 6 m.y. after the predicted time of passage (Figure 10b). Many of the points that lie far to the right of the line are dates on flat-lying, post-orogenic basalts. The data are biased toward these younger rocks, because of the difficulty of dating older altered and faulted rocks. Because of uncertainties in the plate reconstruction, no special significance should be attached to the apparent time lag between passage of the fracture zone and beginning of volcanism.

Data from several sources (Coney and Reynolds, 1977; Keith, 1978; Cross and Pilger, 1978) show a significant decrease in age of volcanism toward the trench. Coney and Reynolds and Keith attributed this seaward shift of volcanism to a rapidly steepening subduction zone, but another explanation is that melting occurred at shallower and shallower levels with time because the subducted plate, south of the fracture zone, was younger and younger (Shafiqullah et al., 1980). This explanation avoids problems inherent in the flapping subduction zone model; namely, that the young plate is thin and close to thermal equilibrium with the surrounding mantle, so its trench-pull is small, and there is no force driving it to dive steeply into the asthenosphere.

Detachment faulting. Passage of the fracture zone under the Southwest apparently triggered detachment faulting as well as volcanism. Figure 11 shows that the ages of faulting in detachment terranes ranging from Tucson to Death Valley agrees closely with passage of the fracture zone. Faulting occurred about 25-30 m.y. ago in the Tucson area, 20 m.y. ago in the central Mojave, and 10 m.y. ago in the Death Valley area. Many of these low-angle faults are related to metamorphic core complexes, but many are not. They record the northward passage of a wave of detachment faulting that coincides with passage of the Mendocino fracture zone under the southwestern United States.

The elastic model presented above suggests that low-angle faulting may have been caused by the slope and associated fracturing developed above the fracture zone. Faulting would take advantage of inhomogeneities in the crust, such as lithologic contrasts, preexisting slopes, and regional northeast-southwest extension. Mylonite zones in metamorphic core complexes may have provided favorable horizons for detachment. Faulting may have been a cause, rather than a consequence, of uplift of the complexes; uplift caused by unroofing by denudational faulting would fix cooling ages at values equal to or slightly less than the time the fracture zone passed under the complex. This model explains why some complexes that had already cooled, such as the Whipple Mountains (Davis et al., 1980), show mylonitization ages much older than the age of faulting, whereas others, such as the South Mountains near Phoenix, show late Oligocene ages that are thought to coincide with faulting (Reynolds and Rehrig, 1980).

If the sole cause of detachment faulting were the slope generated by the fracture zone, then transport of the upper plate should have been to the north, perpendicular to the fracture zone. However, most of the terranes listed in Figure 11 show transport to the northeast, with a few to the east and a few to the west. This indicates that northeast-southwest crustal extension played a large part in directing detachment faulting, as suggested by many authors (e.g., papers in Crittenden et al., 1980). But if pure extension were the only cause of detachment faulting, then transport directions should be bimodal, with some to the northeast and some to the southwest. The lack of transport to the south or southwest, which would have been up the slope, suggests that the fracture zone also controlled the direction of transport. This combination of northeast-southwest extension with a north-facing slope could account for the pronounced asymmetry (Rehrig and Reynolds, 1980) exhibited by many metamorphic core complex-detachment fault terranes.

Paleogeography and sedimentation. Studies of Oligocene-Miocene paleogeography support the concept of a regional north-facing slope in the southwestern United States. Cooley and Davidson (1963), Nilsen and McKee (1979), Cole and Armentrout (1979), and McKee and McKee (1972) showed that drainage in the Southwest was generally to the north until the middle Miocene, when it reversed and flowed south. Reversal occurred after the predicted time of passage of the slope.

Detailed studies of individual basins in southern California lend further support. Many of these basins show thick sequences of Oligocene-early Miocene, nonmarine, redbed conglomerates, breccias, and megabreccias (Bohannon, 1975; Dibblee, 1977). Early Miocene sedimentary units of the Mojave block (Dokka, 1980; Siefke, 1980; Miller, 1978) are included in this category. The redbeds are locally underlain by Oligocene or older marine sediments, and overlain by middle Miocene or younger nonmarine and marine sediments. Paleocurrent directions in units bounding the redbeds are generally to the west or south (Ehlig et al., 1975; Woodburne, 1975; Peterson, 1975; Sage, 1973), but in the redbeds, transport was dominantly to the north# (Bohannon, 1975; Kahle, 1966; cf. Spittler and Arthur, 1973). These deposits accumulated at the bases of east-west trending normal faults that were downthrown to the north (Bohannon, 1975; Crowell, 1968). If the redbeds are realigned by restoring slip on the San Andreas and San Gabriel faults, they line up with the Chocolate-Orocopia terrane of southeastern California (Crowell, 1962; Bohannon, 1975; cf. Woodburne, 1975; Baird et al., 1974; Spittler and Arthur, 1973). Figure 11 predicts that the Mendocino fracture zone should have passed under this area about 23 m.y. ago; dates on volcanic rocks intercalated with the redbeds cluster around this same age (Crowell, 1973). Thus, passage of the fracture zone under these terranes coincided with basin development. Early Miocene basins in the Mojave (Dokka, 1980; Miller, 1978;

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These directions must be interpreted in light of paleomagnetic data that shows clockwise rotation of 90 degrees or more during Miocene time for parts of southern California (Kamerling and Luyendyk, 1979; Luyendyk et al., 1980). However, Luyendyk et al. show rotations in the area of many of the redbeds (e.g., Soledad Basin) to be small.

Moseley, 1978; Siefke, 1980) also show generally north to northeast transport, often from the bases of up-on-the-south faults, and formed when the fracture zone passed under them.

Data from the Los Angeles and Ventura basins do not fit the model as well as data from basins nearer the San Andreas fault, perhaps because of the imprecision of palinspastic reconstructions. In the Los Angeles basin, the nonmarine Sespe Formation of Oligocene age is overlain by the marine Vaqueros Formation of early Miocene age (Yerkes et al., 1965); the transition was roughly 23-25 m.y. ago. This would coincide with uplift of the basin by the fracture zone, if palinspastic reconstructions correctly indicate the basin's southern location during deposition of the Sespe (e.g., Dibblee, 1977). Thus, uplift predicted by the model is incompatible with the observed marine transgression. In addition, paleocurrent directions for parts of the Sespe are inconsistent with the model (Woodford and Gander, 1980). However, paleomagnetic data suggests that some of these basins may have originated even farther south than fault reconstructions indicate (Kamerling and Luyendyk, 1979), so the original position of the basins is in doubt. Also, the age of the Sespe is unclear (late Eocene to early Miocene; Woodford et al., 1954), and the proposed uplift coincided with the statewide marine transgression that heralded the Miocene (Reed, 1933). It is clear that studies of marine-nonmarine relations in middle Tertiary sediments of southern California will provide a powerful test of the model.

This analysis suggests that in southern California, the crust failed by normal faulting when the Mendocino fracture zone passed beneath it, producing a northward-moving wave of east-west normal faults, upthrown on the south. Breccias, megabreccias, and conglomerates accumulated at the bases of the scarps, and were rapidly uplifted after deposition as the slope moved underneath them. In the Soledad basin of southern California, redbeds of the Vasquez Formation are overlain in angular unconformity by the early-to-middle Miocene Tick Canyon Formation, which was derived in large part from the Vasquez (Muehlberger, 1958). In this model, tilting of the Vasquez occurred during faulting as it rode up the slope, post-uplift and the Tick Canyon Formation represents post-uplift erosion and redeposition of the Vasquez. The unconformity between early and middle Miocene sediments in the central Mojave (e.g., Dibblee, 1968) may represent this same period of uplift.

This model also suggests that east-west faults are concentrated in the Transverse Ranges area because that is where topographic relief on the subducted Mendocino fracture zone was greatest. Relief on the fracture zone decreased to the east (away from the ridge) and was less when the fracture zone was under areas to the south because the ridge was farther from the coast (Figure 5). In the Transverse Ranges area, the crust failed by east-west, down-on-the-north normal faults; to the east, it failed by low-angle faulting and warping. Crowell (1968) showed that many east-west faults in the Transverse Ranges showed a period of dip-slip movement in late Oligocene-early Miocene time. Some of these faults, such as the Big Pine, were reactivated as strike-slip faults when north-south compression developed in the Transverse Ranges (see below). (Luyendyk et al. (1980) proposed that east-west faults in the Transverse Ranges do not need explanation because they originally had north-south orientations, and were later rotated.)

A major objection to the concept that the Mendocino fracture zone triggered volcanism and detachment faulting in the Southwest is that much of the volcanism occurred far inland, up to 800 km or more from the trench. Even if the subducted plate retained its identity this far inland, relief on the fracture zone on that part of the plate would be small. However, if the fracture zone marked a tear in the slab, as seen today in South America (Barazangi and Isacks, 1976), it could affect the overlying plate. For example, if the old subplate descended steeply and the young subplate descended shallowly, along the base of the continental plate, the young subplate could serve as a density anomaly and cause stress in the continental plate. The problem would be less severe if east-west extension in the Basin and Range is as large as 100 percent, as some authors have proposed (see Stewart, 1978), because then rocks that are currently far from the paleotrench would have been hundreds of kilometers closer (e.g., Elston and Bornhorst, 1979).

The Barstow-Bristol Trough. The Barstow-Bristol trough developed when volcanism began. It probably initially formed as a volcano-bearing graben similar to those found above active subduction zones (Williams and McBirney, 1979, p. 293-295). The southwestern boundary of the trough was the volcanic front. Bimodal volcanism that followed early andesitic eruptions developed in the trough, because the crust there was already fractured and weakened, allowing easy passage to the surface.

The trough trends at about 45 degrees to the paleotrench. Why it developed where it did is unknown; it may be controlled by an old crustal flaw. The trough is parallel to the Salton trough, the Big Bend of the San Andreas fault, and the Las Vegas shear zone, all of which are zones of crustal weakness. Kistler and Peterman (1978) suggested, on the basis of Sr-isotope studies, that the Mojave block is underlain by an old crustal rift that coincides with the trough.

2.3.3.3 Post-early Miocene

Sometime after the fracture zone passed under the Mojave, uplift ceased because there was no younger lithosphere to be moved under the area. Internal drainage began, and sediments were trapped in basins along the Barstow-Bristol trough. Reed (1933, p. 164) showed that this change from external to internal drainage in "Mohavia" is recorded in coastal sediments by the change from coarse clastics (e.g., lower Miocene Temblor Formation) to finer clastics and chemical precipitates (e.g., upper Miocene Monterey Shale). Voluminous sedimentation continued through the middle Miocene in shifting, deep, areally restricted basins. The basins are clearly not related to basin-range faulting, because they are elongate east-west. They may be pull-apart basins, formed in the same way as the Quaternary basins described below, or they may have inherited their structural grain from earlier tectonic events related to passage of the fracture zone. A true understanding of their development awaits detailed mapping and facies analysis.

The dacites that cap most of the volcanic sections in the Mojave block are not explained in any simple way by this plate model. In general, dacites in the northern part of the block are younger than those in the central part. This may record the northward passage of a thermal event (perhaps fracture-zone spreading, as described above for the Pioneer fracture zone) related to passage of the Mendocino fracture zone, or they may be related to breakup and final assimilation of part of the Farallon plate under the Mojave block. Other possible origins for this enigmatic suite are discussed in Chapter 3.

The Mojave block was relatively quiet in the late Miocene and Pliocene, as strike-slip motion between the Pacific and North American plates was taken up in the coastal and borderland parts of southern California. Sedimentation and volcanism began anew in the Quaternary (or possibly Pliocene) when deep basins formed and scattered alkali basalt cinder cones were erupted. Basins and volcanoes were restricted to the Barstow-Bristol trough.

This late Tertiary or Quaternary rejuvenation of the block may be related to formation of the Big Bend of the San Andreas fault and opening of the Gulf of California. The Mojave block is currently under north-south compression as it is squeezed between the Big Bend and the Sierra Nevada block (Figure 12). Northwest-striking, right-lateral faults that cut the block are a result of this stress (Hill and Dibblee, 1953; Garfunkel, 1974; Cummings, 1976; Hill, 1981). Compression probably began when the Big Bend formed, as the Pacific-North American plate boundary jumped inland to the Gulf of California, about 4.5 m.y. ago (Larson et al., 1968). Alternatively, the bend may have formed by rotation of that segment of the fault, at about the same time. In either case, north-south compression of the block resulted in right-lateral stress on the Barstow-Bristol trough. Volcanic zones, such as the trough, are weak zones in the crust; for example, Gastil et al. (1981) showed that the Gulf of California opened along an old line of volcanoes, and Karig (1970) showed that marginal basins often form by splitting an island arc. Therefore, north-south compression could cause right-lateral shear along a broad zone defined by the Barstow-Bristol trough. Interaction of right-lateral slip on the favorably oriented northwest-trending faults with right-lateral shear on the trough would form pull-apart basins where faults are bent or offset (Figure 12b). As the fault system evolves, transient left-stepping zones could form, causing local compression. The Barstow syncline (Dibblee, 1968), one of the few well-developed folds in Tertiary rocks in the Mojave block, probably formed in this way. It lies at a restraining bend, where the Calico fault steps left to the Blackwater-Harper faults.

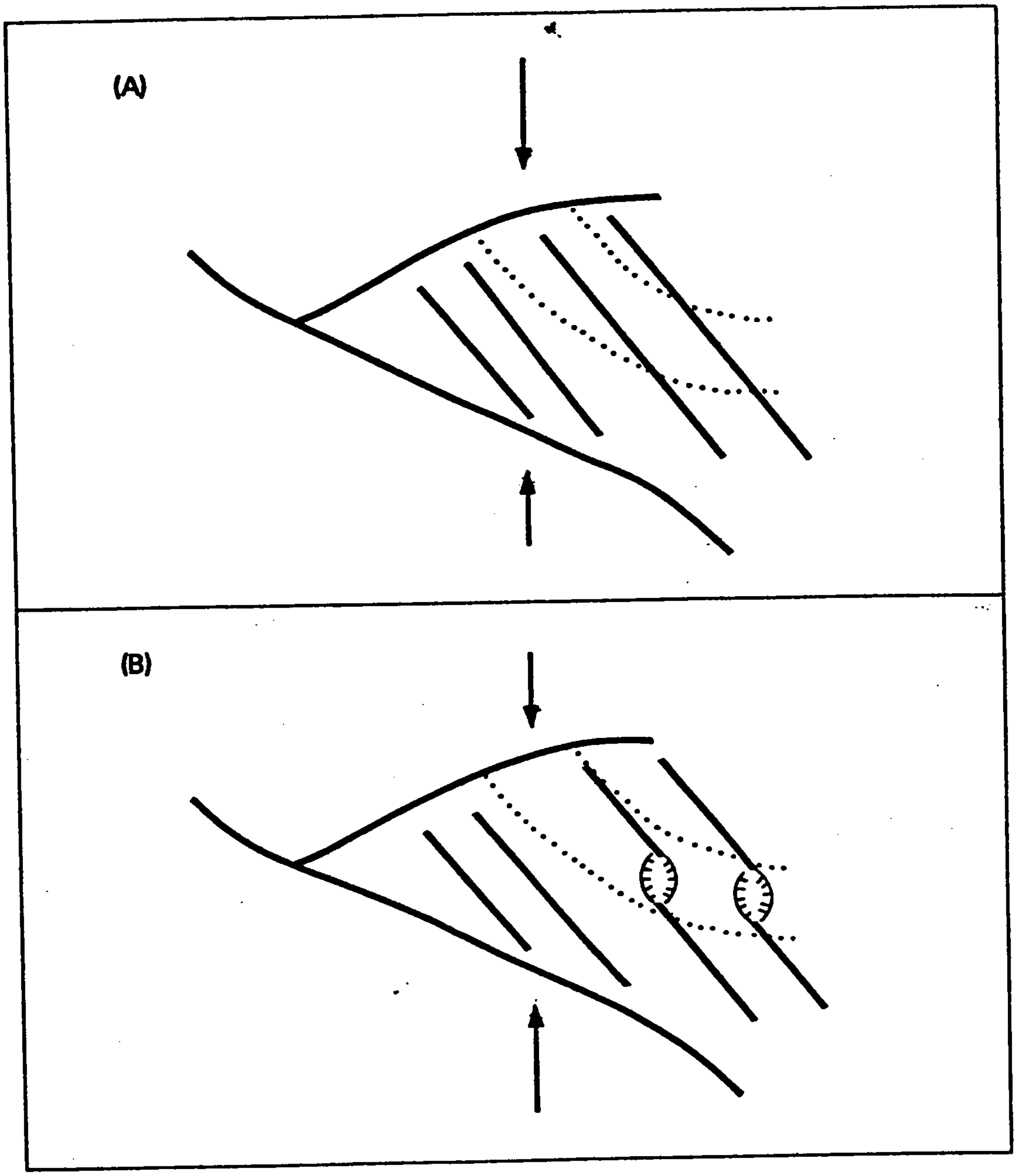

Figure 12: Evolution of the right-lateral fault system

Active Quaternary basins in the Mojave Block, such as Bristol and Lavic Lakes, have features suggestive of pull-apart origin. Cores drilled from these basins have penetrated hundreds of meters of sediments without hitting basement, and some extend below sea level. They are clearly tectonic in origin, and yet they do not display high-angle bounding faults, or any faults that join one basin with the next. A pull-apart origin is likely; short, high-angle bounding faults would likely be buried by alluvial debris. Many mountain fronts are truncated at the trough by east-west trending slopes that may be fault-line scarps. Squared-off Lavic Lake basin (Dibblee, 1966), with its attendant cinder cones, is a good example of a deep, small basin of possible pull-apart origin.

Pull-apart areas in the Mojave block would be zones of tension in an otherwise compressive environment, and could serve as conduits for alkali basalt magmas, which are generally emplaced in extensional settings (Carmichael et al., 1974, p. 488-500; Pearce, 1976). Muessig (1978) and Crowe et al. (1980) have observed the association of alkali basalts with pull-apart basins along strike-slip faults.

2.3.4 Summary

1) In the early Tertiary, the Mojave block was quiet and sat above an active subduction zone that was consuming the

Farallon plate. Slow uplift was caused by subduction of younger and younger crust.

2) By the middle Oligocene, the spreading Pacific-Farallon ridge was close to the trench. The uplift rate increased because elevation of the Farallon plate increased rapidly near the ridge.

3) About 30 m.y. ago, the Pioneer-Murray subplate of the Farallon plate broke up, slowed down, and rotated clockwise, perhaps causing secondary spreading along the Pioneer fracture zone. The location and age of this postulated spreading under the continent coincides with development of southern basin-range structure.

4) By 30 m.y. ago, relief at the trench on the Mendocino fracture zone was about 1 km, and increasing. The fracture zone separated old crust on the north from very young crust on the south. As it passed under the Southwest, moving north at about 3.5 cm/year, it triggered volcanism and detachment faulting along a westnorthwest corridor running from southern Arizona to Death Valley. Crust in the Transverse Ranges area failed by east-west normal faults, and coarse redbeds accumulated at the scarps. Volcanism and faulting moved west as the fracture zone moved north, presumably because the lithosphere being subducted became younger and thinner with time. Volcanism and faulting probably resulted from disruptions in the overlying plate caused by the topographic and thermal step in the subducted lithosphere.

5) The Mendocino fracture zone probably opened and spread sometime after 30 m.y. ago, like the Pioneer did, but evidence is meager. Spreading and consequent upwelling of asthenosphere, if it happened, would have aided the processes described above.

6) When the fracture zone was under the Mojave block, the last segment of ridge reached the trench. Subduction ceased south of the fracture zone as the young subplate slowed and was assimilated. Volcanism in the Mojave block changed from intermediate to bimodal, as predicted by the LPC model.

7) After the Mendocino fracture zone passed under the Mojave block, about 20 m.y. ago, uplift ceased because there was no higher-standing lithosphere to be brought under the block. Volcanism ceased, and the block was quiet, with local sedimentation.

8) In the Pliocene or early Quaternary, volcanism and sedimentation began anew in pull-apart basins along the Barstow-Bristol trough. These basins probably developed in response to north-south compression of the block caused by opening of the Gulf of California.

2.4 CONCLUSIONS

The main points of this tectonic history of the Mojave block and adjacent areas can be summarized as follows:

1) The Mojave block was characterized by quiet, avolcanic uplift during the early Tertiary.

2) In the early Miocene, the block was involved in a brief but intense episode of volcanism, erosion, and high- and low-angle normal faulting.

3) Volcanism, downwarping, and sedimentation were largely confined to the Barstow-Bristol trough.

4) After the early Miocene disturbance, sedimentation and minor volcanism continued along the Barstow-Bristol trough. Volcanism was largely bimodal (high-Ti basalts and basaltic andesites interbedded with rhyodacite to rhyolite tuffs), but the last rocks erupted at most centers were dacites. A few centers (e.g., southeastern Cady Mountains) show an early episode of andesitic volcanism that predates the bimodal sequence. Quaternary eruptions were exclusively alkali basalts.

5) The pattern of quiet uplift during the early Tertiary, severe volcanism and tectonism for a brief time during the mid-Tertiary, and quiet sedimentation and basaltic volcanism after the disturbance, applies to the entire Southwest.

6) The mid-Tertiary disturbance occurred at the same time at a given latitude, regardless of distance from the coast.

7) The disturbance moved north with time, occurring about 25 m.y. ago at the latitude of southeastern California and Tucson, and 10 m.y. ago at the latitude of Death Valley and Las Vegas. The main locus of volcanism and attendant fault-

ing moved west as well as north, probably because the plate being subducted grew younger with time.

8) The disturbance occurred at the time that the subducted Mendocino fracture zone passed under each disturbed terrane.

9) Volcanism, low-angle faulting, sedimentation, and other aspects of the disturbance were probably the consequence of disruptions in the North American plate caused by passage of the fracture zone.

This model for the tectonic evolution of the Southwest is appealing because it is predictive and many of the predictions can be tested by careful geologic studies. For example, if sedimentological studies show that major south-flowing drainage systems existed when the fracture zone should have passed under a given area, then the model will be severely weakened. Key areas to test the model will be southeastern California and southern Arizona (e.g., Gilluly, 1946; Crowe, 1978; Cooper, 1960; Olmsted et al., 1973), where Tertiary conglomerate units can be used to infer paleoslope directions. Tests that have already been applied to the model (see earlier section in this chapter on paleogeography) verify the presence of the predicted north-facing slope.

A drawback of this model is that it only applies to the trends of volcanism and faulting in the Arizona-southern Nevada-eastern California corridor, and does not explain the northern trend that runs along the Nevada-Utah border. Very few theories have been offered to explain this trend. The ad hoc suggestion of a southward-propagating warp in the subducted plate (Lipman, 1975, quoted in Stewart et al., 1977) has no supporting evidence, and gives no mechanism by which the warp moves south, against the plate's motion. Bird's (1979) suggestion of southward-moving delamination of the continental lithosphere accounts for many observations in the Nevada-Utah area. It is not clear how this model could be rigorously tested; a delamination event would, in many ways, resemble the migration of a subducted fracture zone, causing a moving front of uplift and volcanism.

In any event, the two belts of volcanism and faulting need not be explained by the same mechanism. Both terranes developed under still-unexplained conditions of northeast-southwest extension (Davis, 1979); the model presented in this chapter provides a triggering mechanism by which extension was expressed in upper-crustal rocks.