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Cenozoic evolution of the Mojave block of southern California

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ABSTRACT

The recorded Cenozoic history of the Mojave Desert region of southern California began in the latest Oligocene, when intense volcanism and tectonism interrupted a long early Tertiary silence. Volcanism commenced across the region in an east-west band ca. 24–22 Ma. Northwest of Barstow, volcanism was accompanied by intense crustal extension and development of a metamorphic core complex. Outside of this relatively restricted area, extension was minor or absent. After extension ceased ca. 18 Ma, volcanism shifted to small-volume eruptions of basalt. Post-extensional deformation has largely been by strike-slip faulting along northwest-striking dextral faults and west-striking sinistral faults, and total dextral slip across the Mojave Desert region since the early Miocene is ~45–60 km. Strike-slip deformation has been overprinted locally by intense north-south contraction that is the dominant style of deformation in the western Mojave block.

Paleomagnetic data indicate that parts of the Mojave block were rotated clockwise, although the magnitude and timing of this rotation are poorly determined. The best evidence for large (>45°) rotation comes from the area east of Barstow, where large clockwise declination anomalies and Mesozoic and Cenozoic dikes with anomalous strikes may reflect early Miocene clockwise deflection along the Mojave River fault.

Volcanism and tectonism in the Mojave block resulted from interactions among the North American, Pacific, and various oceanic plates. Patterns of volcanism and tectonism do not correlate with growth of slab windows beneath the continent, but do correlate with the position of the subducted Mendocino fracture zone. Plate-circuit reconstructions suggest that the driving force for extension was divergence between the Pacific and North American plates along the transform margin that separated the two. This hypothesis accounts for the direction, magnitude, and rate of extension in the Mojave block.

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INTRODUCTION

The Mojave Desert region of southern California (Figs. 1, 2) occupies a key position in southwestern North America because it is located at the junction of several geologic provinces. The region includes the wedge-shaped Mojave block that lies between the Big Bend segment of the dextral San Andreas fault and the sinistral Garlock fault, adjoining the narrow junction between the northern and southern segments of the Basin and Range province and straddling the transition from the Basin and Range to the transform plate boundary between the North American and Pacific plates. It also lies in the gap between the Sierra Nevada and Transverse Ranges physiographic provinces and between the Sierra Nevada and Peninsular Ranges batholiths. The geologic history of the Mojave Desert region records elements of the diverse histories of these adjoining provinces and therefore provides important information about relationships among them.

We define the Mojave Desert region as that area bounded by the Garlock fault to the north, the San Andreas fault to the southwest, and the Colorado River to the east (Fig. 1). The Mojave block is that part of the Mojave Desert region that lies west of the southern extension of the Death Valley fault zone. The eastern limit of the Mojave block is a prominent but poorly understood geologic boundary that separates a geologically stable region of abundant Paleozoic rocks and basin-and-range topography on the east from an area of disorganized topography, sparse Paleozoic rocks, and active strike-slip faulting on the west.

This paper summarizes current thought regarding the Cenozoic evolution of the Mojave block. This paper, a companion paper (by Walker, Martin, and Glazner, this volume), and a guidebook (Glazner et al., 1994) provide a reconstruction of the Phanerozoic history of the Mojave block. Although the broad outlines of Mojave geologic history are well known, several key issues remain controversial and are discussed herein. These include the nature and areal extent of Miocene crustal extension, the character of late Cenozoic strike-slip deformation, and the ultimate causes and controls of Cenozoic tectonism and magmatism.

PREVIOUS WORK

In spite of its key position, relatively little work had been done in the Mojave Desert region until the past few decades. Early reports (e.g., Thompson, 1929; Hewett, 1954) laid out the general stratigraphy and structure and established that the Mojave Desert region was distinct from the Basin and Range province. Much of our knowledge of Mojave geology comes from the astounding volume of quadrangle mapping accomplished by T.W. Dibblee, Jr. (see dibblee.geol.ucsb.edu.) His maps and accompanying reports form an excellent base for interpreting the tectonic evolution of the region and were invaluable in our work. Dibblee (1961) also was first to recognize the importance of strike-slip faulting in the Mojave Desert region.

Starting in the 1970s, academic and U.S. Geological Survey geologists turned their attention to the Mojave Desert region in an effort to understand its resources and relationships to surrounding provinces. Continued regional mapping and geochemical and geochronologic studies, including dozens of M.S. and Ph.D. theses, have resulted in a much clearer under-

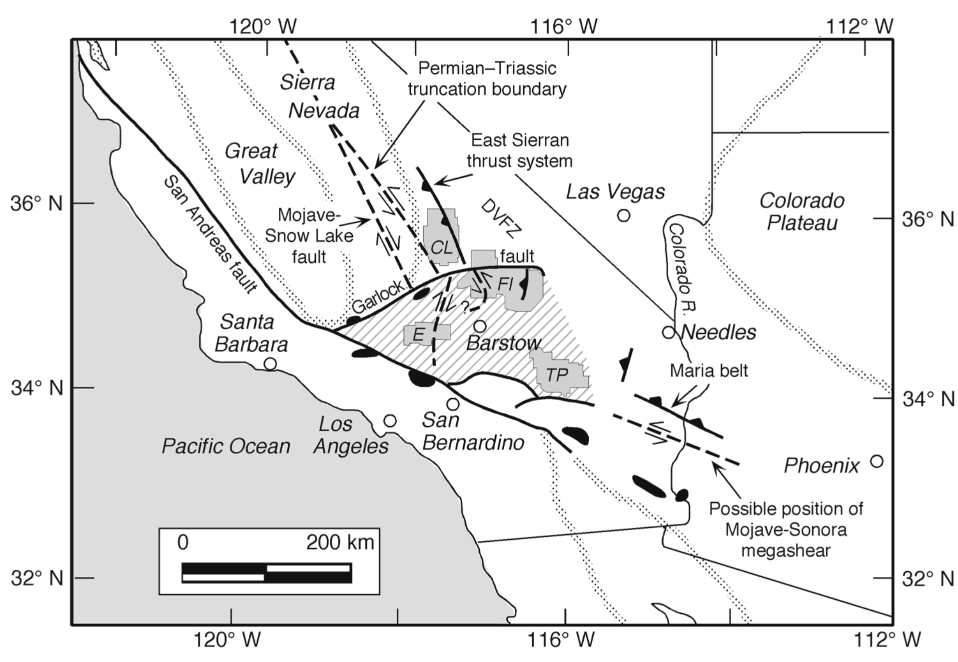


Figure 1. Locations of the Mojave Desert region and the Mojave block. Also shown are several important faults that are either observed (solid lines) or inferred (dashed lines). Black blobs are outcrops of Pelona, Rand, and Orocopia Schists. Diagonal-ruled area is the Mojave block. The Mojave Desert region encompasses this area and eastward to the Colorado River. DVFZ—Death Valley fault zone; CL—China Lake; E—Edwards; FI—Fort Irwin, Goldstone, and China Lake South Range; TP—Twentynine Palms.

standing of the region's geology. The recognition of late Cenozoic strike-slip faulting (Dibblee, 1961) and Miocene low-angle normal faulting in the Colorado River trough (Davis et al., 1980) provided a framework for understanding regional Cenozoic deformation in the Mojave Desert region and how it relates to surrounding regions.

SUMMARY OF THE CENOZOIC HISTORY OF THE MOJAVE BLOCK

Early Tertiary: A meager record

The recorded Cenozoic history of the Mojave block begins around the Oligocene–Miocene boundary. The early Tertiary was apparently a time of quiescence in the Mojave block; few rocks and fewer structures younger than Late Cretaceous and older than late Oligocene have been identified. This circumstance suggests that the region was a tectonically static area that was drained efficiently and externally (Hewett, 1954; Nilsen, 1977; Howard, 1996).

Locally, Oligocene, Eocene, and probable Upper Cretaceous strata are known around the margins of the Mojave block. At least 4 km of the Paleocene and Eocene Goler Formation accumulated in a basin immediately north of the Garlock fault (Cox, 1987). This sequence is largely nonmarine but includes a thin marine interval (Cox, 1987; McDougall, 1987). No equivalent rocks are known in the Mojave block, and the tectonic significance of this sequence is unclear. In the Death Valley region, a thick sequence of nonmarine Oligocene strata of the Titus Canyon Formation (Schweickert and Caskey, 1990; Saylor and Hodges, 1991) may have accumulated in an extensional basin at the southern end of a north-trending extensional belt that runs from eastern California to northern Nevada (Axen et al., 1993). In Cajon Pass, a thin, enigmatic sequence of marine strata depositionally overlies pre-Tertiary basement. These strata contain plesiosaur remains and are probably Late Cretaceous in age (Lucas and Reynolds, 1991).

Hewett (1954) estimated early Tertiary unroofing of more than 4 km, on the basis of the thickness of pre-Mesozoic strata on the Colorado Plateau and their absence within the Mojave block. New data indicate that this estimate is tenuous at best. Such strata are present within the Mojave block, but they have been fragmented and obscured by intense Mesozoic and Cenozoic tectonism and plutonism (Kiser, 1981; Miller and Cameron, 1982; Boettcher and Walker, 1993). The eastern boundary of the Mojave block is thus analogous to Owens Valley to the north; preplutonic strata west of Owens Valley are engulfed by plutons of the Sierra Nevada batholith.

Early Miocene return of magmatism

The Oligocene–Miocene boundary marked a dramatic return of magmatism, sedimentation, and tectonism to the Mojave block. At ca. 24–22 Ma, volcanic rocks were erupted along an east-trending belt that stretched from the westernmost Mojave Desert region inland to the Whipple Mountains and beyond (Glazner and Bartley, 1984; Glazner, 1990). The onset of magmatism was accompanied by the onset of extensional faulting, as both swept northwestward out of Arizona (Glazner and Supplee, 1982; Glazner and Bartley, 1984). Abundant coarse-clastic sedimentation accompanied volcanism and deformation (Fillmore and Walker, 1996).

The northwestward sweep of volcanism is evident within the Mojave Desert region from the stratigraphic data compiled by Sherrod and Nielson (1993). Late Oligocene volcanism was predominant in the southern part of the region and adjacent Arizona, early Miocene volcanism was prevalent at the latitude of the central part of the region, and late early Miocene to middle Miocene volcanism dominated farther north, at the latitude of the northern Mojave Desert region and southernmost Nevada.

In the central Mojave block, 24–20 Ma volcanic strata are widespread in the ranges southeast of Barstow (Glazner, 1990; Walker et al., 1995) and extend west in scattered outcrops to the very western edge of the Mojave block (e.g., Armstrong and Higgins, 1973; Matthews, 1976; Dokka and Baksi, 1989). Volcanic rocks north of the latitude of Barstow are younger, predominantly 20–14 Ma, with scattered outcrops of late Miocene and younger basalts (Burke et al., 1982; Schermer et al., 1996; Sabin et al., 1994; Smith et al., this volume).

Volcanism, which locally produced piles up to several kilometers thick, was calc-alkalic and spanned the compositional range from basalt to rhyolite. Composite volcanoes have been identified locally (Glazner, 1988; Sabin et al., 1994). Some areas are dominated by intermediate-composition and silicic rocks, whereas others are bimodal accumulations of basalts and basaltic andesites with silicic tuffs (Glazner, 1990; Miller and Miller, 1991). East of Barstow, mafic flows and silicic tuffs typically overlie thick sequences of andesite and dacite lavas, but geochronologic data indicate that these lithologically correlative sequences are not strictly time correlative (Gardner, 1940; Glazner, 1988; Glazner et al., 2000).

Volcanic rocks of the Mojave block are broadly calc-alkalic, but the mafic end of the spectrum is typically high in titanium and mildly alkalic, unlike typical subduction-related suites such as the Cascades (Glazner, 1990). In a given area, the most mafic rocks are typically basaltic andesites. Petrographic and isotope data clearly indicate that these rocks are basalts that were contaminated by assimilation of crustal material (Glazner, 1990; Miller and Miller, 1991; Miller et al., 2000), in contrast to similar widespread basaltic andesites in Arizona and northern Mexico, which Cameron et al. (1989) interpreted to be uncontaminated.

Isotopic data indicate that magmatism involved significant recycling of preexisting crust. For example, $^{87}Sr/^{86}Sr$ increases and ε_{Nd} decreases with both SiO_2 and with distance from the coast (Glazner and O'Neil, 1989; Miller et al., 2000). The increase of $^{87}Sr/^{86}Sr$ with SiO_2 is caused by a greater proportion


Ridgecrest
China Lake
Inyokern
Sierra Nevada
El Paso Mountains
118°W
35°30'N
Garlock fault
Pilot Knob Valley
Slate
Range
Granite Mountains
Silurian Hills
Death Valley fault Zone
35°30'N
117°W
Eagle
Crags
Blackwater flt.
Rand Mountains
NTM
Baker
Ft. Irwin
Bicycle Lake flt.
SM
STM
Fremont
Pk.
MH
Coyote Lake flt.
Cronese
Hills
Cronese
Mt.
Alvord
Mt.
Afton fault
Mojave
Buttes
Lockhart flt.
Harper Lake flt.
Boron
BH
WHMR
CaM
Manix fault
CM
Kramer
Hills
LR
HH
Iron
Mt.
Edwards
Barstow
Rosamond
Newberry
Springs
Calico fault
Camp Rock
fault
Helendale flt.
NM
AM
Ludlow
Shadow
Mts.
RM
Lancaster
San Andreas fault
BM
Palmdale
QM
Oro Grande
OM
118°W
Littlerock
34°30'N
Victorville
34°30'
117°W
Lucerne

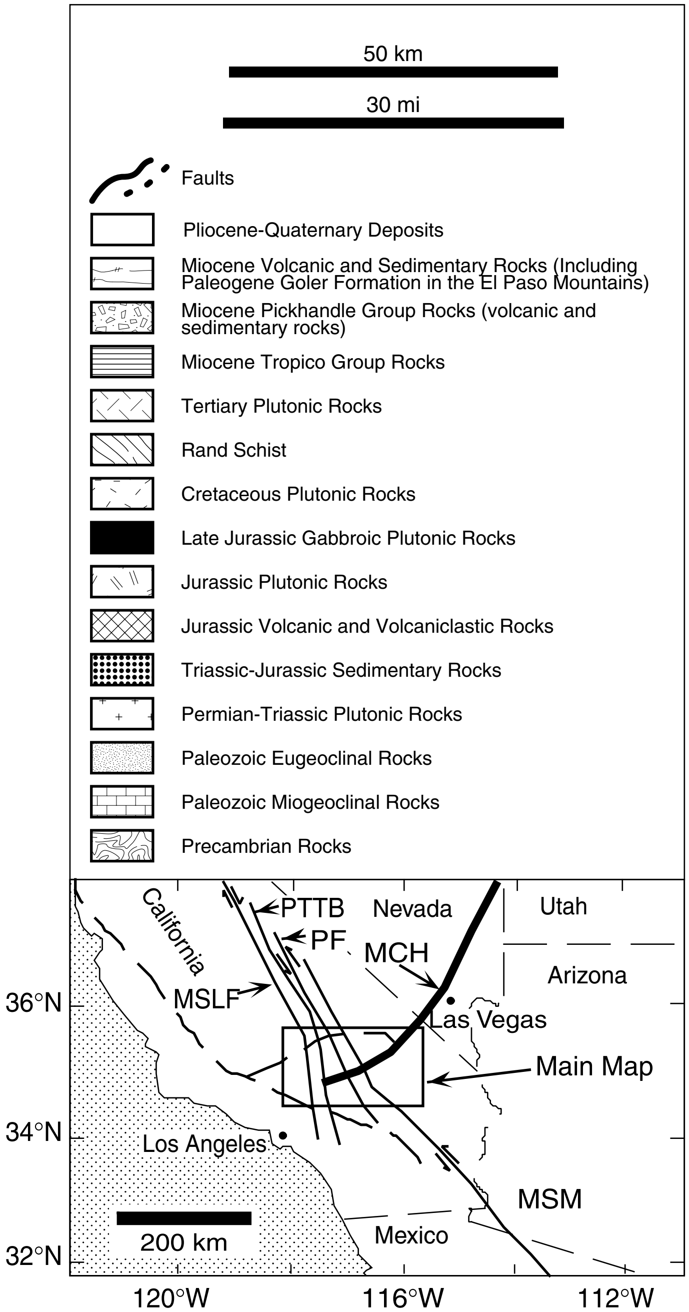


Figure 2. Geologic map of the Mojave block. Modified, on the basis of our work, from Dibblee (1968a) and other sources. AM—Azucar Mine, BH—Bissell Hills, BM—Black Mountain, CM—Cady Mountains, CaM—Calico Mountains, HH—Hinkley Hills, LR—Leuhman Ridge, MH—Mud Hills, NM—Newberry Mountains, NTM—North Tiefort Mountain, OM—Ord Mountain, QM—Quartzite Mountain, RM—Rodman Mountains, SM—Soda Mountains, STM—South Tiefort Mountain, WHMR—Waterman Hills and Mitchel Range. Only ranges mentioned in the text are labeled. Location map with legend: MCH—miogeoclinal-cratonal hinge line; MSLF—Mojave-Snow Lake fault; MSM—Mojave-Sonora megashear; PF—Pine Nut fault; PTTB—Permian-Triassic truncation boundary; dot pattern indicates locus of arc plutonic rocks.

of old crust in more silicic rocks. The correlation with position probably reflects both an eastward increase in the proportion of Proterozoic rocks in the crust and changes in the underlying mantle lithosphere. Rocks from the north-central Mojave block have uniformly low $^{87}Sr/^{86}Sr$ and high ε_{Nd}, consistent with derivation from oceanic lithosphere (Keith et al., 1994; Miller et al., 2000).

Early Miocene extension

Evidence for large-magnitude extension. Dokka (1986) and Dokka and Woodburne (1986) first proposed that the lithosphere of the central Mojave Desert region was greatly extended in the early Miocene, on the basis of relationships in the Newberry Mountains, which lie 20 km east of Barstow. New work in the Newberry Mountains calls the existence of a detachment fault there into question (see Discussion). Unequivocal evidence for large-scale extension was first provided by Glazner et al. (1989; also see Dokka, 1989; Walker et al., 1990), who showed that the area north and northwest of Barstow (Waterman Hills, Mitchel Range, and Hinkley Hills) contains a classic detachment fault system with a well-exposed low-angle normal fault, a chloritic, ultramylonitic footwall with synkinematic intrusions, and a highly extended hanging wall of early Miocene volcanic and coarse clastic rocks (Figs. 3, 4). The most intensely extended rocks (as indicated by mylonitization of footwall rocks and extreme distension and tilting of upper-plate rocks) are only found in the area from the Mitchel Range to The Buttes, roughly coincident with the areal extent of the Waterman Hills granodiorite (Fletcher et al., 1995; Walker et al., 1995; Fig. 3). The detachment fault system is regionally folded into a dome-and-basin geometry typical of Cordilleran metamorphic complexes (Fletcher et al., 1995). Correlations of upper- and lower-plate lithologic assemblages and offset pre-Miocene markers indicate 40–60 km of northeast-directed displacement across this fault system (Glazner et al., 1989; Walker et al., 1990; Martin et al., 1993).

The mylonitic shear zone is thickest and most penetrative in the Mitchel Range where all rock types of the heterogeneous pre-Tertiary basement—dominated by plutonic rocks ranging from hornblende diorite to leucogranite with minor calcite and dolomite marbles and quartzite—form ultramylonites (Fletcher and Bartley, 1994; Fletcher et al., 1995). Although the base of the shear zone is not exposed, the mylonitic sequence is at least 1000 m thick, and ultramylonites are found at the structurally lowest level exposed. Relative to the Mitchel Range, the Hinkley Hills lie structurally up the dip of the detachment, along the direction of transport. Here, mylonitization is distinctly less penetrative. The shear zone forms anastomosing strands, generally $<$100 m in thickness, and only the weakest rock types (calcite marble and quartzite) were mylonitized (Fletcher et al., 1995). The Buttes region contains the westernmost exposures of mylonitic footwall; the shear zone there reaches $\sim$200 m thick (Fletcher et al., 1995).

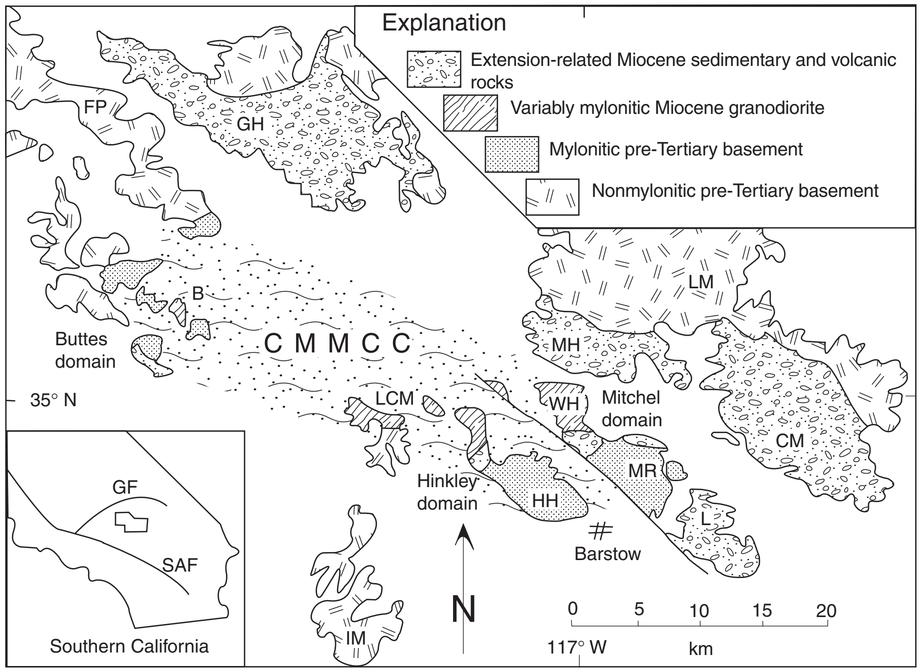


Figure 3. Tectonic map of the Central Mojave metamorphic core complex (CMMCC). The zone of ductile deformation is largely coextensive with outcrops of the Waterman Hills granodiorite (diagonal-line pattern). Locations: B—The Buttes, CM—Calico Mountains, FP—Fremont Peak, GH—Gravel Hills, HH—Hinkley Hills, IM—Iron Mountain, L—Lead Mountain, LCM—Lynx Cat Mountain, LM—Lane Mountain, MH—Mud Hills, MR—Mitchel Range, WH—Waterman Hills. Abbreviations in inset map: GF—Garlock fault, SAF—San Andreas fault; location of main map is shown. Modified from Fletcher et al. (1995).

Age and relationship of extension and magmatism. Near Barstow, magmatism and intense crustal extension were synchronous. The oldest volcanic rocks in this area were erupted at ca. 24–23 Ma, about the same time that the Waterman Hills granodiorite was intruded into what is now the footwall of the Waterman Hills detachment fault (Walker et al., 1995). Extensional-basin development and accumulation of the Pickhandle Formation began at about the same time (Fillmore, 1993; Fillmore and Walker, 1996).

Field observations from the Central Mojave metamorphic core complex indicate that magmatism and mylonitic deformation were closely linked (Walker et al., 1995; Fletcher et al., 1995). The spatial distributions of Miocene dikes and plutons and of the brittle-ductile detachment coincide. Although all Miocene intrusions demonstrably were emplaced during slip across the detachment, there are important variations in crosscutting relationships in different areas of the core complex. In The Buttes, mylonite is restricted to close proximity to Miocene intrusions. Thin mylonitic margins are common along the walls of most dikes (Fletcher et al., 1995). It is interesting that dikes in the Hinkley Hills ubiquitously cut the mylonitic shear zone but not the brittle detachment, which suggests that they were emplaced synkinematically at a time when their wall rocks resided at a level above the brittle-ductile transition (Fletcher et al., 1995). In contrast, dikes in the Mitchel Range ubiquitously display and are transposed into parallelism with the mylonitic fabric, which suggests that they were emplaced at a time when their wall rocks resided at a level below the brittle-ductile transition (Fletcher et al., 1995). Although crosscutting relationships in the Mitchel Range indicate either pre- or synkinematic emplacement, we infer that the dikes were likely to have been emplaced after some period of ductile shear, as can be observed in the Hinkley Hills.

Sedimentation. Sedimentary rocks deposited during the early Miocene vary greatly depending on their position relative to the extensional basin. Strata deposited west of Barstow are typically fine grained and tuffaceous (Tropico Group of Dibblee, 1967a). These strata host the huge boron deposits near the town of Boron (Gale, 1946) and attest to deposition in relatively quiet water. In contrast, strata deposited near Barstow are predominantly conglomerates, breccias, megabreccias, and pyroclastic rocks assigned to the Pickhandle and Mud Hills Formations (Fillmore and Walker, 1996; Ingersoll et al., 1996). These rocks clearly record intense tectonism. Strata deposited east of the highly extended region include a mixture of coarse- and fine-grained clastic sedimentary rocks (e.g., Hector Formation of Woodburne et al., 1974; Clews Formation of Byers, 1960).

Fillmore et al. (1994) interpreted these stratal assemblages in terms of three basin types developed during extension: (1) the intrarift Pickhandle basin, which received a thick section of coarse clastic and volcanic detritus; (2) the extrarift Tropico basin, which lay to the southwest, involved quiet-water deposition, and may have formed by flexure of the footwall during extension; and (3) intra–hanging-wall basins to the east, including the Clews basin at Alvord Mountain and the Hector basin in the Cady Mountains. Ingersoll et al. (1996) further demonstrated the complex interplay of sedimentation and tectonism in the Mud Hills.

Offset of paleogeographic markers. The Mojave block has been difficult to fit into regional geologic syntheses because many regional paleogeographic patterns lose continuity within

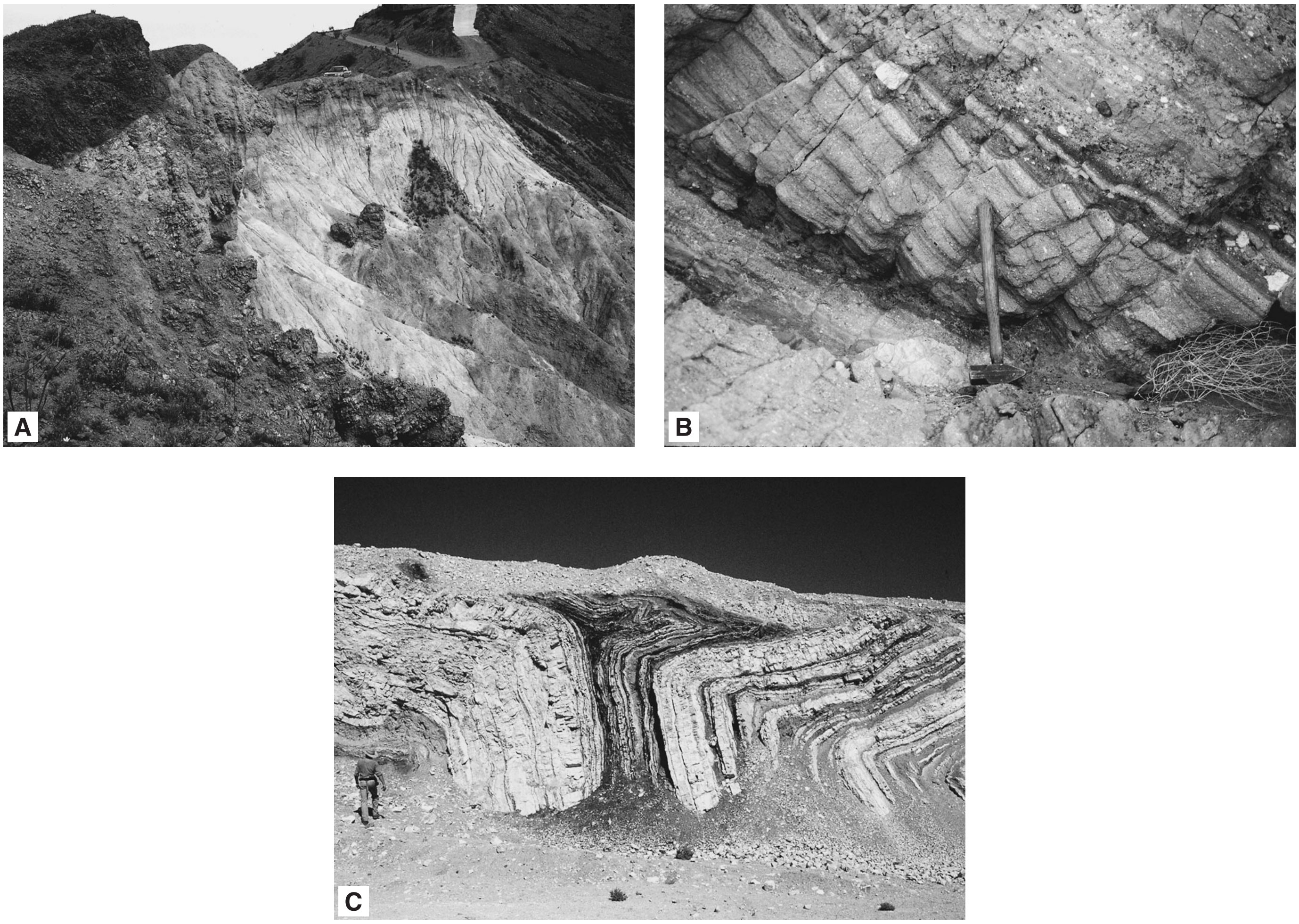


Figure 4. Photographs of deformation styles in the Mojave block. (A) Waterman Hills detachment fault exposed at the summit of the Waterman Hills north of Barstow. Light-colored rocks are early Miocene granodiorite of the footwall that have undergone cataclasis, chloritization, and mylonitization; darker rocks above are brecciated and potassium-metasomatized early Miocene rhyolite flows and plugs. Automobile and roads give scale. The detachment fault is warped into a culmination here, but is regionally gently dipping. (B) Typical fault style in hanging-wall strata of the Waterman Hills detachment fault. Here, near the Waterman Mine, sandstone, conglomerate, and siltstone layers are cut by domino-style faults that accommodate extension of the hanging wall. (C) Contractional deformation style that characterizes the western Mojave block: complex refolded folds in fine-grained Tropico Group rocks, Bissell Hills (northwest of Edwards Air Force Base). This style of deformation is common throughout the western Mojave block, including in the Kramer Hills.

it. For example, many Mesozoic features of the Sierra Nevada and eastern California—such as the Independence dike swarm, Mesozoic thrust faults, and isotopic boundaries—can be tracked southward to or across the Garlock fault, but then are lost.

Much of this pattern complexity is simplified when extension near Barstow is removed (Glazner et al., 1989). Martin et al. (1993) demonstrated that several important paleogeographic markers—including the Independence dike swarm, a belt of Mesozoic volcanic rocks, the Mesozoic thrust belt, and the Paleozoic miogeoclinal-cratonal hinge line—can be aligned by restoring 50–70 km of right-lateral displacement across a postulated fault, designated the Mojave Valley fault (see subsequent section on Displacement Transfer in the Extensional Systems). They proposed that this fault formed the southeastern boundary of the highly extended region. Although the Mojave Valley fault has not been located in the field, recent mapping in the Newberry and Rodman Mountains (see subsequent section on Reinterpretation of the Newberry Mountains, and Glazner et al. [2000]) reinforces the need for such a structure along which extension in the Barstow area was transferred to the coeval extensional belt in the Colorado River trough.

Late Neogene–Holocene sedimentation, faulting, transpression, and volcanism

Following early Miocene extension, which was over by the time of eruption of the Peach Springs Tuff (18.5 Ma; Nielson et al., 1990), the central Mojave Desert region was the site of fluviolacustrine deposition of the lower Barstow Formation, upper Tropico Group, and upper Hector Formation. The Barstow Formation sits in angular unconformity upon Pickhandle and Mud Hills strata in the Mud Hills (Dibblee, 1968a; Ingersoll et al., 1996) and records quieter deposition and less volcanism. Silicic tuffs are common in the Barstow Formation, although their sources are unknown. They may have been derived from the Eagle Crags area to the north (Burke et al., 1982; Sabin et al., 1994). A similar transition is recorded at Alvord Mountain to the east, where the Barstow Formation overlies deformed lower Miocene Clews Formation strata that were deposited in a hanging-wall basin (Fillmore, 1993). We attribute this sedimentation to filling of extensional and flexural basins, coupled with thermal subsidence.

Volcanism continued its northward migration during the middle Miocene. Volcanism at the latitude of Barstow shut off at ca. 18 Ma, although some of the undated silicic plugs around Barstow could be younger. Post–18 Ma volcanism was concentrated in the northern Mojave block, northwest of Barstow (Burke et al., 1982), on the China Lake and Fort Irwin military bases (Schermer et al., 1996), and in the far-eastern part of the Mojave Desert region (Turner and Glazner, 1991; Sherrod and Nielson, 1993). Post–18 Ma volcanic rocks in the northern Mojave block are predominantly mafic or bimodal (Keith et al., 1994), sit nonconformably on pre-Tertiary basement, and have not been affected by extension.

Locally, basaltic volcanism continued throughout the Miocene and into the Quaternary. For example, tilted 20 Ma volcanic rocks near Ludlow are overlain unconformably by basalt flows that are relatively flat lying (basalt of Ash Hill of Dibblee, 1967c). Two samples of this unit and a sample from the nearby Sunshine Peak cinder cone were dated by K/Ar at 15.6, 4.9, and 0.4 Ma, respectively (H.G. Wilshire, personal commun., 1994). These ages indicate persistent alkalic volcanism over a 20 m.y. time span.

Elsewhere in the Mojave Desert region, alkali basalt cinder cones and lava flows sit in angular unconformity on tilted lower Miocene strata (Wise, 1969). K/Ar dating indicates that most of these lavas were erupted within the past 10 m.y. (Glazner and Farmer, 1993). They bear little relationship to current structure in the region, and some were erupted through areas undergoing active crustal shortening (Glazner and Bartley, 1994).

The dominant post–early Miocene deformation comprised strike-slip faulting and related transpression (Dibblee, 1961; Garfunkel, 1974; Dokka and Travis, 1990). Transpressional structures are ubiquitous across the Mojave block and are overprinted on extended rocks in the eastern part of the area (Bartley et al., 1990). Although it is commonly assumed that strike-slip faulting began when the Gulf of California opened at 5–4 Ma, there is evidence that it began at least locally in the early Miocene immediately following the major extensional phase (Bartley et al., 1990). For example, the Lenwood anticline west of Barstow is an active transpressional structure related to the Camp Rock–Harper Lake fault system. Lower Miocene strata exposed in the core of the Lenwood anticline are much more tightly folded than overlying Miocene-Pliocene alluvial-fan deposits (Dibblee, 1967a; Glazner et al., 1994), implying that most of the growth of the structure predated the fan deposits. Early Miocene volcanic and volcanogenic strata on the southeast side of the Newberry Mountains are folded into a west-trending south-vergent asymmetric anticline. We interpret the fold be a hanging-wall anticline above a north-dipping reverse-slip segment of the Calico fault system (Bartley et al., 1990). Nearby exposures of the Peach Springs Tuff are flat lying and thus imply that the anticline formed before 18.5 Ma.

DISCUSSION

Key controversies and enigmas

Although the general outlines of the Mojave block's Cenozoic history, as just discussed, are well known, several controversies remain. These are discussed here and include the following: (1) How much vertical-axis rotation occurred during Cenozoic extension and strike-slip faulting? (2) How widespread was Cenozoic extension? (3) How much strike-slip faulting has taken place, and how is this deformation areally distributed? (4) How widespread is late Cenozoic transpression? (5) What are the relative roles of extension, transpression, and strike-slip faulting in producing the topography of the Mojave block? (6) What was the driving mechanism for extension? (7) How are these events tied to the region's plate-tectonic history?

Vertical-axis rotation

Paleomagnetic studies in southern California commonly indicate clockwise rotation of fault blocks during the Miocene (e.g., Luyendyk, 1991). However, such studies in the Mojave Desert region have produced a bewildering variation in paleomagnetic declinations, with studies in neighboring areas commonly giving contradictory results, and studies in the same area yielding both clockwise and counterclockwise declination anomalies over brief stratigraphic intervals (e.g., Valentine et al., 1993; Dokka et al., 1998).

There are two basic types of paleomagnetic studies on Tertiary rocks from the Mojave block. In the first type, data have been collected from several lava flows in a given structural area and averaged to smooth out secular variation and structural correction errors (e.g., Ross et al., 1989; Valentine et al., 1993). Strata involved in the studies usually are tilted to dips of $>20°$ (e.g., the average dip of strata at 68 sites measured by Ross [1988] is 30°), at least locally in the limbs of plunging folds. The studies typically show significant clockwise (and locally counterclockwise) declination anomalies, but are hampered by significant scatter (both within and between areas) and by lack of evidence that secular variation was adequately averaged (e.g., data are typically unipolar, or nearly so; Ross, 1988). The second type involves analysis of sedimentary strata (e.g., MacFadden et al., 1990a, 1990b) or the Peach Springs Tuff, a widespread ignimbrite that blanketed most of the eastern Mojave Desert region (Wells and Hillhouse, 1989). Strata analyzed in these studies are typically postkinematic and relatively flat lying. These studies solve the secular-variation problem by either more effective averaging (sedimentary-rock studies) or by examining deflection relative to a reference section of the paleomagnetic pole in a single rapidly cooled unit (in this case, the Peach Springs Tuff on the Colorado Plateau).

Results from studies of sedimentary strata and the Peach Springs Tuff typically show relatively small or negligible declination anomalies. For example, MacFadden et al. (1990b) determined ~20° of clockwise rotation of the lower Miocene Hector Formation in the Cady Mountains, and MacFadden et al. (1990a) found no significant rotation of the middle Miocene Barstow Formation near Barstow. Data from Wells and Hillhouse (1989) indicate no rotation in much of the Mojave Desert region since eruption of the 18.5 ± 0.2 Ma Peach Springs Tuff.

Significant declination anomalies are confined to areas of tilted volcanic rocks. This restriction could indicate that the anomalies result from inadequate structural corrections and/or inadequate averaging of secular variation, but several lines of evidence indicate that the anomalies record at least some amount of true vertical-axis rotation. First, the declination anomalies are overwhelmingly clockwise (Ross et al., 1989). Second, analysis of data from Ross (1988) indicates no correlation between average declination anomaly and either average or maximum bedding dip in a given structural subblock. Such a correlation would be expected if the anomalies resulted from either incorrect structural correction or wrench faulting (e.g., Miller, 1998). Third, the tilted strata are at least slightly older than the weakly rotated, less-deformed strata, allowing for the possibility that significant rotation occurred before deposition of the weakly rotated strata.

This last point implies that significant block rotations could only have occurred in the early Miocene either during or immediately following crustal extension and, therefore, cannot be related to late Miocene and younger dextral faulting. This timing relationship, the consistent clockwise-rotation sense, and the spatial correlation between declination anomalies and stratal tilting led Bartley and Glazner (1991) to propose that the declination anomalies reflect dextral shearing that transferred displacement between the Central Mojave metamorphic core complex and the coeval Colorado River trough extensional corridor.

Dike orientation. Orientations of Mesozoic dikes provide another test of block-rotation models. The northwest-striking Independence dike swarm (Moore and Hopson, 1961; Smith, 1962; Carl and Glazner, this volume, Chapter 7) crosses eastern California and provides a structural datum. For example, Ron and Nur (1996) concluded that dikes in the northeastern and southern Mojave block are rotated clockwise, whereas dikes in the central Mojave block are not significantly rotated. They concluded that the block-rotation model of Luyendyk et al. (1985) best matched available data. Hopson et al. (2000) looked at a more complete set of dikes and found that dike orientations are roughly concordant with paleomagnetically determined rotations in those few places where both types of study have been done.

Figure 5 is a compilation of dike orientations in the Mojave block, based on the compilation of Carl and Glazner (this volume, Chapter 7) and supplemented by published geologic maps of T.W. Dibblee, Jr. We have included dikes of all ages, because Jurassic, Cretaceous, and Cenozoic dikes are subparallel across the region (e.g., Coleman et al. [2000] showed that Jurassic and Cretaceous dikes are interleaved in the type locality of the Independence dike swarm) and few of the dikes have been dated. Most of the dikes in Figure 5 are probably Jurassic. Figure 5 shows that most of these dikes strike northwest, but that there is significant scatter. In several ranges there are conjugate(?) sets, one striking north and the other northwest. A conspicuous region east of Barstow (oval in Fig. 5) contains dikes that only strike north or northeast (however, the number of such dikes is curiously small, given the widespread area over which declination anomalies are reported). This region contains some of the largest declination anomalies found by Ross et al. (1989), as well as the trace of the proposed Mojave Valley fault (see the previous section on Offset of Paleogeographic Markers). We infer that these rotations may have been caused by dextral movement across this northeast-striking fault (Martin et al., 1993).

Counterclockwise anomalies. Bidirectional declination anomalies occur in some areas. Valentine et al. (1993) and Dokka et al. (1998) argued that such anomalies represent vertical-axis rotations caused by drag along, or decoupled rotation between, faults that are inferred to separate subblocks with different anomalies. This interpretation is possible, but structural and stratigraphic complexities render it debatable and current data are inadequate to test it. For example, many of the units sampled by these authors have been affected by intense noncylindrical folding, which makes standard structural corrections inadequate (Bartley et al., 1990; Walker et al., 1990). The Kramer Hills study reported by Dokka et al. (1998), for example, was performed in rocks that were strongly folded, locally isoclinally, in the late Cenozoic (Fig. 4; Linn et al., this volume, Chapter 10). The data from the study by Dokka et al. have not been published; therefore these concerns cannot be evaluated. The Valentine et al. (1993) study of volcanic strata near Barstow revealed several declination anomalies of varying magnitude and sense. However, some of these units have anomalously shallow magnetic inclinations that are inconsistent with nearby units and would require large northward transport relative to North America; such transport is inconsistent with geologic and other paleomagnetic data. We therefore suspect that these declination anomalies at least partly reflect eruption during a magnetic excursion and are not reliable indicators of structural deformation.

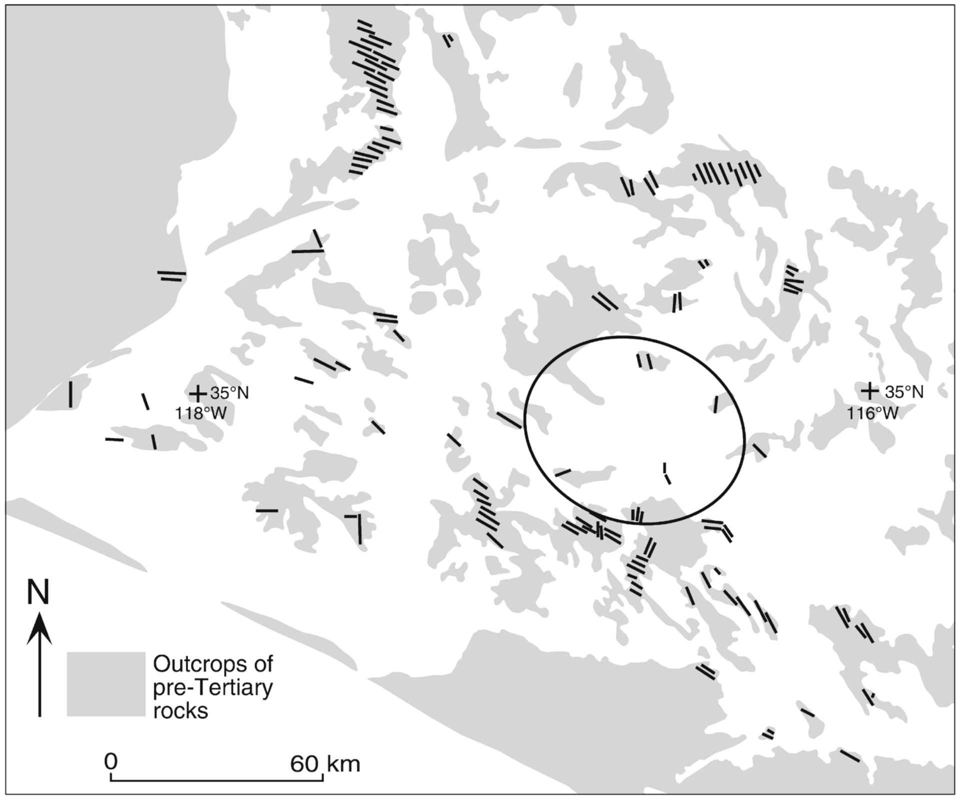


Figure 5. Summary of dike orientations in the Mojave block, modified from Carl and Glazner (this volume). Although conjugate dike sets are not uncommon, in an area (oval) east of Barstow, mapped dikes strike only north or northeast, consistent with large paleomagnetic declination anomalies in Miocene volcanic rocks. These rotations may record deformation along a transfer fault that bounds the highly extended area near Barstow (see Fig. 6).

Schermer et al.'s (1996) study of the structure and paleomagnetism of volcanic rocks in the northeastern Mojave block bears on this question. Faults in this area are well exposed and well mapped, and Schermer and coworkers carefully noted the relationship of paleomagnetic samples to these structures. They concluded that Independence dikes and Miocene volcanic rocks have similar rotations, ~25° clockwise. Larger clockwise rotations are present, but mostly come from areas around fault terminations where larger strains are probable (Schermer et al., 1996). A modest rotation of 25° clockwise is consistent with most models of strike-slip deformation in the Mojave block (see Schermer et al., 1996, for discussion). Schermer et al. found no evidence for counterclockwise rotations near left-lateral faults that accommodate rotation within the larger subblock, as predicted by the Dokka et al. (1998) hypothesis.

Summary. In summary, we find evidence—i.e., the consistent relationship between older Mesozoic structural markers and paleomagnetic measurements on younger Cenozoic rocks—for moderate rotation (~25°) of fault subblocks in the northeastern Mojave block. The mechanism for rotation is deflection of east-trending fault subblocks in an overall right-lateral shear system (e.g., Garfunkel, 1974; Schermer et al., 1996). Rotations proposed for the western and southern parts of the Mojave block are possible but unverified. Although some paleomagnetic data from Cenozoic rocks (e.g., Golombek and Brown, 1988) suggest similar clockwise rotations, these observations are at odds with older structural markers such as dikes. Without more data, the hypothesized rotations are impossible to evaluate. Data from the eastern Mojave block east of Barstow indicate significant clockwise rotation, probably along the Mojave Valley fault, but the precise structural mechanism of this rotation is undetermined.

Extension direction

Kinematic indicators such as tilt direction, mylonitic lineation, and synkinematic dikes require that hanging-wall rocks moved to the northeast in present coordinates. However, Dokka (1989) and Ross (1995) interpreted paleomagnetic data to indicate that extension originally occurred with the hanging wall moving to the north and that the current northeast orientation of extension vectors results from clockwise rotation. We view this interpretation as unlikely for several reasons.

First, northeast-directed extension parallels that in much of the rest of southern California and western Arizona (Wust, 1986; Bartley and Glazner, 1991) and particularly parallels the displacement vector of coeval extension in the Colorado River extensional corridor that we interpret to be kinematically linked to extension in the central part of the Mojave Desert region. As Ingersoll (1982) noted, the extension vector pointed toward the position of the Mendocino triple junction throughout the Neogene, indicating that space-making processes at the continental margin control how and where extension occurred (Glazner and Bartley, 1984; Bohannon and Parsons, 1995). North-directed extension in the Mojave Desert region would have been highly discordant to this trend.

Second, structural markers across the Mojave Desert region, including the dike swarms already noted, maintain a consistent northwest strike (Fig. 5). Although the factors that produced this consistent orientation are not well known, their parallelism over a 120 m.y. span and their general parallelism to the continental margin indicate that plate-boundary orientation exerts a major control.

Finally, Ross's (1995) study of the western Cady Mountains is consistent with an original north-south orientation of extension in that local area but does not require it. Ross found large clockwise declination anomalies in Miocene strata. Extension orientation was inferred on the basis of a single fault of unknown kinematics that he assumed to be a large-displacement normal fault. Other interpretations of this poorly exposed fault clearly are possible.

Given these considerations, we interpret the present northeast-southwest orientation of early Miocene kinematic indicators to be close to their original orientation. Extension was probably coupled with the evolving plate margin in the manner proposed by Ingersoll (1982) and Glazner and Bartley (1984), such that extension is a response of the plate margin to the divergent component of Pacific–North American plate interaction (see the subsequent section on Plate-Tectonic Setting).

Areal extent of extension

The fraction of the Mojave Desert region that was affected by mid-Tertiary extension is highly controversial (Fig. 6). Dokka (1989) and Tennyson (1989) proposed that much of the region, including virtually all of the western and most of the eastern Mojave block, was significantly extended in the Miocene. However, field observations indicate that much of the area included by these authors probably was unaffected by extension and that the dominant form of Cenozoic deformation was crustal shortening.

Dokka (1989) proposed that steeply dipping Miocene strata in the Kramer Hills (western Mojave block) were tilted above a shallow extensional detachment fault that surfaces near Leuhman Ridge on Edwards Air Force Base. However, Dokka's (1989) cross section is incompatible with geologic relationships exposed in these hills. Field data clearly demonstrate that these strata and their basal nonconformity are tightly folded (Dibblee, 1967a; Bartley et al., 1990; Linn et al., this volume). Leuhman Ridge consists of shattered basement rocks and is probably the core of a denuded late Cenozoic anticline. Isoclinal folds are spectacularly exposed in nearby ranges (Fig. 4; Bartley et al., 1990). Our reconnaissance of Cenozoic strata in most of the hills of the western part of the Mojave block corroborates Dibblee's (1967a) observation that this style of deformation is common and that most contacts between basement and cover rocks in the area are depositional.

Stratigraphic data also are inconsistent with significant extension in the western part of the Mojave block. Lower Miocene strata there are predominantly fine-grained lake deposits and tuffs, unlike the conglomerates and breccias that were deposited during extension in the central part of the Mojave Desert region. These strata are consistent with an origin outside the area of significant extension (Fillmore et al., 1994).

In the eastern Mojave block, many ranges that lie within the Daggett terrane (see Fig. 6) of Dokka (1989) are essentially devoid of Cenozoic deformation (Dibblee and Bassett, 1966, 1967b, 1967c; Glazner and Bartley, 1990). Closer to Barstow, modest amounts of extension are expressed by homoclinally tilted strata in the Newberry and Cady Mountains (Dokka, 1986; Glazner, 1988; see subsequent discussion), but aggregate extension in these areas is likely to have been small, on the order of a few kilometers. Field relationships in the Rodman Mountains indicate no evidence for significant extension and, in fact, that tilting there results from late Cenozoic transpression (Dibblee, 1990; Glazner et al., 2000). We conclude that significant extension in the Mojave block was restricted to the area near and northwest of Barstow (Fig. 6).

Reinterpretation of the Newberry Mountains

The Newberry Mountains occupy a key area in the Mojave block between highly extended rocks in the area northwest of Barstow and weakly to unextended rocks in the Rodman Mountains and ranges to the south and east. Dokka (1986, 1989) and Dokka and Woodburne (1986) proposed that the Newberry Mountains are underlain by a major extensional structure, the Newberry Mountains detachment fault. However, our reexamination of most of the exposures of the proposed Newberry Mountains detachment fault yielded no evidence for low-angle faulting. The contacts interpreted to be the Newberry Mountains detachment fault and related low-angle normal faults are high- to moderate-angle faults, intrusive contacts, or nonconformities.

Geologic maps of two key areas are displayed in Figure 7. Contacts between basement and cover rocks southwest of Newberry Springs were described as spectacular examples of a low-angle normal fault (e.g., Figs. 24 and 25 in Dokka and Woodburne, 1986; Fig. 12 in Dokka, 1986). However, the contact shown in these figures is intrusive and dips 50° to the north (Fig. 7A). The contact between basement and Tertiary rocks on the north side of the same hill is a nonconformity with Miocene tuffaceous rocks deposited on Mesozoic granitic rocks. Dikes emanating from the plug cut both the tuffaceous rocks and granitic rocks, demonstrating no displacement across the contact between basement and Tertiary rocks. Other such contacts in the area southwest of Newberry Springs are depositional, intrusive, or high-angle faults.

Figure 7B is a geologic map of the north-central Newberry Mountains. Much of the contact between basement and Tertiary rocks in this region was interpreted to be the Newberry Mountains detachment fault (Figs. 4 and 11 in Dokka, 1986). How-

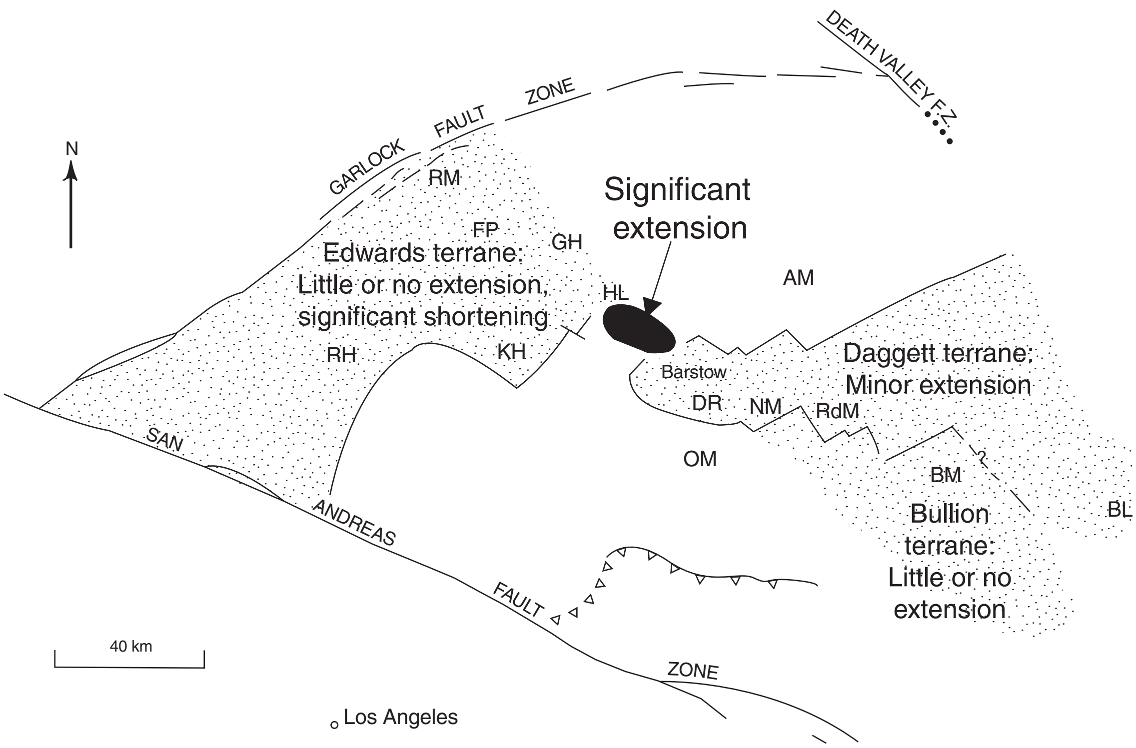


Figure 6. Interpretation of the area affected by extension. Patterned areas outline the extensional domains of Dokka (1986). Data presented herein indicate that significant extension was confined to a small area northwest of Barstow; see also Figure 10. Locations: AM—Alvord Mountain, BL—Bristol Lake, BM—Bullion Mountains, DR—Daggett Ridge, FP—Fremont Peak, GH—Gravel Hills, HL—Harper Lake, KH—Kramer Hills, NM—Newberry Mountains, OM—Ord Mountains, RdM—Rodman Mountains, RH—Rosamond Hills, RM—Rand Mountains.

ever, our mapping shows that this contact is defined by an array of intersecting east-striking and northwest-striking high-angle faults that put Tertiary strata on the south against brecciated granite. Kinematic data from a 5 km reach of this fault are shown in Figure 8; these indicate predominantly oblique-normal displacement (Fig. 9). None of the exposed faults dips shallowly and most dip >50°. In several areas, outcrops of brecciated granitic rocks north of the fault rise up steeply 20–75 m above adjacent Tertiary rocks (Fig. 7), precluding a low-angle fault contact with Tertiary rocks in the hanging wall as shown by Dokka (1986, his Fig. 11).

Several other lines of evidence argue against exposure of a large-displacement, low-angle normal fault in the Newberry Mountains. For example, the northwest- to north-striking dacite dike swarm mapped by Dibblee and Bassett (1966) intrudes both cover rocks and basement. Individual dikes are subperpendicular to bedding in cover rocks regardless of bedding attitude, showing that dike injection predated tilting. Because the dikes are tilted and cut contacts between basement and Tertiary rocks, they demonstrate that there has been no significant movement across proposed strands of the Newberry Mountains detachment fault in the vicinity of the dike swarm. Conversely, basement and cover exposures west of the swarm lack dikes, indicating that there has been no significant relative movement between cover and basement since the early Miocene dike swarm was emplaced.

Another argument against major extension in the Newberry Mountains is the character of the proposed Newberry Mountains detachment fault. Where not intrusive or depositional, contacts between basement and cover rocks are steeply to moderately dipping faults that differ from well-studied detachment faults in other parts of the southwestern United States (e.g., Davis et al., 1980, 1986; Glazner et al., 1989) in the following ways: (1) The contacts rarely dip less than ~50°, and footwall rocks typically stand topographically well above hanging-wall rocks. (2) Footwall rocks lack the distinctive structures and minerals of detachment-fault footwalls (e.g., chlorite breccia and mylonite). (3) Kinematic indicators (generally grooved and striated fault surfaces) typically rake steeply in the fault plane at a high angle to the proposed transport direction on the Newberry Mountains detachment fault (Fig. 9), precluding these fault surfaces from being the upturned edges of an otherwise low-angle fault. (4) Mesozoic granitic rocks near the Azucar Mine, which were described by Dokka (1986) as lying immediately below the Newberry Mountains detachment fault, are undeformed and unbrecciated.

Moderate extension of perhaps a few kilometers across moderately to steeply dipping domino-style normal faults, most

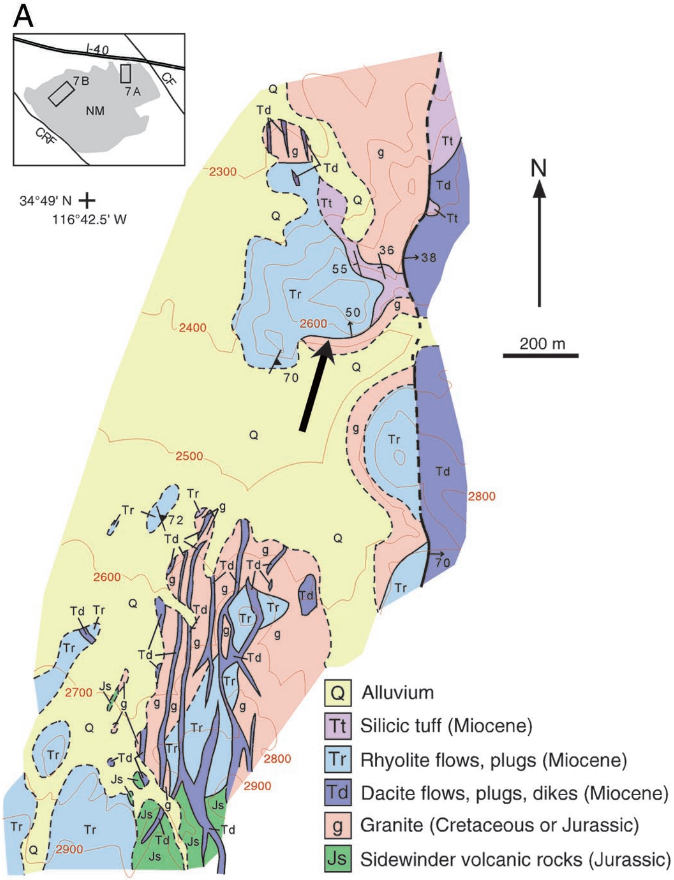
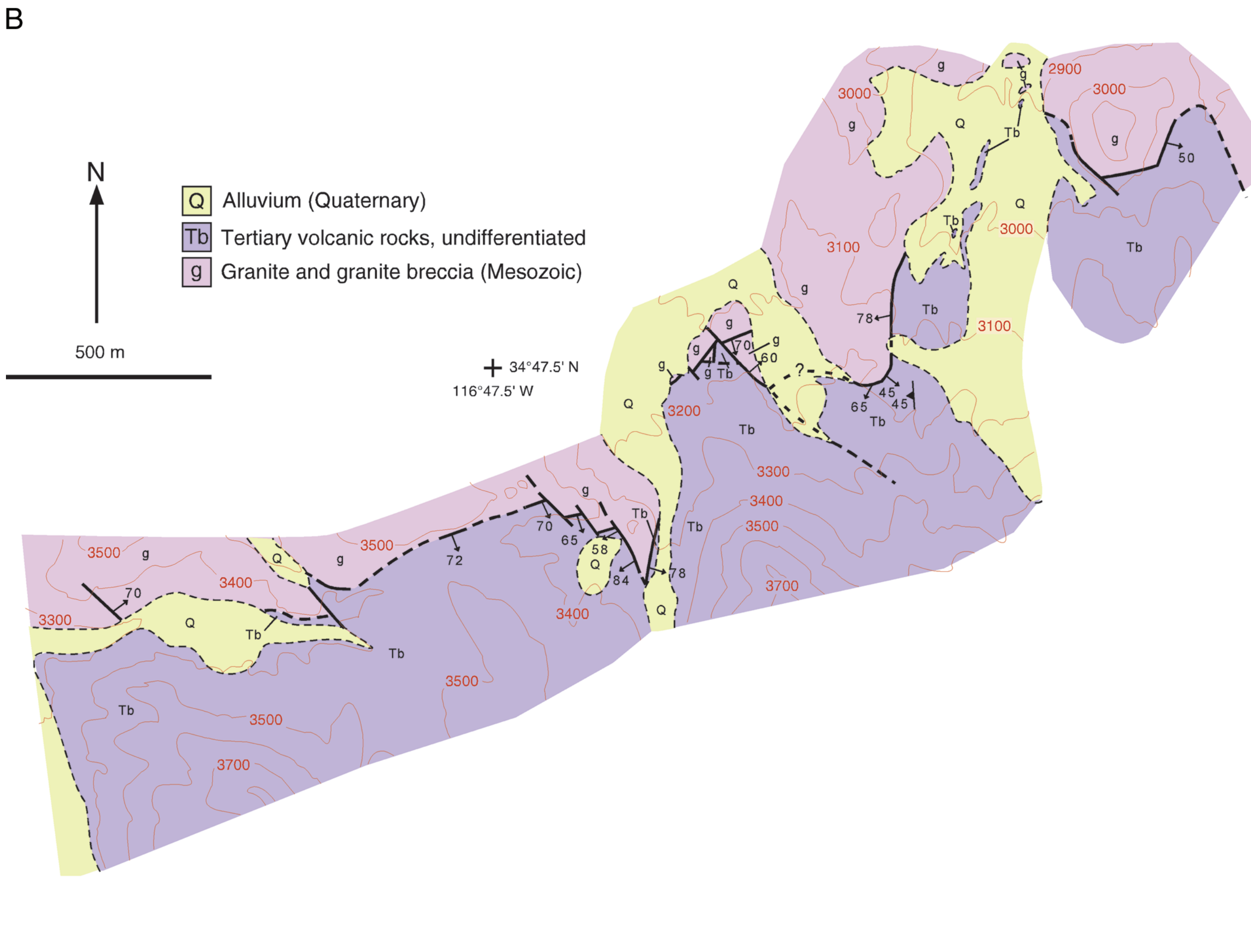


Figure 7. (A) Geologic map of the area southwest of Newberry Springs; contour interval is 100 m. The contact between rhyolite (Tr) and granite in the northern part of this area (bold arrow), mapped as the Newberry Mountains detachment fault by Dokka (1986), is here interpreted as an intrusive contact that dips 50° to the north. Inset map: CF—Calico fault, CRF—Camp Rock fault, NM—Newberry Mountains; locations of maps A and B are shown. (B) Geologic map of the north-central Newberry Mountains; contour interval is 100 m. Much of the contact between Tertiary rocks and granite was mapped as a detachment fault by Dokka (1986). We interpret the contact as an intersecting set of high- to moderate-angle faults, as shown.



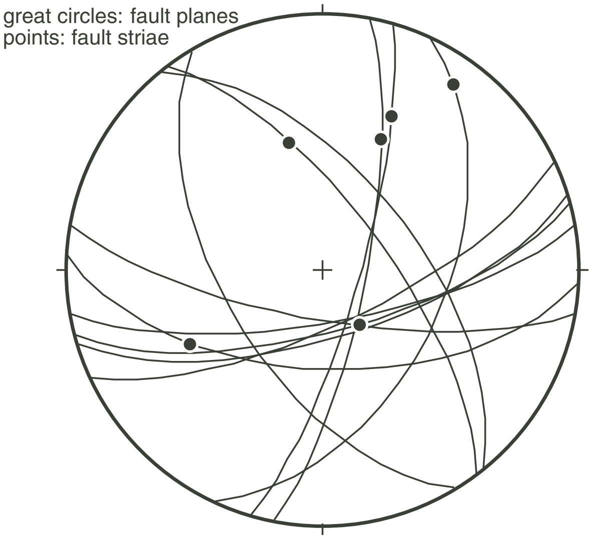


Figure 8. Kinematic data from the faults in the north-central Newberry Mountains (Fig. 7B). None of the measured faults dips less than 50°; most are steep, and slickenlines and grooves are consistent with oblique extension of the area.

Figure 9. View to west of grooves along a planar fault surface in the north-central Newberry Mountains. Grooves on this fault, which strikes 011° and dips 76° toward the camera, indicate left-normal displacement.

of which were recognized by Dokka (1986, 1989) and assigned postdetachment ages, clearly affected the Newberry Mountains. Whether these normal faults root into an unexposed detachment is unknown. The Peach Springs Tuff (18.5 Ma; Nielson et al., 1990) was deposited in angular unconformity across tilted lower Miocene strata in the Newberry Mountains (Bartley et al., 1990; Buesch, 1992); therefore, modest extensional tilting in the Newberry Mountains probably overlapped in time with formation of the metamorphic core complex to the northwest.

Many outcrops of orange- and red-stained, cavernous, brecciated granitic rocks in the northwestern Newberry Mountains are landslide sheets and megabreccias. This can be seen in the area northwest of the Azucar Mine, where conglomeratic rocks are interbedded with granite megabreccia. Although complicated by later faults, the megabreccias appear to grade upward and laterally northward into highly brecciated granitic rocks. Many of the rocks were mapped as granite breccia by Dibblee (1970), and some were mapped as intact basement. Sedimentary interbeds are generally lacking, but the breccias are crudely stratified on the 1 to 10 m scale. The general appearance and continuity of the brecciated rocks leads us to interpret most of these outcrops as landslide deposits (e.g., Fillmore, 1993). The landslide deposits must have been shed off a significant topographic escarpment, probably the northeast-striking fault system mapped in Figure 7B.

We therefore conclude that extension is relatively modest in the Newberry Mountains and that the southern limit of highly extended crust in the Mojave block is located north of the Newberry Mountains. Relative uplift across the southern boundary of the extended domain may have provided the source for the granite landslides in the northern Newberry Mountains.

Displacement transfer in the extensional systems

Extension was probably accommodated laterally by various transfer mechanisms (Fig. 10). Bartley and Glazner (1991) proposed that early Miocene extension in the Colorado River trough is kinematically linked to extension near Barstow by distributed dextral shear and clockwise rotation of a weakly extended area in the central part of the Mojave block. Martin et al. (1993) proposed that the highly extended region near Barstow is bounded on the southeast by a cryptic right-lateral fault that runs under the Mojave River valley and separates an extended terrane to the northwest from modestly extended crust to the southeast.

The northwestern limit of extension is less well defined. It is tempting to invoke Miocene extension to unroof the Rand Schist in the northern Mojave block, but late Mesozoic biotite Ar cooling ages are widespread across the area; therefore, unroofing of the Rand Schist is not related to Miocene extension (Jacobson, 1990). Mapping in the northern Mojave block (e.g., Fletcher et al., this volume, Chapter 8; Sabin et al., 1994) has not yielded evidence for significant Cenozoic extension, consistent with the Ar studies. Goodman and Malin (1992) and Tennyson (1989) presented evidence for extension in the southern San Joaquin Valley, to the west-northwest of the Mojave block, but it is not clear whether this deformation was linked to that near Barstow.

Transpression, extension, and the origin of Mojave block topography

Transpression and strike-slip faulting have shaped much of the present-day topography of the Mojave block (Bartley et al.,

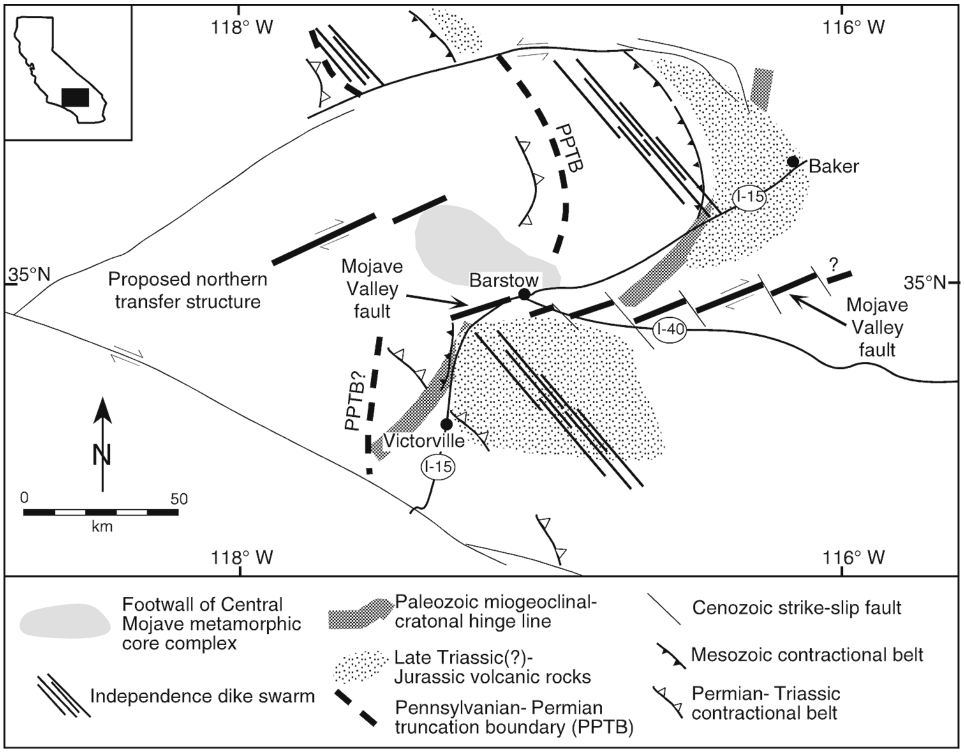


Figure 10. Map showing pre-Tertiary structural and stratigraphic features that are offset along the Mojave Valley fault, an inferred transfer fault that bounds the Central Mojave metamorphic core complex on the south. Modified from Martin et al. (1993).

1990; Glazner and Bartley, 1994; Glazner et al., 1994). This view is in sharp contrast to that of Dokka and Travis (1990), who proposed that much of the region's topography is controlled by transtension, which produced several large pull-apart basins.

There are several problems with their interpretation, the most important of which is that many of the basins that they consider to be pull-aparts are bounded by or contain contractional structures. Specific examples of this geometry include (1) the Mojave River valley south of the Calico Mountains, which is bounded by steep dextral-reverse faults (Glazner and Bartley, 1994; Glazner et al., 1994); (2) valleys in the southern Mojave block, east of the San Bernardino Mountains, where Dibblee (1967b, 1968b) mapped contractional structures in Quaternary alluvium; and (3) most of the northeastern Mojave block, where Schermer et al. (1996) reported that most of the east-trending faults have a significant component of reverse slip. Thus, although some basins in the Mojave block may be transtensional in origin, contraction caused by transpressional faulting has produced much of the current topography in the region.

Strike-slip faulting

Perhaps the most apparent structural features of the Mojave Desert region are the Miocene–Holocene strike-slip faults that cut across it (Fig. 11). In fact, the Mojave block is defined in terms of the bounding strike-slip faults that serve to isolate it from surrounding areas (e.g., Davis and Burchfiel, 1973). These faults and their slip histories have been the subject of numerous investigations (e.g., Dibblee, 1961; Garfunkel, 1974; Dokka, 1983; Dokka and Travis, 1990; Luyendyk, 1991; Schermer et al., 1996).

There are two basic domains of strike-slip faults in the Mojave block: (1) northwest-striking, right-lateral faults throughout much of what is referred to as fault domain 1 in Figure 11 and (2) west-striking, left-lateral faults that are mainly found in the northeastern Mojave block (fault domain 2 in Fig. 11). Other significant left-slip faults include the Garlock fault and faults bounding the eastern Transverse Ranges in the southern part of the Mojave block. The first attempt to relate these strike-slip fault domains was made by Garfunkel (1974), and his model still forms the basic framework being tested at present.

Our interpretation for the development of the strike-slip faults combines interpretations made by Schermer et al. (1996) for the northeastern Mojave block, Dokka (1983) for the western Mojave block, and Richard (1993) for the eastern Transverse Ranges and the southeastern Mojave block. These interpretations of kinematics are fairly complete, honor geologic relationships, and are consistent with most of the paleomagnetic data and geologic markers. Slip along the eastern boundary is less certain (see later description). We discuss the faulting by dividing structures into four fault domains (Fig. 11) on the basis of location and kinematics. We summarize our interpretation by summing up the amount of northwest-directed shear accumulated across the Mojave block.

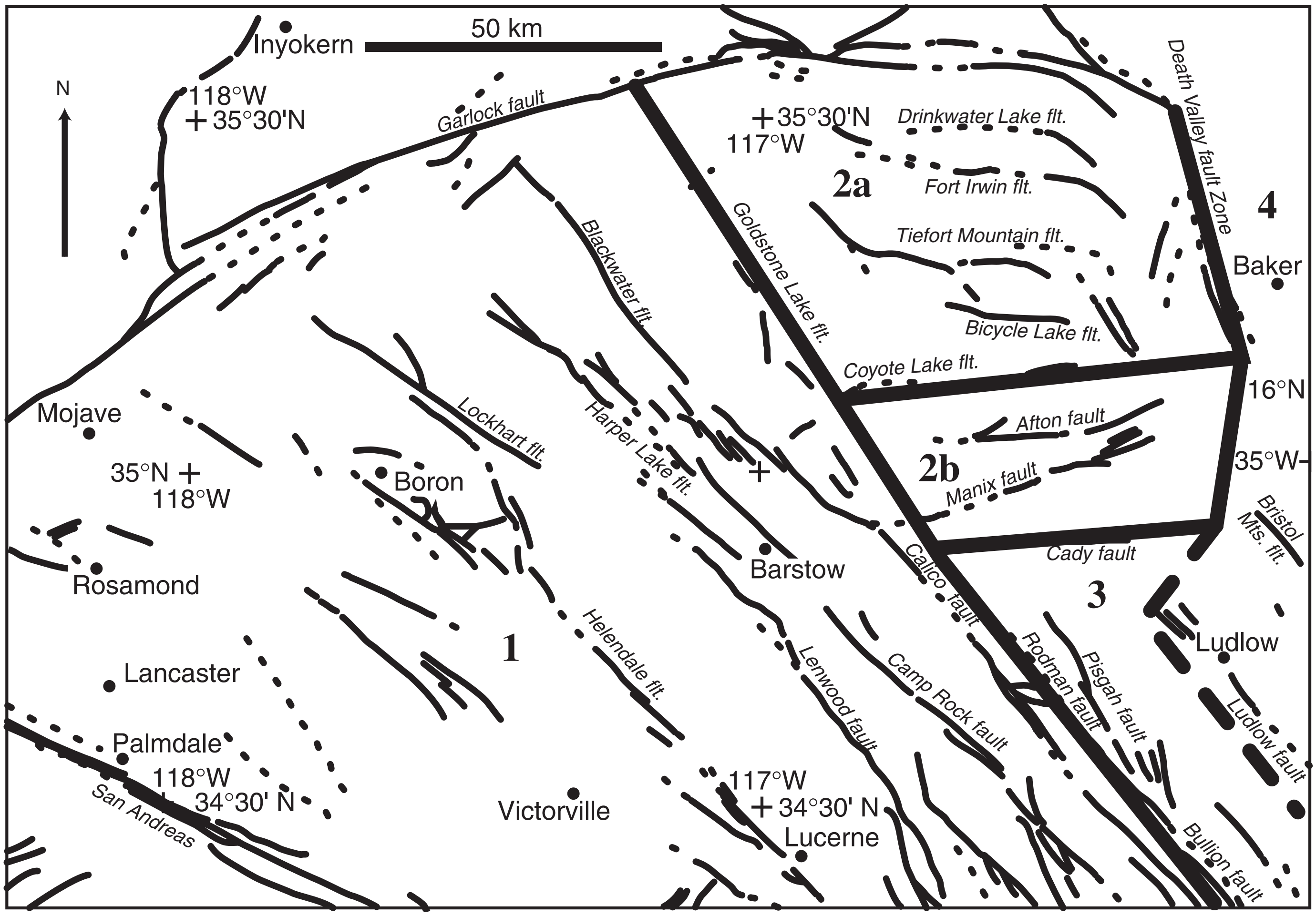


Figure 11. Fault domains 1–4 discussed in text.

Schermer et al. (1996) presented the results of detailed mapping and paleomagnetic studies for the northeastern Mojave block (Fig. 11, domain 2a). Their conclusion was that displacement is distributed across roughly east-striking faults that bound structural subblocks roughly 50 km long and 7 to 10 km wide. The eastern boundary of this fault array is the southern Death Valley fault zone (Soda-Avawatz fault zone of Schermer et al., 1996); the western boundary is the Goldstone Lake fault; the northern boundary is the Garlock fault; the southern boundary is the Coyote Lake fault. Clockwise block rotation accomplished by field-documented sinistral slip results in ~22 km of dextral shear across the region (~23° of clockwise rotation). An additional ~11 km may result from rigid-body rotation of the area as a whole according to paleomagnetic results (an added 15° of rotation; Fig. 14 in Schermer et al., 1996). This deformation results in 33 km of dextral shear across a roughly northwest-striking plane (Fig. 11).

Faults in domain 2b give similar results for rotation. Assuming subblocks ~7 km wide with ~5 km of slip (on the Afton and Manix faults; mapping by J.D. Walker; Meek and Battles, 1990) gives ~22° of clockwise rotation for this subblock (by using the method of Ron et al., 1984). This value is very similar to that derived by Schermer et al. (1996). Movements on these faults do not, however, add to the total documented slip in domains 2a and 2b (e.g., ~22 km).

This displacement must be balanced by slip across faults between the Calico and Ludlow faults (domain 3). The best estimate for slip across these faults, 20 km, comes from Richard (1993), who estimated ~30 km of cumulative slip across faults from the Camp Rock to the Ludlow fault. Subtracting 13 km for the Camp Rock and Calico faults (e.g., Dokka and Travis, 1990) leaves ~17 km to feed into the southern part of domain 2, ~13 km less than the estimate that is given by Schermer et al. (1996). We see two possible causes for this discrepancy: (1) there is deformation in domain 2b that results in an increase in the amount of right shear from south to north or (2) the paleomagnetic results in domain 2a do not reflect actual vertical-axis rotations. At present, we take 21 km as the best estimate of right slip across domains 2a, 2b, and 3 (average of Schermer et al. [1996] without rigid-body rotation, and Richard [1993]).

The next component we consider is slip between domains 2 and 4. Faults that accommodate this deformation are the Death Valley fault zone to the north and the Ludlow, Broadwell Lake, Bristol Mountains, and Granite Mountains faults (hereafter, Ludlow–Granite Mountains fault system) to the south (Fig. 11; Granite Mountains fault is not shown, but is located immediately east of the Bristol Mountains fault). Davis (1977) and Davis and Burchfiel (1993) estimated ~8 km of right slip across the southern Death Valley fault zone on the basis of offset of pre-Cenozoic rocks and the inferred continuation of the Garlock fault. Alternatively, Brady (1984) reported ~20 km of slip from the distance between alluvial-fan deposits and their probable source. Richard (1993) reported a maximum of 16 km of right slip based on relationships in southeastern California; no minimum was given. We take 8 km as the minimum and 20 km for the maximum estimates of dextral slip across this zone.

Dokka and Travis (1990) estimated a combined slip of 37.5 km across the Ludlow–Granite Mountains fault system based on palinspastic restoration of fault-bounded subblocks. Their interpretation requires ~20 km of slip across the Granite Mountains fault, but Howard and Miller (1992) estimated significantly less slip across this fault (0–10 km of strike slip, with a significant reverse component) on the basis of geologic relationships. We take right slip across the Death Valley fault zone to be between 8 and 20 km. We are unsure exactly how to distribute the slip among the various faults within the Ludlow–Granite Mountains fault system, but an average slip of ~4 km across each fault does not violate any geologic relationships of which we are aware.

The discrepancy between Dokka and Travis's (1990) estimate and ours for net slip across the Ludlow–Granite Mountains fault system appears to be explained by differing assumptions. Dokka and Travis assumed little or no slip across faults now known to have accommodated significant right slip (e.g., Harper Lake fault). Also, Dokka and Travis assumed that misfits between fault subblocks in the western and central Mojave block were accommodated by opening of pull-apart basins between rigid subblocks, whereas we interpret the field evidence to favor north-south intrablock contraction as a major mechanism for accommodating misfits. These differing assumptions lead us to infer a substantially larger amount of deformation in the western Mojave block and forced Dokka and Travis to transfer an equivalent amount of displacement eastward to the Ludlow–Granite Mountains fault system.

The last region to consider is domain 1, the western Mojave block. Net-slip values across the main faults are relatively well known and include Helendale, 3 km (Miller and Morton, 1980); Camp Rock–Harper Lake, 3 km (Bartley et al., 1992; Glazner et al., 1994); and Calico–Blackwater, 10 km (Garfunkel, 1974). The only regionally extensive fault with unknown slip is the Lockhart-Lenwood fault. There is fault-zone deformation associated with the Lenwood fault (e.g., the Lenwood anticline west of Barstow), but no clearly offset markers. Hence, right slip across the western Mojave block is ~16 km, with the possibility of significant addition from the Lenwood fault.

Summing geologically demonstrated slips across the Mojave block yields a minimum of ~44 km and a maximum of ~72 km of right shear (Table 1). Most of the strain is concentrated in the band from the southern Death Valley fault zone to the Calico fault. This result makes sense if strike-slip in the Mojave block balances Basin and Range extension (i.e., Davis and Burchfiel, 1973; Walker and Glazner, 1999): dextral shear is greatest in the region south of the area stretching from Death Valley to the Panamint Valley, where extension has been most active over the past 12 m.y. This estimate is similar in magnitude but different in detail to the 65 km value given by Dokka and Travis (1990).

Plate-tectonic setting

The early Miocene episode of volcanism and deformation in the Mojave Desert occurred during the changeover from subduction to transform-fault motion at the continental margin (Ingersoll, 1982; Glazner and Bartley, 1984). The kinematics of this process have been refined in a series of papers (Atwater, 1970; Nicholson et al., 1994; Bohannon and Parsons, 1995; Atwater and Stock, 1998). Initial contact of the Pacific and North American plates occurred in the late Oligocene, forming two triple junctions separated by a transform fault that evolved into the San Andreas system. The northern triple junction (the Mendocino triple junction) migrated past southern California from late Oligocene to middle Miocene time.

Several studies have linked volcanism and tectonism in the Mojave Desert region to migration of the Mendocino triple junction. For example, Glazner and Supplee (1982) and Glazner and Bartley (1984) showed that volcanism and tectonism migrated northward through the Mojave Desert region, tracking the triple junction. They proposed that volcanism and tectonism were triggered by two effects: flexure of the North American plate above the subducted part of the Mendocino Fracture Zone, and extension of the North American plate into the Mendocino triple junction, which was unstable and migrated away from the

TABLE 1. NORTHWEST-DIRECTED DEXTRAL SHEAR ACROSS THE MOJAVE BLOCK

Domain	Minimum	Maximum
Domain 1	16 km	19 km
Domain 2a	20 km	33 km
Domain 3	10 km	20 km
Domain 4	8 km	20 km
Total	44 km	72 km

Note: Slips in domains 2 and 3 do not contribute to the total displacement. Minimum and maximum slips for domain 1 and domain 2a are inferred from Richard (1993) and taken from Schermer et al. (1996), respectively. Slip in domain 2b (not listed) is consistent with that in domain 2a. The maximum slip for domain 1 assumes that the Lenwood-Lockhart fault has 3 km of right slip, similar to that of the Helendale and Camp Rock faults.

North American plate (Ingersoll, 1982; Atwater and Stock, 1998). Stratigraphic studies (Glazner and Loomis, 1984; Glazner et al., 2000) support this flexure model. Dickinson (1997) and Atwater and Stock (1998) related volcanism and tectonism in southern California to development of slab windows inboard of the transform margin and south of the Mendocino Fracture Zone.

Correlating geologic events in the Mojave block with the plate-tectonic record requires knowing the location of the Mojave block relative to stable North America in the late Oligocene and early Miocene. The plate reconstruction of Atwater and Stock (1998) locates points on the Pacific plate with respect to stable North America, but the Mojave block lies in the deformed western margin of North America and must be restored.

Atwater and Stock (1998) used the reconstruction of Wernicke and Snow (1998) to restore the Sierran block to an early Miocene position significantly south of its present location. Northwestward movement of the Sierran block from 8 Ma to the present in this reconstruction drags the Mojave block to the northwest. Thus, in the early Miocene, this reconstruction places the Mojave block ~100 km south and 150 km east of its present position relative to the Colorado Plateau. However, uncertainties in the reconstruction (Wernicke et al., 1988) allow that the northward shift could have been significantly smaller.

We see two significant problems with 100 km of northward translation of the Mojave block relative to stable North America. First, this shift requires 100 km of dextral displacement since 8 Ma across a fault or set of faults between the western Mojave block and the Colorado Plateau. Northwest-striking dextral faults in the Mojave block have observed slips of about half this amount (as previously described), and no significant faults of appropriate age and kinematics are known between the Mojave block and the Colorado Plateau. Second, if this reconstruction is followed, then there is little correlation between plate-tectonic events and geologic events in the Mojave block and areas north (discussed subsequently). However, if the Mojave block is interpreted to have remained at its present latitude since the early Miocene, then the correlation is excellent.

These concepts are presented in Figure 12. In the Atwater and Stock reconstruction, at 28 Ma the subducted part of the Mendocino Fracture Zone was under the middle of the Mojave block, but there are no geologic events that record its passage. At 24 Ma, the Mendocino triple junction and subducted part of the Mendocino Fracture Zone were well north of the Mojave block at about the latitude of the southernmost Sierra Nevada. As a result, a slab window would have underlain the southern San Joaquin basin, and most of the Mojave block would have been underlain by the subducted Farallon plate. There are no known late Oligocene–early Miocene events (volcanism, faulting, basin formation) in the southern Sierra Nevada or Owens Valley region that record these events, and the intense extension and magmatism that began in the Mojave block at ca. 24 Ma are inconsistent with the placement of these slab windows. Subsidence of the southernmost San Joaquin basin in the late Oligocene may be related to passage of the Mendocino triple junction, but the restored locations of this area and the Tehachapi Mountains are especially in doubt owing to uncertainties in how to restore the southern tail of the Sierra Nevada (Atwater and Stock, 1998). At 19 Ma, the Mendocino triple junction was well north of the southern Sierra Nevada, and the predicted slab windows underlay most of the southern half of California. Growth of the slab windows in this analysis would lead to eastward expansion of the volcanic fields, inconsistent with observation.

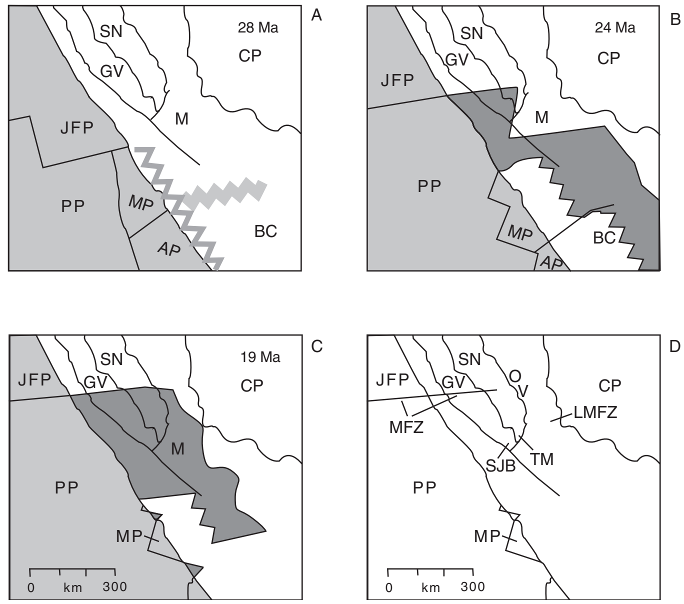


Figure 12. Slab-window reconstruction of Atwater and Stock (1998). Lighter gray marks oceanic plates; darker gray marks slab windows; zigzags indicate incipient breaks in subducted slabs. Arguello, Juan de Fuca, and Monterey plates are remnants of the Farallon plate. This reconstruction of the Mojave Desert region and the Sierra Nevada is not entirely consistent with geologic events in detail (see text). In particular, at 19 Ma, most of the southern Sierra Nevada and Owens Valley would have been underlain by slab windows, but there is no geologic record of such geometry. Panel D gives locations of features discussed in text superimposed on 19 Ma reconstruction. AP—Arguello plate, BC—Baja California, CP—Colorado Plateau, GV—Great Valley, JFP—Juan de Fuca plate, LFMZ—Lake Mead fault zone, M—Mojave block, MFZ—Mendocino Fracture Zone, MP—Monterey plate, OV—Owens Valley, PP—Pacific plate, SJB—San Joaquin basin, SN—Sierra Nevada.

We therefore favor an alternative reconstruction in which early to middle Miocene motion of the Sierra Nevada relative to the Colorado Plateau was more toward southwest than west. This extension vector lies within the uncertainties of the Wernicke and Snow (1998) reconstruction, and it has at least three advantages over the reconstruction in which the Mojave block moved significantly northward. First, it positions the Mojave block in the early Miocene at a more northern latitude where its geologic history correlates well with the position of the Mendocino triple junction and associated slab window. Second, the

Lake Mead fault zone, which forms the southeastern sidewall of the extensional domain analyzed by Wernicke and Snow (1998), strikes southwest. It is likely that the Garlock fault, which forms a similar lateral boundary farther to the west, had a similar southwestern strike prior to late Cenozoic transpressional modification (e.g., Garfunkel, 1974; Dokka and Travis, 1990; Bartley et al., 1990). Third, southwest-directed Miocene extension required by this reconstruction matches the middle Tertiary extension vector throughout the southwestern United States.

Figure 13 demonstrates that volcanism in the Mojave Desert region was not triggered by the enlarging slab window, but may have been triggered by the northern edge of the slab window and the subducted Mendocino Fracture Zone. It is apparent that the fit between the inception of volcanism and the position of the Mendocino Fracture Zone would be improved if the Mojave Desert region was restored somewhat southward in the Miocene relative to stable North America—perhaps 50 km, about half the distance used by Atwater and Stock (1998) and well within the uncertainties of the Wernicke and Snow (1998) reconstruction.

The kinematics of extension calculated from the Atwater and Stock (1998) reconstruction match observations in the Mojave block well (Fig. 14). From their reconstruction (Atwater and Stock, 1998, their Table 2 and Figure 3), in the early Miocene (20–15 Ma), the Pacific plate was moving away from the North American plate at 35 mm/yr along a vector oriented 300°. The orientation of the Pacific-North American boundary (the evolving San Andreas transform) was ~323°. This geometry resolves into 32 mm/yr parallel to the plate boundary and 14 mm/yr perpendicular to it (azimuth 053°). This azimuth is close to the observed extension direction of ~045°, and the rate of extension would require ~4 m.y. to accumulate the observed extension of ~60 km, consistent with the geochronologic data (ca. 23–18 Ma) presented by Walker et al. (1995).

CONCLUSIONS

The Cenozoic geology of the Mojave Desert region is dominated by three tectonic regimes. Prior to late Oligocene time, the region was a tectonically quiescent, externally drained plateau that left little geologic record. This condition ended in the late Oligocene when the North America–Farallon subduction zone encountered the Farallon–Pacific spreading ridge. This ridge-trench encounter formed the unstable Mendocino trench-fault-fault triple junction, the proto–San Andreas dextral transform plate boundary, and one or more slab windows beneath

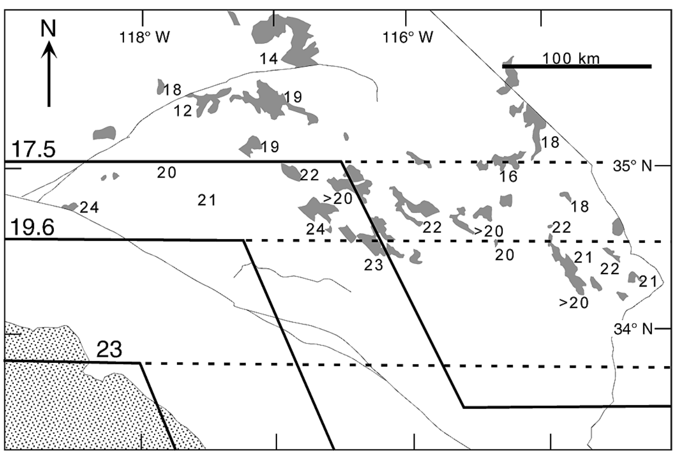


Figure 13. Evolving slab windows according to the reconstruction of Dickinson (1997). In this reconstruction, plate boundaries are plotted on an unrestored base map of southern California. For each time (23, 19.6, and 17.5 Ma), the corresponding slab window is delimited on its north and east by solid lines. The east-west line along the northern boundary of each window represents the Mendocino Fracture Zone; the dashed extension represents the Mendocino Fracture Zone in the subducted plate. Gray areas are outcrops of early Miocene volcanic rocks; numbers are ages of inception of volcanism in each field. Note that volcanism began simultaneously across the Mojave Desert region in the early Miocene. If volcanism was triggered by development of the slab window, then the volcanic activity should have migrated inland to the northeast, a pattern that is inconsistent with observation (although coastal volcanism may have been triggered by the slab window; Dickinson, 1997). The pattern of inception of volcanism is consistent with triggering by subduction of the Mendocino Fracture Zone (Glazner and Bartley, 1984). Sources for inception of volcanism: Armstrong and Higgins, 1973; Burke et al., 1982; Cox and Diggles, 1986; Davis and Fleck, 1977; Dokka and Baksi, 1989; Glazner, 1988; Glazner et al., 2000; McCurry, 1988; Sabin et al., 1994; Sherrod and Nielson, 1993; Smith et al. (this volume); Walker et al., 1995; Weigand, 1982.

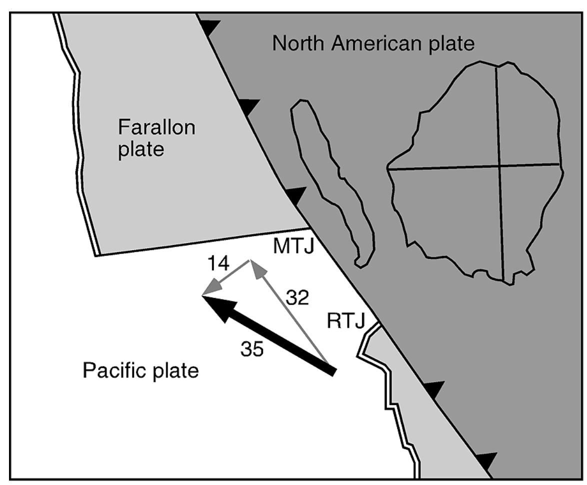


Figure 14. Early Miocene plate kinematics of the Mojave Desert region, from Atwater and Stock (1998). Relative motion of 35 mm/yr between the Pacific plate and stable North America can be resolved into 32 mm/yr parallel to the transform plate margin and 14 mm/yr perpendicular to it. Black teeth indicate remnant subduction zones north and south of the transform margin. Slip partitioning like this explains the direction, magnitude, and rate of extension in the Mojave block. Outlines of the Colorado Plateau and Sierra Nevada shown for reference. MTJ—Mendocino triple junction; RTJ—Rivera triple junction.

the North American plate. These three plate-tectonic features governed later evolution of the Mojave Desert area.

Instability of the triple junction, transtensional obliquity of the Pacific plate-North American plate relative-motion vector, and the slab window all probably contributed to a wave of lithospheric extension and magmatism that migrated northwestward across the southwestern United States. Early Miocene crustal extension mainly affected the Basin and Range province to the east of the Mojave Desert region, but 40–60 km of early Miocene extension took place to form the Central Mojave metamorphic core complex in a restricted area that is surrounded by areas of little or no extension.

We interpret this pattern of highly localized large-magnitude extension to record an east-northeast-trending belt of dextral transtension that linked the northern end of early Miocene extension in the Colorado River trough southwestward to the active proto-San Andreas transform. The inferred Mojave Valley fault linked the Colorado River extensional corridor to the Central Mojave metamorphic core complex. No specific structure has yet been identified that links the northwestern termination of the Central Mojave metamorphic core complex westward to the early Miocene plate boundary, but the absence of evidence for significant early Miocene extension in the northern Mojave block indicates that such a structure must trend westward from a location between The Buttes and Fremont Peak. The estimated extension rate across the Central Mojave metamorphic core complex, ~15 mm/yr, is compatible with extension being driven by partitioning of the divergent component of the Pacific-North America relative plate motion into intracontinental extension.

Northward migration of the Mendocino triple junction away from the Mojave Desert area correlated with the change from transtensional to transpressional deformation that has dominated Mojave geology from the middle or late Miocene to the present. About 50 km of dextral shear have accumulated across a complexly branching array of northwest-striking right-slip and west-striking left-slip faults that transfer motion from the San Andreas fault system to the Walker Lane belt. Sporadic but locally intense folding and reverse faulting accompanied late Cenozoic dextral shear and accommodated a yet-undetermined amount of north-south transpression across the Mojave block.

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