DAVID BLOOM

Displacements on late Cenozoic strike-slip faults of the central Mojave Desert, California

began late as Pliocene or Quaternary time— early stage of development.

p308.

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ABSTRACT

Field studies demonstrate that displacements on northwest-striking wrench faults of the central Mojave Desert are too small to support hypotheses suggesting large interior translations and associated rotation of the province during late Cenozoic time. The margin of an early Miocene structural belt provides the marker with which to establish lateral displacement on individual faults. Displacement values for faults are as follows: Lenwood fault = 1.5–3 km, Camp Rock Fault = 1.6–4.0 km, Calico fault = 8.2 km, and Rodman-Pisgah faults = 6.4–14.4 km. Cumulative displacement on all the major northwest-striking faults of the Mojave Desert is about 26.7–38.4 km. Most, if not all, regionally distributed right shear (presumably related to Pacific–North American plate interaction) developed in the central Mojave Desert after 20 m.y. B.P. Right shear was preceded by significant amounts of kinematically unrelated northeast-southwest crustal extension.

INTRODUCTION

Reconstruction of the Mojave Desert region in light of late Cenozoic deformations is critical if we are to understand fully the tectonic evolution of the southwestern United States. Previous regional syntheses have misjudged the degree of continental extension that occurred in the Mojave during the early Miocene and have overestimated the amount of late Cenozoic right strike-slip displacement. This paper attempts to document the movement along these later faults and discusses the viability of hypotheses for the tectonic evolution of this province in light of these new constraints.

The Mojave Desert block of southern California is defined here as a triangle-shaped structural province bounded on the north by the Garlock fault and on the south by the San Andreas fault system (Fig. 1). Its eastern limit is considered to be a north-trending line defined by geophysics (i.e., Bouguer gravity and seismicity), crustal thickness, and physiography (Dokka, 1980). The dominant, active structural elements of the Mojave Desert block are northwest-striking wrench faults that are responsible for the neotectonics and present-day physiography. This fault system consists of at least seven major strands that include (from west to east) the Helendale, Lenwood, Camp Rock, Calico, Rodman-Pisgah, Ludlow, and Bristol Mountain faults (Fig. 1). They are high-angle, display dominantly right slip, and are composed of anastomosing and en echelon segments. These faults are best seen on aerial photographs where they form topographic lineaments defined by fault scarps, aligned truncated spurs, and fault-line scarps.

The late Cenozoic tectonic history of the central Mojave Desert block is marked by several periods of different faulting styles (Dokka, 1979, 1980, 1983) that were initiated near the beginning of the Miocene. Prior to this time, the central Mojave region was of low relief and served as a sediment source for basins to the south and west (Hewett, 1954). This low-relief surface was disrupted during a short-lived interval of detachment faulting and high-angle normal faulting that was probably related to intraplate extension (Dokka, 1980; Dokka and Glazner, 1982). Chaotic monolithologic breccias and conglomerates as well as newly erupted volcanic rocks and their detritus were deposited in rapidly evolving tectonic basins within and peripheral to the extending terrane (Dokka,

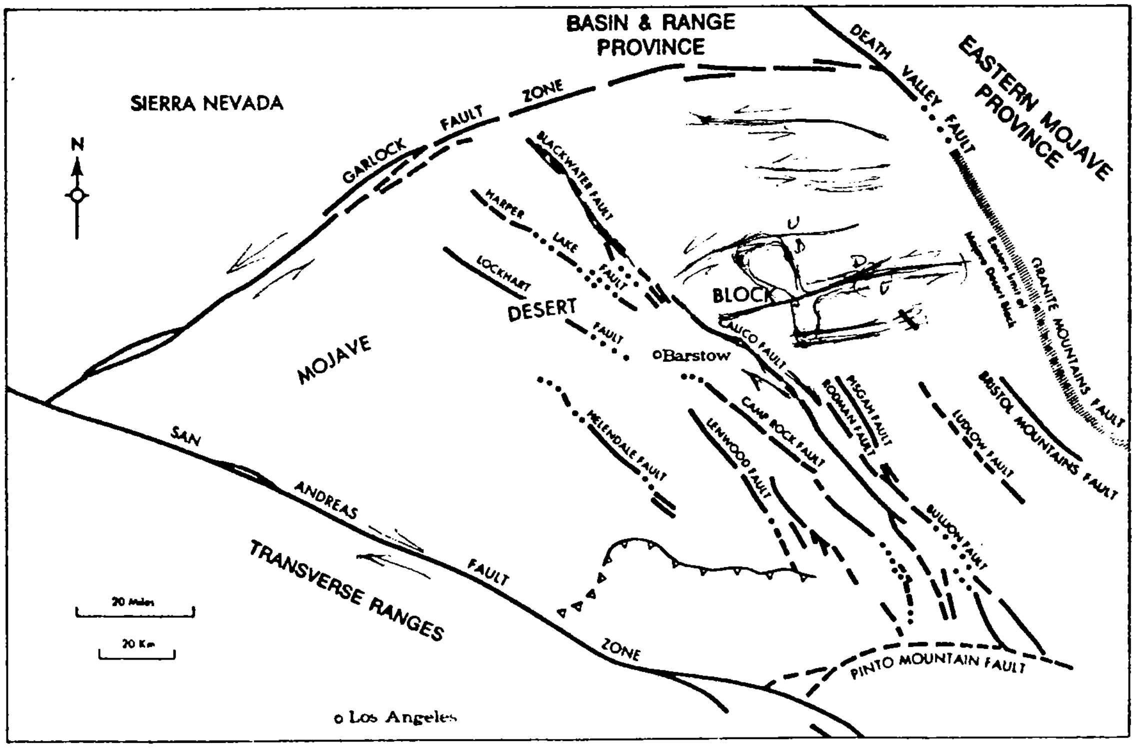

Figure 1. Index map for central Mojave Desert.

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1979, 1980; Dokka and Glazner, 1982). This deformation is important to the study of later northwest-striking strike-slip faulting because it created a regional marker (terrane margin) that allows one to determine amounts of strike-slip displacements of younger faults.

The origin of late Cenozoic strike-slip faulting in the central Mojave Desert has been speculated upon by several workers. Dibblee (1961) first recognized the presence of wrench faults on the basis of their geometry and associated structures and suggested that they were related to movement along the San Andreas fault. Garfunkel (1974), on the basis of Dibblee's data, proposed that these intraprovince faults developed because of broadly distributed shear induced by local geometric irregularities along the Pacific and North American plate boundary. Movement between individual fault slices was thought to be accompanied by the counterclockwise rotation of both slices and faults. Garfunkel predicted that rocks of the Mojave block may have been rotated as much as 30°. Luyendyk et al. (1980) proposed a tectonic model for southern California that predicted tens of kilometres of slip on each of the Mojave faults. Their slip estimate (their Fig. 3) was based on a paleomagnetic reconstruction of the region. Hadley and Kanamori (1977) suggested that the faults of the central Mojave may be the surface expression of the mantle transform boundary between the North American and Pacific plates, a boundary that is inboard (northeast) of the crustal transform boundary at the San Andreas fault. These conclusions were based on the northeast termination of an east-northeast–trending high-velocity ridge in the upper mantle centered beneath the Transverse Ranges.

KINEMATICS

Previous estimates of movements on central Mojave Desert strike-slip faults have generally not been based on dated offset geologic features. Garfunkel (1974) suggested, on the basis of offsets of the pre-Tertiary–early Miocene "unconformity" (of Dibblee, 1971), that the Lenwood, Camp Rock, and Calico faults have slipped 15–20 km, 10 km, and 20 km, respectively. Hawkins (1975) recognized the nondepositional nature of that contact and concluded that the strike slip on the Camp Rock was only 1.5 km, occurring between early Tertiary and late Holocene time. Hawkins was not able to find evidence of latest Holocene displacement. S. Miller (1980) determined by correlating offset volcanic strata that 3.75 km of slip had occurred on the Camp Rock fault since the early Miocene. Additional northwest-striking faults lie east of the Ludlow fault, between the Bristol and Granite Mountains. Davis (1977) considered and dismissed the hypothesis of Hamilton and Myers (1966) that this fault was the southern extension of the recently active Death Valley fault zone. Davis found no evidence to support the existence of a through-going strike-slip fault of Quaternary age. Pre-Quaternary movement, however, was not ruled out. Farther south along this trend, Miller et al. (1982) have documented >6 km of right separation for a fault system along the southwest border of the Bristol Mountains. This fault cuts the lower beds of Pleistocene(?) alluvium. The region east of the Bristol Mountains fault is tectonically and seismically inactive (Hileman et al., 1973; Carr and Dickey, 1976).

The once continuous southern edge of the early Miocene detachment fault terrane provides a regional marker with which to determine lateral displacements (Fig. 2) on late Cenozoic strike-slip faults of the central Mojave Desert. This edge is a high-angle fault and is named the Kane Springs fault for exposures in the southern Newberry Mountains (Dokka, 1980). The Kane Springs fault originated as a transform structure, accommodating the differential extension of regions within the central Mojave detachment terrane (Dokka, 1980; Dokka and Glazner, 1982; Dokka, 1983). In the Newberry and Rodman Mountains, the fault separates the extended terrane from a region of no extension. However, east of the Rodman Mountains, the Kane Springs fault becomes intraterrane, dividing two oppositely tilted half-grabens (Dokka, 1983).

Although no piercement points required for net slip determination were found, strike-separation values presented here are considered to be close approximations because (1) kinematic indicators along faults suggest dominantly horizontal movements; (2) fault trace geometry (straight, narrow fault zone with anastomosing strands) and associated structures (folds, other faults) are similar to known strike-slip zones (e.g., Wilcox et al., 1973); and (3) displaced planes (faults) are high-angle and are oriented nearly perpendicular to the faults.

Table 1 summarizes the post-20-m.y.-ago strike separations on wrench faults of the central Mojave Desert as determined from this study and from other sources. An undetermined but probably minor amount of strain in the form of drag can also be observed along some of the faults. For example, along one part of the Calico fault (Fig. 2b), the early Miocene marker (detachment terrane margin) and nearby rocks are bent to an extent (shear strain = 1.73) that suggests that an additional 1.4 km of distributed right shear has occurred.

The finite slip and the time of initiation of right-slip faulting in the central Mojave Desert are difficult to determine because of the lack of narrowly constrained dated crosscutting relationships. Relations along the Camp Rock fault, however, suggest that the displacement of Mesozoic and older rocks is similar to the post-20-m.y.-ago slip. Miller and Carr (1978) correlated two distinctive stratigraphic sections across the fault in the central Rodman Mountains area. These rocks occur as roof pendants in Upper Cretaceous biotite quartz monzonite and consist of a sequence of quartzite, calc-silicate rocks, carbonates, and volcanic-

TABLE 1. ESTIMATES OF SLIP ON NORTHWEST-STRIKING WRENCH FAULTS OF THE CENTRAL MOJAVE DESERT

Fault	Garfunkel (1974)	This Paper
Helendale	10-15	3.0 *
Lenwood	15-20	1.5-3
Camp Rock	10	1.6-4.0†§
Calico	10-20	8.2 #
Rodman-Pisgah	20-40	6.4-14.4
Bristol Mountains	-----	6.0 **
Ludlow	-----	Small?
Cumulative	65-105	26.7-38.4

Note: All estimates are kilometers.

*Based on estimate (Miller and Morton, 1980) of 3 km of net slip.

†Hawkins (1975) estimated 1.5 km of strike separation.

§S. Miller (1980) estimated 3.75 km of strike separation.

#Does not include an additional 1.4 km of right shear expressed as strain.

**D. Miller et al. (1982).

clast conglomerates. Miller and Carr's (1978) mapping indicates that the two sections have been laterally displaced 3-5 km from each other along a straight, vertical segment of the Camp Rock fault. Although the available data are not well constrained enough to suggest that the fault was initiated after 20 m.y. ago, it does strongly indicate that most of the movement did occur after that time. Determination of the lower limit of initiation is even more elusive. Pleistocene(?) sedimentary deposits are only partially displaced along the Camp Rock, Lenwood, and Calico faults (Hawkins, 1975; Dokka, unpub. mapping). Thus, field relations suggest that most if not all displacements along active northwest-striking right strike-slip faults occurred and probably began between early Miocene (post-20 m.y. ago) and Pleistocene(?) time.

DISCUSSION

Two important points emerge from the study of late Cenozoic northwest-striking wrench faults of the central Mojave Desert block. The first is that most if not all right-slip movements in this region (presumably related to distributed transform shear) began *after* the area had undergone an intense interval of regional extension (northeast-southwest-directed detachment faulting). This reinforces the notion put forth by several authors (e.g., Davis and Burchfiel, 1973; Proffett, 1977; Zoback and Thompson, 1978; Dokka and Merriam, 1982) that regional strike-slip faulting associated with the Pacific-North American transform boundary cannot be dynamically related to major extension of western North America (Great Basin, proto-Gulf of California, Rio Grande Rift, etc.) during the late Cenozoic. In addition to timing problems, transform-related extension models (e.g., Carey, 1958; Wise, 1963; Hamilton and Myers, 1966; Atwater, 1970; Livaccari, 1979) predict that dilation was directed parallel to the strike of the transcurrent faults (northwest-southeast, in this case). These hypotheses, therefore, cannot explain the geometries and kinematics of the structures produced during the earlier events in the central Mojave Desert. One

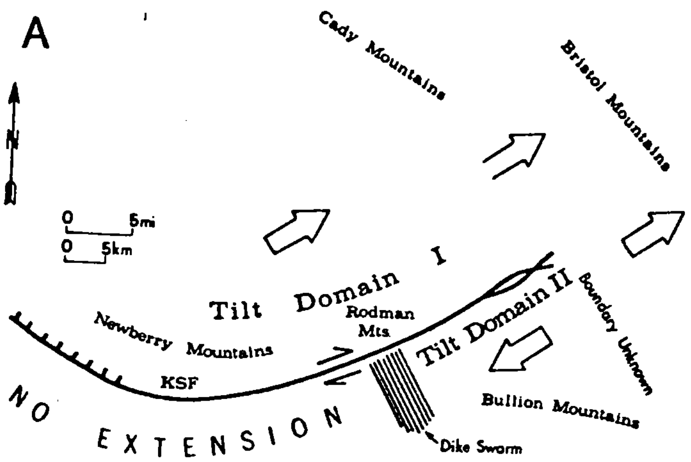
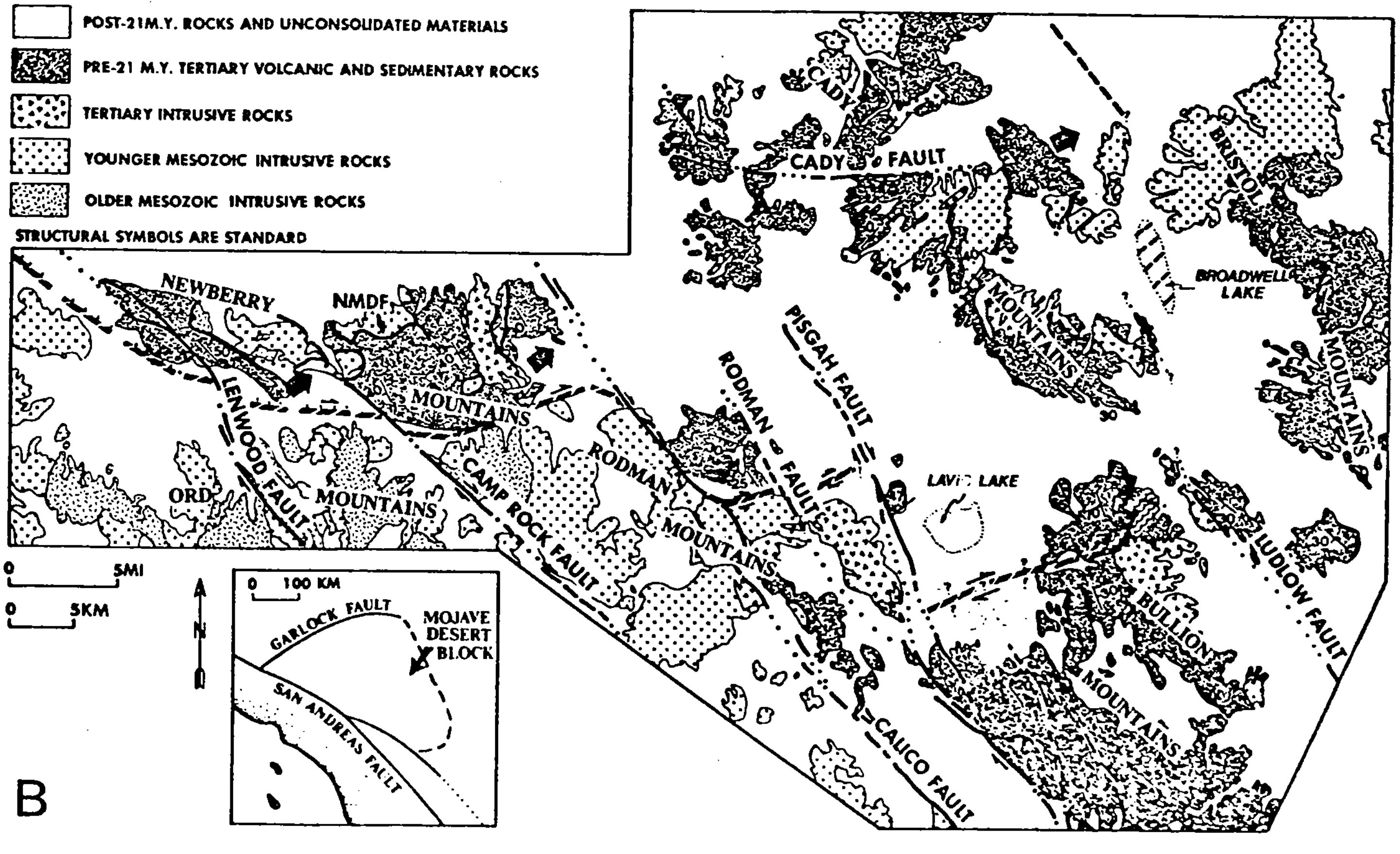


Figure 2. (A) Pre-strike-slip faulting (ca. 20 m.y. ago) configuration of central Mojave Desert. Structure symbols are standard. Kane Springs fault (KSF) is major accommodation structure that separates regions that extended differently during early Miocene detachment faulting interval. (B) Present-da, geology of central Mojave Desert. Broken line segments are Kane Springs fault. Displacements along individual faults are given in Table 1.



might argue that these earlier deformations were related to northwest-southeast extension but were subsequently rotated clockwise to their present position in a manner such as has been suggested by Garfunkel (1974). Such rotations of early formed structures are not uncommon in wrench fault terranes (e.g., Tchalenko, 1970). However, Garfunkel's model is untenable because it requires that strike-slip faults of the Mojave have lateral displacements of up to ten times greater than can actually be demonstrated. This leads to the second point regarding a more realistic estimate of the cumulative and individual slip on faults of the Mojave. The once continuous edge of the early Miocene detachment fault terrane provides a unique marker with which to determine displacements. About 26.7–38.4 km of cumulative right slip has occurred on the strike-slip faults of the central Mojave (Table 1) since 20 m.y. ago. Pre-20-m.y.-ago displacements, if any, must be regarded as extremely small. The upper limit on the time of fault inception is poorly constrained by the lack of offset pairs of rocks along the faults. It is conceivable, however—and very probable, in my opinion—that faulting began later, perhaps as late as Pliocene or Quaternary time. This speculation is founded on the overall geometric arrangement of structures and the high ratio of fault length to slip. These observations, coupled with displacement data, suggest that the central Mojave Desert strike-slip faults may be in an early stage of development. More detailed study is needed.

SUMMARY AND CONCLUSIONS

The amount of slip on individual faults is determined to be 3.0 km for the Helendale, 1.5–3.0 km for the Lenwood, 1.6–4.0 km for the Camp Rock, 8.2 km for the Calico, 6.4–14.4 km for the Rodman-Pisgah, and small for the Ludlow. Cumulative right slip on northwest-striking wrench faults of the central Mojave from Helendale to the Granite Mountains is 26.7–38.4 km, on the basis of the restoration of the high-angle southern margin of an early Miocene detachment fault terrane. This value is about five times less than some previous speculations and therefore invalidates models that propose large interior translations of the Mojave Desert block. Large rotations of the block as a whole, however, cannot be ruled out. Distributed right shear probably did not develop in the central Mojave Desert before 20 m.y. ago. Strike-slip faulting in this region was preceded by significant amounts of kinematically unrelated northeast-southwest-directed crustal extension.

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trend. Subordinate and older N-S to NE-SW striking normal faults cut these volcanic units.

A series of rhyodacite to rhyolite domes and associated air-fall tuffs covering 40 km^2 postdating the faulting were erupted .15±.006 m.y.a. at the western edge of the center. Present-day geothermal activity is spatially linked to the older rhyolites and is virtually absent in the zone of the younger silicic volcanics, since movement of fluids in the geothermal field is strongly controlled by the fault sets. Fault movement between .37 and .15 m.y.a. may be due in part to the emplacement of a high-level silicic magma chamber which would serve as a heat source for the active geothermal system as well as a magma reservoir for the younger rhyolite domes.

NEW OCCURRENCES OF SCHALLERITE AND BAFERTISITE IN MN-RICH ROCKS AND IMPLICATIONS FOR FUGACITY GRADIENTS DURING METAMORPHISM

Nº 32015

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The rare minerals schallerite - $Mn_{16}Si_{12}As_xO_{30+2x}(OH)_{20-x}$ and bafertisite - $Ba(Mn,Fe)_2TiSi_2O_7(OH,F)_2$ occur in metamorphosed Mn-rich rocks from W. Massachusetts. Schallerite occurs with barite, rhodochrosite, tephroite, pyrophanite, fluoro-sonolite, jacobsite, arsenopyrite, pyrrhotite, and fluorite. The As content of schallerite varies between 6 and 13 wt. % between grains but is constant within individual grains. Bafertisite occurs with the above minerals excepting barite, and in addition coexists with alabandite. Ignoring minor solid solution in the minerals (CaMn, FeMn exchanges) calculated phase relations imply an increase in fO_2 and possibly a minor decrease in fS_2 between the two assemblages. No As-poor schallerite occurs in the previous assemblages. This suggests that schallerite may be stabilized by its As content. Using the As exchange proposed by Dunn, et al (1981), a possible reaction explaining the occurrence of schallerite is:

$$2FeAsS + 3/2\ O_2 = 2AsO_2\overline{(OH)\lambda\square}_{schall} + 2FeS + H_2O$$

In addition, a reaction for the disappearance of bafertisite might be:

$$BaMn_2TiSi_2O_7(OH)_2 + 3MnS + 7/2\ O_2 = BaSO_4 + MnTiO_3 + 2Mn_2SiO_4 + H_2O + S_2$$

DOLOMITIZATION, AN HYPOTHESIS OF THE PROCESS

Nº 30132

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Preservation within a dolostone of undistorted ghosts of the primary rock fabric dictates that dolomitization is a volume for volume replacement of calcite by dolomite, and the volumetric rate of dolomite precipitation must equal the rate of calcite dissolution. Geochemical conditions within the pore system prerequisite to dolomitization are therefore very limited, yet the volume of dolomitized calcite in the stratigraphic record implies that the process is a common event. It is hypothesized here that the pore system chemistry has only an indirect effect on the process in that it serves as a source and sink for the ions involved in the reaction and that the physical-chemical process of dolomitization is described by the conditions that exists within a narrow boundary zone located between the dissolving calcite crystal and precipitating dolomite. Within this zone the concentrations of dissolved ions approximate that of the pore system but the pressure of the fluid within the zone is drastically different due to a greater volumetric potential for dolomite growth relative to the potential for calcite dissolution. The potential growth rate differential attempts to reduce the volume of the zone hence distance between the growth surface of the dolomite and dissolution surface of the calcite. This reduction in width of the boundary zone is resisted by molecular attraction of the solution to the crystal surface. Reduction in width therefore must be accompanied by an increase in pressure within the zone in order to force the water out. Since reaction rates are a function of pressure the physical-chemical condition of dolomitization is established by adjustments to the boundary zone width. Dolomitization therefore proceeds as a combination of "pressure solution" and "force of crystallization" in a wide range of chemical environments limited only by the mechanical strengths of the dolomite and calcite crystal lattices.

SHEAR INSTABILITIES AND GLACIAL SURGES

Nº 27533

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It seems generally accepted that the high rates of motion observed during glacial surges must be the result of sliding. Several authors have proposed mechanisms for surging, based on a instability at the base of the glacier. However, surges are accompanied by thickness changes. Analysis of the shearing which must accompany these changes suggests an instability mechanism occurring within the ice, that may make a major contribution to glacial surges.

As a glacier thickens prior to surging, shearing characteristic of compressive flow will occur. The shearing will cause the ice to recrystalize with basal planes parallel to the direction of shear, reducing the resistance to shear, and increasing the rate of shear. Eventually, this may result in fracturing and the formation of discrete shear zones. The shear zones will curve upward from the base of the ice to the surface and basal debris will be carried upward within these zones. The accumulation of debris within the shear zones, in conjunction with melting, will create a situation where shearing is taking place between wet rocks, rather than within glacial ice. At this point the glacier will slide quite rapidly, until the driving forces drop below the frictional forces. Then the ice will stagnate, the shear zones will refreeze, and the whole process will begin another cycle.

This model provides a mechanism for instability in glacier flow and also allows for the spatial variations in velocity observed in surging glaciers. Furthermore, the shearing mechanism will produce large quantities of englacial and supraglacial debris, which may remain after glacial retreat, as evidence of surging glaciers in the past.

A NON-UNIFORM EXTENSION MODEL FOR CONTINENTAL RIFTING

Nº 18993

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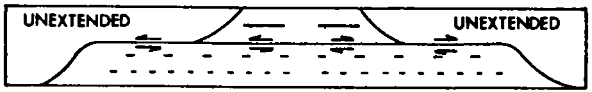
We propose a model to reconcile geophysical observations with field structural studies of ancient continental rifts. Extension develops in two major mechanical domains within the lithosphere. The upper domain (<15km) extends by brittle processes which are concentrated in a relatively narrow zone in comparison with deeper levels. In the lower domain, extension is accomplished by flow and occurs over a broader area, reaching beyond the limits suggested by surface rupture. The geometry of the extended lithosphere is probably temperature-controlled, and thus related to earlier thermal events. Extension within each domain is also non-uniform. Although the displacement field is inhomogeneous, the integrated strain at all levels is equal (see figure below).

Decoupling within the lithosphere along detachment faults is the result of abrupt changes in the displacement field and/or transition from one mode of extension to another (e.g., brittle to ductile). Thus, a section of extended lithosphere should be expected to contain low-angle normal faults at upper levels and ductile shear zones at deeper levels. A major detachment would be expected to form at the transition from the upper to the lower domain. Beneath the upper domain, the detachment serves to accommodate distension and rotation of crustal blocks by high-angle normal faulting. The detachment continues to deeper levels (thereby rooting), separating the moderately extended lower crust from unextended portions of the upper crust.



LENGTH OF LINES PROPORTIONAL TO STRAIN RATE

COASTAL HAZARDS MAPPING

Nº 24164

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In 1979 we reported on rates of shoreline change along the mid-Atlantic coast. Since then, under sponsorship of the U.S. Geological Survey, we have assembled data on shoreline changes for the remainder of the United States, including Chesapeake Bay, Delaware Bay, and the Great Lakes. The information is presented on a 1:7,500,000 scale map for the National Atlas and as a series of 1:2,000,000 maps for regional planning applications. The data are contained in a user-oriented computerized information system (CEIS)

The data base has been expanded to include coastal hazards information. Eleven process and response variables were defined as posing a risk to coastal inhabitants, including shoreline rates of change, overwash, storm surge, storm frequencies, tsunami frequency, seismic and tectonic activity, ice and permafrost cover, and tendency for subsidence and slope failure. Factors contributing to risk mitigation or intensification, such as relief and stabilization, are also included. Data were compiled from primary sources using the sampling base developed for the erosion map series. An overall "risk factor" was determined statistically for each 3' (latitude or longitude) segment of the coast. These data are presented on a 1:7,500,000 scale map for the National Atlas and are included in the information system (CEIS). Prototypes of a 1:2,000,000 hazard map series have also been designed.

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Geometric model for Neogene crustal rotations in southern California

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ABSTRACT

Paleomagnetic data from mainly Miocene igneous rocks in southern California suggest that large crustal regions have undergone clockwise rotation during that time. We propose a model whereby many crustal blocks presently bounded on the north and south by east-west–trending sinistral faults have undergone rotations of about 70° to 80° within the Pacific-American right-lateral shear couple. The data suggest that these crustal blocks include the western Transverse Ranges and parts of the offshore Borderland. Our model predicts that the eastern Transverse Ranges, the central Mojave Desert, and the Tehachapi Mountains region have also rotated. The rotated blocks are nested between blocks bounded by northwest-southeast–trending dextral faults. The rotations probably ceased in late Miocene time when the San Andreas fault system broke through southern California and may have begun when the Pacific plate contacted the North American plate in late Oligocene time. This geometric model for rotated blocks predicts that left-slip, right-slip, and rotation occur simultaneously; that the displacements can be calculated from the rotation (and vice versa); and that during the rotation, deep triangular basins open at the join between the rotated and unrotated blocks. It also suggests that dextral slip can occur on northwest-southeast faults without cutting the Transverse Ranges.

INTRODUCTION

Recent paleomagnetic studies of Neogene igneous rocks in southern California and environs have found evidence for apparent clockwise rotations of magnitudes of about 75° (Kamerling and Luyendyk, 1977, 1979; Kamerling and others, 1978; Greenhaus and Cox, 1978, 1979). Separately, geologic data have also suggested rotations of large crustal units in southern California (Jones and Irwin, 1975; Jones and others, 1976; Hamilton, 1978; Crouch, 1979). One explanation of these observations is that small lithospheric plates have been separated from the North American plate in the right-lateral shear couple between this plate and the Pacific plate. Within this San Andreas–type of shear, the microplates are translated northward and rotated clockwise into place (Crouch, 1979; Kamerling and Luyendyk, 1979). This general concept was previously discussed by Beck (1976) to explain east-deflected paleomagnetic directions along the western American margin.

We have noticed that in southern California the rotated crustal units, or domains, appear to be bounded on their north and south sides by east-west–trending, left-lateral (sinistral) faults. The paleomagnetic data and the pattern of sinistral and dextral faults in southern California suggest an idea, following Freund (1970, 1974), Dibblee (1977), and Livaccari (1979), whereby the blocks bounded by sinistral faults rotated clockwise within a northwest-southeast–trending, right-lateral shear couple. These rotated domains are nested between blocks bounded by northwest-southeast–trending dextral faults. Thus, a right-lateral shear couple rotated the sinistral fault-bounded blocks clockwise. Garfunkel (1974) proposed a rotational tectonics model for the late Cenozoic evolution of the Mojave Desert. Rather than being related to the Pacific-American shear couple as we discuss, his rotation model is keyed to Basin and Range extension: The rotation he proposed is 30° counterclockwise for the now northwest-southeast–trending crustal blocks in the Mojave.

ROTATIONAL MODEL

In Figure 1, we show paleomagnetic declination unit vectors determined at sites within southern California. Directions in the Santa Monica Mountains and Anacapa Island are those reported for middle and late middle Miocene flows and dikes by Kamerling and Luyendyk (1979). Directions for the Oligocene Morro Rock–Islay Hill intrusive complex are from Greenhaus and Cox (1979). The remaining directions shown are as of yet unpublished but represent work completed at the University of California, Santa Barbara and at San Diego State University (M. Marshall, unpub. data). Each arrow represents a few cooling units and a dozen or more samples. Thus, secular variation is not averaged. Each result shown is believed to be statistically significant, but we will demonstrate this elsewhere. The rocks studied are of Miocene age except for Oligocene rocks in the San Gabriel Mountains region. Nearly every site shows an apparent clockwise rotation. Undeflected directions have been found in the extreme eastern Mojave (Neogene and Quaternary lavas) and in San Diego County (Miocene lavas). This immediately weakens the arguments presented below, in that we have yet to define accurately regions which are not rotated. However, our proposal is that the unrotated regions are bounded by northwest-southeast–trending, right-slip faults. From the data available, it appears that the rotations probably ended in late Miocene time (Kamerling and Luyendyk, 1979). The rotations may have begun at the earliest, when the Pacific and North American plates came into contact in late Oligocene time about 29 m.y. ago (Atwater and Molnar, 1973; Dickinson and Snyder, 1979).

In Figure 2, we have identified crustal blocks, or domains, in southern California which we propose have been rotated clockwise during mainly Miocene time (shaded). All of the proposed rotated

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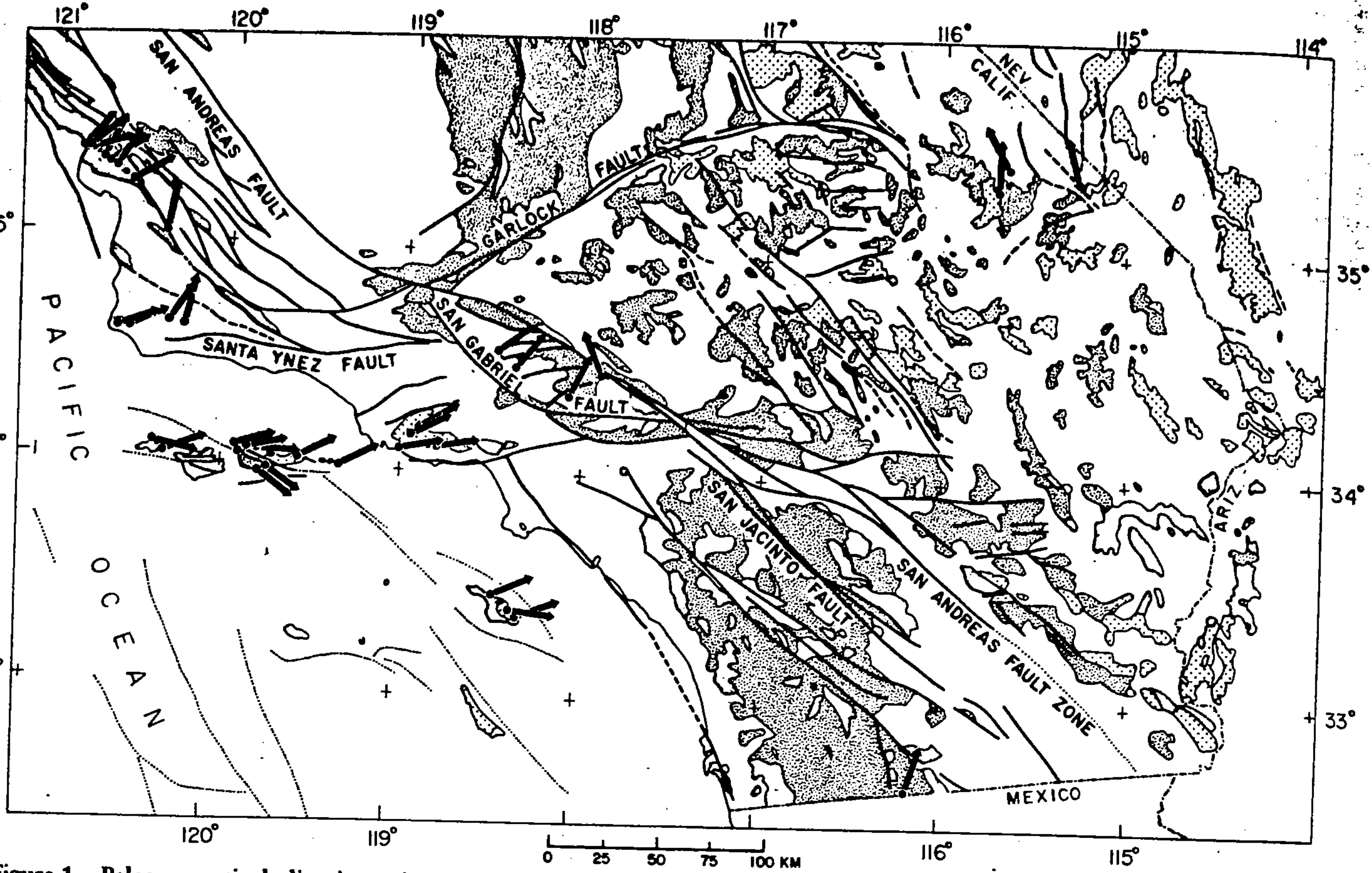


Figure 1. Paleomagnetic declination unit vectors determined at sites in southern California for Neogene rocks. Each vector represents determinations from one or more volcanic units and a dozen or more samples. Geology and faults from Jennings (1973).

blocks are bounded on the north and south by east-west–trending faults which in most cases have been shown to have left-slip components of motion. For the faults south of Catalina and San Nicolas Islands, we infer that the motion has been sinistral, but it also must have had a dip-slip component. The paleomagnetic data from the western Transverse Ranges suggest a 70° to 80° rotation for this area (Kamerling and Luyendyk, 1979; Kamerling and others, 1978). Restoration of this rotation aligns the left-lateral faults almost north-south so that the angle between these faults and the north-west–trending, right-lateral faults is about 55° and no less than 45°.

Simplified diagrams (Fig. 3) illustrate a proposed sequence of events. The first diagram (Fig. 3A) shows the fracture pattern in late Oligocene time resulting from the first contact of the Pacific and North American plates. The faults at this time had no major displacements, except possibly on the westernmost right-lateral faults which may be near the edge of the North American plate. This diagram (Fig. 3A) depicts the right-lateral faults in the Peninsular and Coast Ranges and the Mojave Desert, and the left-lateral faults of the Transverse Ranges and north-central Mojave. Notice that the San Andreas fault (and other dextral faults) do not cut through the Transverse Ranges into southernmost California.

After this fracture pattern was formed, deformation began by simple shear in the Pacific–North American dextral shear couple (Fig. 3B). The Transverse Ranges and other crustal domains rotated clockwise as the northwest-trending blocks underwent simple shear. A consequence of the geometry is that, simultaneously with the rotation, left slip occurred on faults within the rotated domains (see Freund, 1970, 1974) and basins opened at the joins of the rotated and unrotated blocks. According to our model, the major sinistral faults which bound the rotated blocks are not conjugate Riedel shears resulting from the shear couple. Riedel prime shears would be sinistral faults within this shear couple, but they would make an angle of about 70° with the dextral faults, prior to rotation, which is larger than the inferred initial angle of 45° to 55°. Rather, the inferred initial angle suggests that these faults first originated as tension gashes in the Pacific-American shear couple. They served to break the crust into blocks which were rotated soon after.

In late Miocene time, the San Andreas fault became active in southern California (Crowell, 1975a, 1975b) and absorbed most of the Pacific-North American displacement. This decreased the width of the shear couple and moved it to the east, in addition to cutting the Transverse Ranges, and possibly ended the rotations (Fig. 3C). The breakthrough probably originated as the San Gabriel fault, which is now abandoned. In late Miocene time, the break jumped eastward to assume the bent San Andreas configuration. Subsequent to the breakthrough, right slip, mainly along the San Andreas fault, separated the rotated blocks by about 260 km (Crowell, 1975b) (Fig. 3D).

Comparing Figures 3D and 2, this model predicts that there are five or six regions containing rotated blocks in southern California. These regions are bounded by the following sinistral faults: the Big Pine and Santa Ynez, and Malibu Coast–Santa Monica faults =

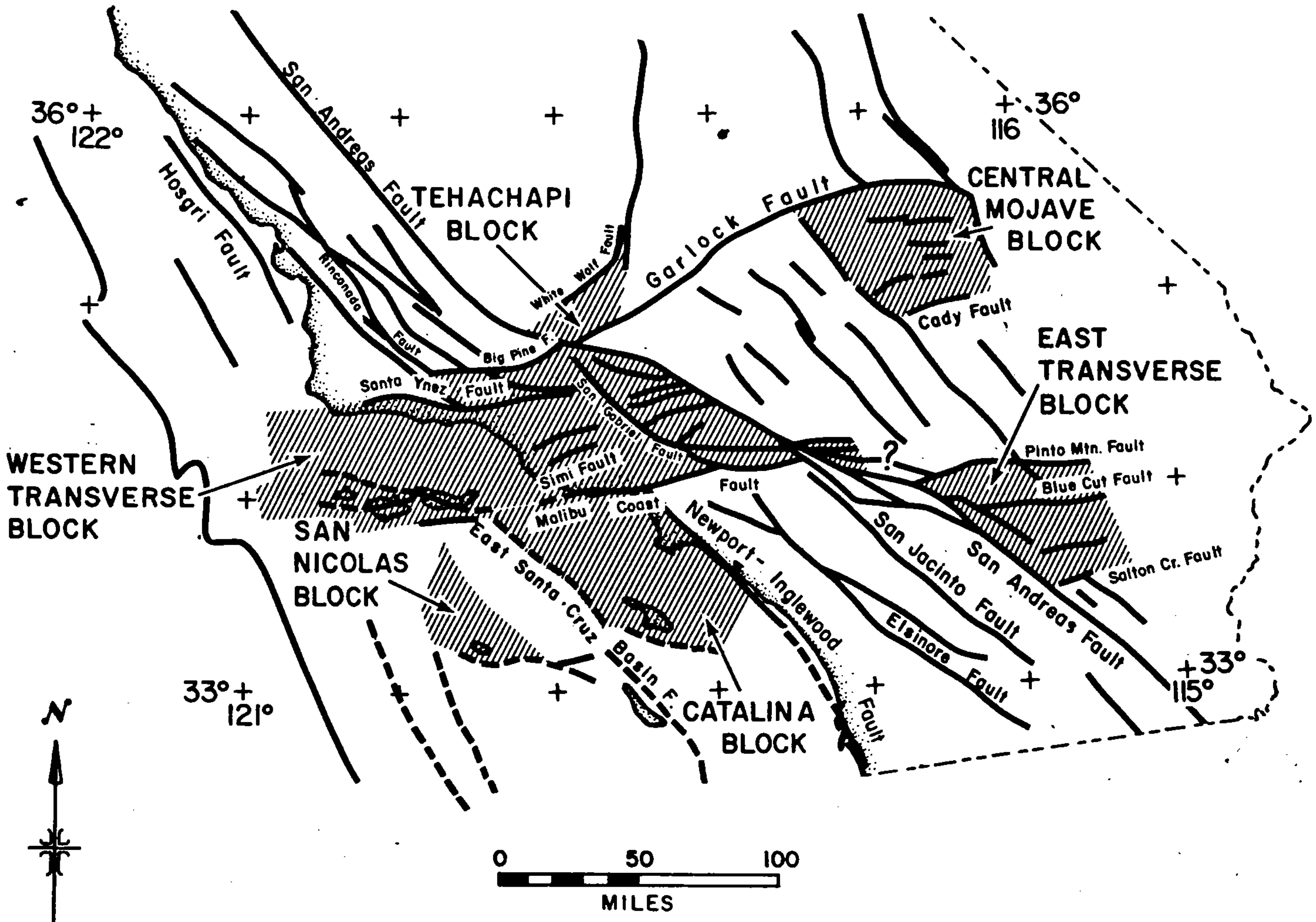


Figure 2. Areas in southern California (shaded) where apparent clockwise rotation is predicted from geometry or inferred from paleomagnetic data. All of the regions contain blocks bounded by sinistral faults. Geology and faults from Jennings (1973).

western Transverse region; the Malibu Coast fault and east-west-trending faults south of San Nicolas and Santa Catalina Islands (Junger, 1976), which now may be or may have been left slip = San Nicolas and Catalina blocks; the Pinto Mountain and Salton Creek faults = eastern Transverse region; and the Garlock and Manix-Cady faults = central Mojave region. At present, paleomagnetic data exist only for the western Transverse Ranges and Catalina block. The White Wolf fault outlines another rotated domain north of the west end of the Garlock fault (= Tehachapi block). Paleomagnetic data suggest that a rotated block also exists in the Morro Bay region (Fig. 1), but no left-lateral boundary faults have been mapped here. Greenhaus and Cox (1978) attribute the deflections to rotations within a local pull-apart basin.

DISCUSSION

The geometric model has many ramifications which can be tested by geologic and geophysical data:

1. **Crustal Units Bounded by Sinistral Faults Have Been Rotated Clockwise.** So far this is indicated by paleomagnetic data from the western Transverse Ranges, including the San Gabriel region, and from the Catalina block. Geologic data support rotation of the western Transverse region (Crouch, 1979; Jones and others, 1976). Structural trends (Jones and Irwin, 1975) and paleocurrent data (Yeats and others, 1974; Carey and Colburn, 1978) in the Santa Monica Mountains also can be shown to support rotations. The San Gabriel block is rotated less than the western Transverse Ranges. Possibly the San Gabriel fault broke through before the rotation was completed, in which case, the continued clockwise rotation of the western Transverse Ranges produced right slip on this fault.

2. **Left Slip Was Simultaneous with the Rotation.** Not all of the faults indicated as sinistral in this report have, in fact, been shown to be so, nor are their histories or amounts of movement known with sufficient accuracy to provide tests for our proposal. This is also true for many of the presumed dextral faults. Nonetheless, some of the known left-slip faults had their major displacements in Miocene time. These include the Malibu Coast fault (Campbell and Yerkes, 1976; Truex, 1976), Santa Ynez fault (see Sylvester and Darrow, 1979), and Garlock fault (Crowell, 1968). Unfortunately, the timing of rotation is not well constrained: at only one site in the Santa Monica Mountains have we found unrotated directions in late middle Miocene age lavas (Kamerling and Luyendyk, 1979).

3. **The Amount of Left Slip (d) on the Faults Can Be Related to**

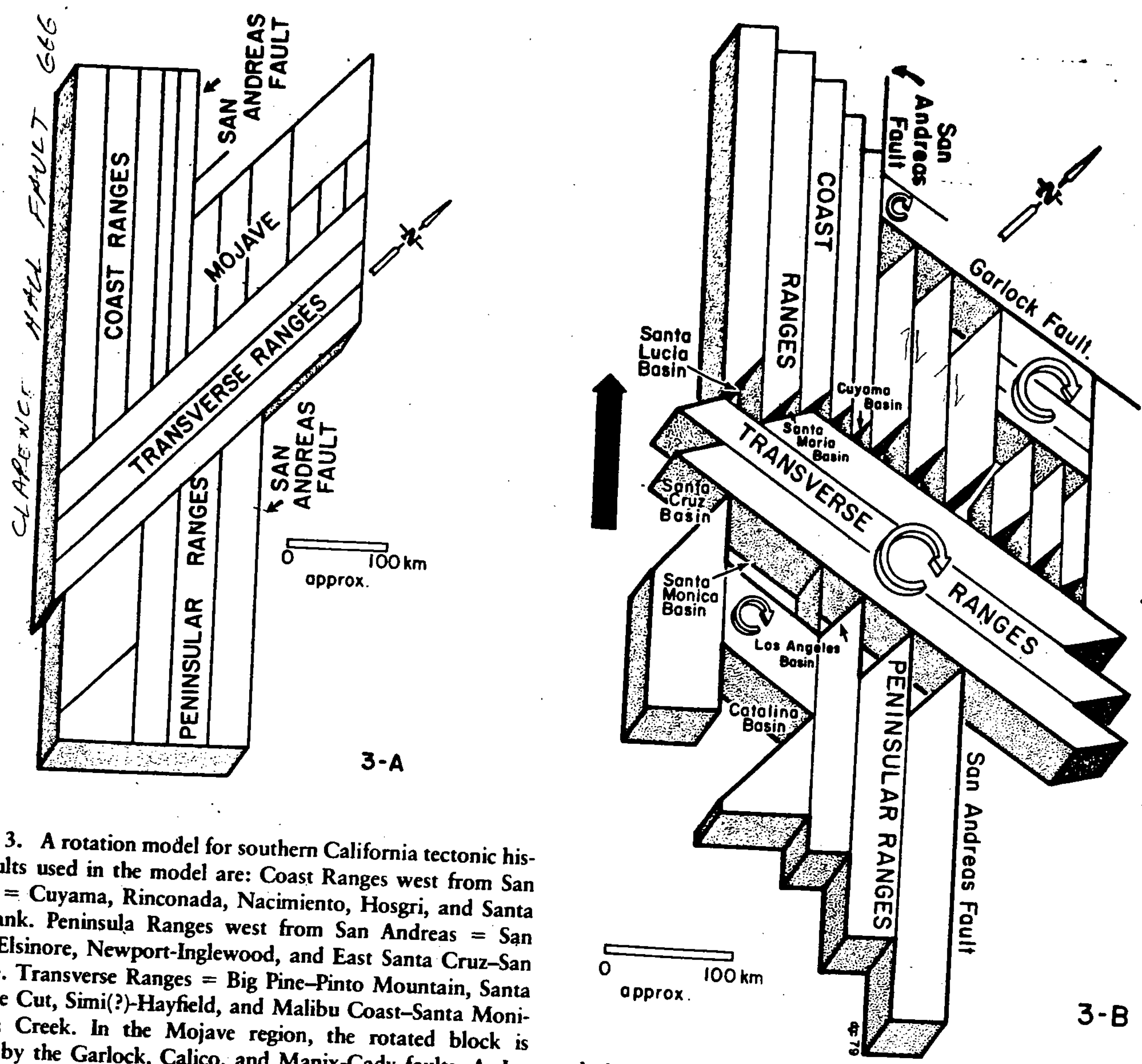


Figure 3. A rotation model for southern California tectonic history. Faults used in the model are: Coast Ranges west from San Andreas = Cuyama, Rinconada, Nacimiento, Hosgri, and Santa Lucia Bank. Peninsula Ranges west from San Andreas = San Jacinto, Elsinore, Newport-Inglewood, and East Santa Cruz–San Clemente. Transverse Ranges = Big Pine–Pinto Mountain, Santa Ynez-Blue Cut, Simi(?)-Hayfield, and Malibu Coast–Santa Monica–Salton Creek. In the Mojave region, the rotated block is bounded by the Garlock, Calico, and Manix-Cady faults. A. Inferred initial fracture pattern and prerotation geometry for Oligocene time in southern California. B. Miocene-Pliocene time (?) geometry after the clockwise rotation event which probably occurred in mainly Miocene time. Sinistral and dextral slip has occurred and deltoid basins have opened at the joins of the rotated and unrotated blocks. C. Late Miocene time geometry showing the through-cutting of the Transverse Ranges by San Andreas, San Gabriel, and Elsinore faults, and the jump of the San Andreas fault east to the San Jacinto. Basins are shown filled. D. Present geometry showing offset of the Transverse Ranges along the San Andreas fault. Miocene basins are not shown here.

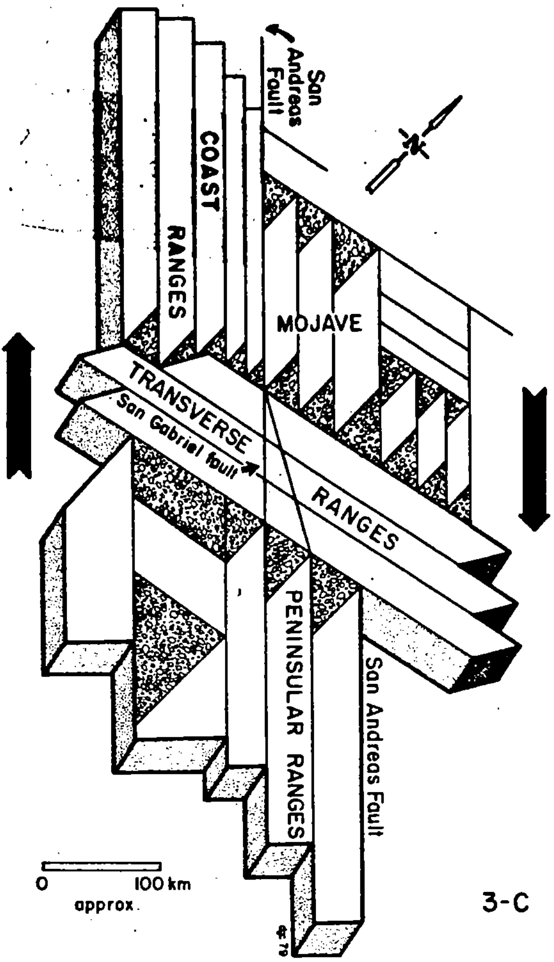
the Width of the Blocks (w), and the Amount of Rotation (r) (or vice-versa). This relationship may be expressed by

$$d = w\frac{\sin r}{\sin 2s}\left(\frac{1}{\sin (r + 2s)}\right)$$

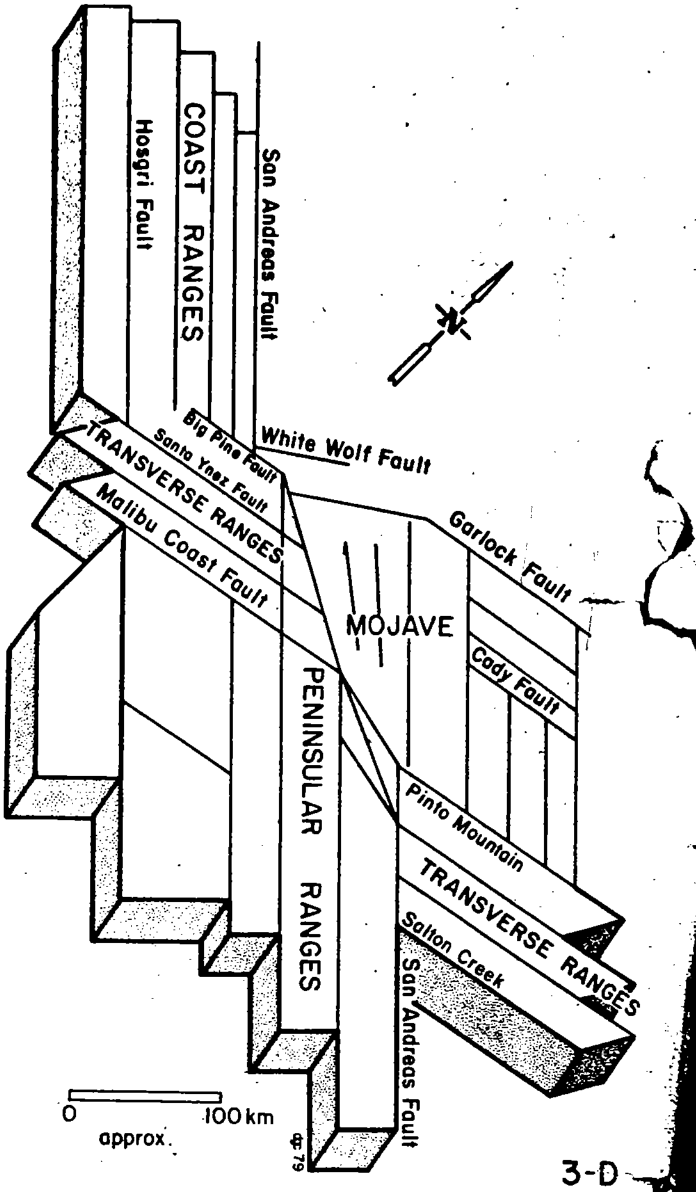
where s is one-half the angle between the original conjugate shears (23° to 28° in this case), and d is measured on the north side of the blocks.

For a block width of 20 km and a rotation of 75 degrees, the slip is calculated to be 32 km. If this is a valid estimate of the block width, then faults such as the Simi, Santa Ynez, and Blue Cut should show this order of displacement. Within the San Gabriel block, the indicated rotation is about 40°. The slip here (on the order of 3 km) on Miocene sinistral faults discussed by Oakeshott (1958) agrees with that calculated by the above relationship.

The displacement of the dextral fault-bounded blocks relative to North America increases westward. Because slip on the dextral faults within the shear couple causes the rotation, the amount of rotation and simultaneous dextral slip can be shown to be related by the same above expression. In this case, the slip (d) is measured on the west side of the block. The Hosgri fault is bounded by two blocks about 40 km wide; the calculated right-offset related to rotation is then 63 km. The maximum total proposed post–early



3-C



3-D

Figure 3. *(Continued).*

Miocene time slip is more than 110 km (Graham and Dickinson, 1977; Greene, 1977). The Miocene slip on this fault is believed to be about 80 km (Hall, 1975), which is near our estimate for slip correlated with rotation. However, the known amount of slip on the Hosgri system remains controversial and is possibly as little as 20 km for Neogene time (Hamilton and Willingham, 1979). The block to the east of the Rinconada fault (second fault east of Hosgri in Fig. 3) is about 25 km wide, which results in a calculated slip of 40 km. This compares favorably with Dibblee's (1976) estimate of 42 km, although Howell and Vedder (1978) suggest only 10 km. About 40 km slip can be calculated for the Elsinore and San Jacinto faults in the Peninsula Ranges which have similar block widths. This agrees with the estimate of 40 km of post-Paleocene slip (Sage, 1973) for the Elsinore, but it is greater than the San Jacinto slip value of 19 km pre-Quaternary (Sharp and others, 1967). However, these faults may in fact be no older than Pliocene, in which case, other faults would be needed to satisfy our model.

Predicting the slip on the northernmost (Big Pine and Santa Ynez) and southernmost (Malibu Coast) Transverse Range faults depends on whether the blocks are allowed to extend eastward or westward during rotation. In Figure 3B, the blocks extend equally on both sides due to the rotation; the block south of the Santa Ynez fault pivots at a fixed point at its northwest end, and the block north of the Malibu Coast fault pivots at a fixed point on its southeast end. Both faults have net left slip. An important aspect of this model is that the slip decreases westward for the northern boundary fault and decreases eastward for the southern fault. The slip as a function of distance L from the pivot point is:

$$d = L\,(1 - \sin 2S)\,\sin\left[\frac{90 \cdot r}{90 - 2s}\right].$$

If the Santa Monica Mountains are about 250 km or less west of the pivot, then slip here on the Malibu Coast fault should be 30 km due to the rotation. If this fault originally connected with the Salton Creek fault, then the latter should show little displacement. The maximum left slip is about 50 km, 400 km west of the pivot. The Santa Ynez fault may display left offset decreasing westward (see

Sylvester and Darrow, 1979). The model predicts that slip on these boundary faults was first left, then right for a lesser amount as the blocks rotated past an angle of 90° from the unrotated blocks. Interestingly, if the Transverse Ranges pivoted at their easternmost ends and thus extended westward, the Santa Ynez and Big Pine faults would have had right slip while the Malibu Coast–Santa Monica fault would have had left slip.

4. The Rotation Caused the Blocks To Extend Eastward and Westward within the Shear Couple and Produced Compression at Their Ends (Fig. 3B). This statement is related to the above discussion. As a manifestation of this compression, Miocene tectonism in the form of thrusting, folding, and crushing should be seen at the edges of the rotated blocks. This may explain some of the folding in the offshore Borderland (Vedder and others, 1974; Junger, 1976). Also, westward extension north of the Garlock produced some left slip on this fault and may have aided in bending the San Andreas fault (Davis and Burchfiel, 1973; Garfunkel, 1974).

5. As the Blocks Rotated Clockwise, Triangular or Deltoid Basins Opened at the Join of the Rotated and Unrotated Blocks (Fig. 3B). Neogene sedimentary basins, in particular those containing mainly Miocene sediments, should be found along the north and south borders of the Transverse Ranges. Some of these are identified in Figure 3B. Offshore the Santa Lucia (offshore Santa Maria), Santa Cruz, Catalina, and San Nicolas basins opened, as well as the Santa Monica and possibly others. Onshore, the Santa Maria, (Hall, 1978), Cuyama, and Los Angeles basins were opened (see Blake and others, 1978). Basins are predicted by the geometry at many locations in the Mojave region. Hamilton (1977) has located a structural depression at the join of the east-trending Manix (Cady) fault and northwest-trending Calico fault from geophysical data. This basin would be outside the southwest edge of our rotated Mojave domain shown in Figure 3B.

Basins need not form at all locations where rotated and unrotated blocks adjoin, nor would they necessarily be triangular in shape. Freund (1974) has shown how the spaces can be filled by splay faulting of the dextral block ends. For example, the Hosgri fault splays at its southern end (Hamilton and Willingham, 1977; Hall, 1978). The Ventura and Santa Barbara basins are not completely explained by our geometric model, but are not discounted by it. Also, these basins may be somewhat younger than most of the other Neogene basins (Crowell, 1976; Blake and others, 1978).

6. Right Slip Can Occur on the Northwest-Southeast–trending Dextral Faults without Cutting through the Transverse Ranges. This accounts for the perplexing large offsets (100 km) on northwest-southeast–trending faults such as the Hosgri and East Santa Cruz Basin (or San Clemente) faults (Howell and others, 1974), which do not appear to offset the Transverse Ranges.

7. The Pre-Rotation Geometry (Fig. 3A) Predicts That the Salinian Terrains Lay West and South of the Mojave Block in Late Oligocene Time and Subsequently Were Displaced Northward. This tectonic evolution agrees with concepts proposed by Johnson and Normark (1974), where the Salinian block lengthened or telescoped by displacements on northwest-southeast–trending dextral faults which, relative to North America, have displacements increasing westward. Our model shows, as they state, that dispersion of the block is not just due to slip on the San Andreas fault.

Finally, there is the question of latitude change. Paleomagnetic data (Kamerling and Luyendyk, 1979) indicate a possible range of about 5° to 15° of northward transport for the western Transverse Ranges. Two effects can account for this in the present discussion: separation along the San Andreas, and block rotation. The combination of these two effects restores the Santa Monica–Anacapa region to a location 3° or 4° south of their present position, which is still less northward transport than the average paleomagnetic results indicate. The difference may be due to northward translation along right-slip faults east of the San Andreas fault (Shakel, 1978).

The first step in testing the above hypothesis is to establish that the blocks in southern California bounded by sinistral faults have been rotated clockwise. This can be done through paleomagnetic studies of Neogene rocks in the eastern Transverse Ranges, the central Mojave, and the Tehachapi region.

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№ 7555

Implications of onshore and offshore structure for location and Cenozoic evolution of the Mendocino triple junction

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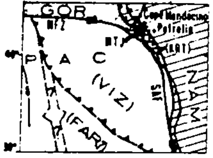
Offshore and onshore structural relations suggest that the Mendocino triple junction (MTJ) is located onshore within the Franciscan Complex. The onshore MTJ area is underlain by the Late Cretaceous and middle to late Eocene Coastal terrane (FCT); onshore it is flanked to the south by the Late Cretaceous to Miocene King Range terrane (KRT) and offshore by the Vizcaino structural block (VIZ) on the Pacific plate (PAC). In the MTJ area, the FCT is divisible into two discordant structural domains delineated by shear fabric orientation and fold trends. Faults of both domains offset and incorporate lower bathyal Miocene and Pliocene strata into the FCT. Structures of the domain north of Petrolia strike northwestward and dip to the northeast. Offshore these northeast-dipping structures bend northward and parallel the convergent boundary between the North American (NAM) and Gorda (GOR) plates. We interpret the northeast-dipping structures to delineate the Plio-Pleistocene subduction zone between the NAM and GOR plates, which has been bent eastward and deformed by the rigid northeast corner of the PAC plate. Structures of the domain southwest of Petrolia parallel the northern and eastern boundary of the KRT and define the Quaternary location of the northeast corner of the PAC.

Structural relations directly offshore from the KRT further suggest that initiation of the San Andreas transform may have occurred 26 to 27 Ma when the Mendocino fracture zone (MFZ) extended eastward into the NAM accreting the offshore VIZ and speculatively, failed segments of the PAC-Farallon (FAR) ridge to the PAC.



№ 26422

LATE CENOZOIC DEFORMATION OF THE CALIFORNIA CONTINENTAL MARGIN NORTH OF CAPE MENDOCINO: IMPLICATIONS FOR MENDOCINO TRIPLE JUNCTION LOCATION

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Late Cenozoic structures in the central and northern parts of the offshore Eel River Basin are dominated by northwest to north-northwest-trending, east-dipping thrust faults that form imbricate thrust-fan systems. Many of these faults merge downward into sole thrusts that probably extend to the Gorda-North America plate interface at depth and result from Pliocene to Recent convergence with strong coupling between the plates. A north-trending structural discontinuity along the western margin of the basin separates slope-parallel thrusts and folds of the seaward part of the accretionary prism from en echelon structures trending obliquely northwest to the basin margin in the landward part of the prism. This discontinuity is locally an east-dipping fault with possible right shear; it may separate accretionary strata that are relatively poorly coupled from those that are relatively well coupled to the underlying plate, or it may reflect an earlier stress regime.

Structures in the southern part of the offshore basin trend west-northwesterly, indicating encroachment from the south by the Pacific plate. The presence of north-dipping thrust faults offshore along the south flank of the basin and of west- to northwest-trending compressional faults and folds and late Miocene and Pliocene deep-marine deposits on land suggests that the late Cenozoic accretionary prism does not extend southward to intersect the Mendocino fracture zone at the commonly depicted location of the Mendocino triple junction; instead the prism turns eastward around the southern part of the offshore basin and extends landward south of the Russ and Bear River fault zones. The Mendocino triple junction is expressed as a broad area of deformation that lies nearshore and/or landward along the north flank of the King Range.

№ 26393

SUBDUCTION ANGLE OF THE FARALLON PLATE AT 25-30 Ma FROM XENOLITH STUDIES

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Minettes and kimberlites of the Colorado Plateau (CP) erupted in close proximity at 25-30 Ma, but their xenolith assemblages are very different. Garnet lherzolite xenoliths from The Thumb minette neck define a geotherm extending from 990° C, 125 km depth to 1300° C, 155 km depth, hotter than a continental conductive geotherm. In contrast, hydrous peridotite xenoliths are characteristic of many CP kimberlites. Unusual sodic eclogite xenoliths bearing lawsonite and other hydrous phases are found at Garnet Ridge, Moses Rock, and Mule Ear diatremes. Stabilities of hydrous minerals require a relatively low temperature origin, near or below the continental geotherm. Eclogite xenoliths resemble eclogites in metamorphosed ophiolite complexes, suggesting that the xenoliths represent oceanic lithosphere emplaced in the uppermost mantle of the CP from the west (Helmstaedt and Doig, 1975), consistent with models for shallow subduction of the Farallon plate during the Laramide orogeny. Prograde hydration of peridotites preceded kimberlite emplacement by no more than 25 m.y. (Smith, 1979), suggesting that the hydration is also associated with warming of the subducted Farallon plate.

Crustal thickness of the CP is 40-50 km, and probably was no less at 25-30 Ma. The subducted Farallon plate could not have heated to T greater than the continental geotherm, so it could not have been located in the 125-155 km depth interval represented by The Thumb xenoliths. If the Farallon plate was subducted as far east
kimberlites and minettes (~1000 km from the trench), then it must have been
either in the 45-125 km interval or below 155 km in this region. Shallow em
is the preferred hypothesis because the subducted plate could be the source of
hydration reactions and of spilitized basalt for formation of sodic lawsonite
Assuming that the Farallon plate had to descend beneath the deep Sierra Neva
root before progressing eastward, the subduction angle thereafter must have
zero degrees. A fragment of the Farallon plate located beneath the CP kimber
have become an "inherited substructure" (Thompson and Zoback, 1979) whic
yet foundered at 25-30 Ma, but sinking of adjacent fragments could hav
convective motion in the mantle, elevating the geotherm at The Thumb locality.

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HOLOCENE DEFORMATION PATTERNS AND PALEOSEISMICITY IN EASTERN SHUMAGIN SEISMIC GAP; SOUTHWESTERN ALASKA

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Deformation of the North American-Pacific Plate boun
in southwestern Alaska during the last 12,000 y
includes both brittle (episodic, seismic), and
ductile processes within the Shumagin seismic gap.
from deformed marine terraces and bathymetry suggest
northeast-trending folds accomplish up to half of
0.10% cumulative shortening strain perpendicular to
plate motion, whereas episodic movement of fault bl
along northeast-trending reverse faults during g
earthquakes accounts for the rest of the calcul
strain. Uplift averages 5mm/yr (0.075% strain) during
last 12,000 years. Within an overall uplift pattern, th
is interseismic subsidence of synclinal troughs
permanent subsidence of northwest-trending extensi
basins. Southwest-northeast extension has lengthened
Shumagin gap parallel to the arc by about 0.0025%.

Seven great (estimated M > 8) earthquakes ruptured
entire Shumagin seismic gap 11,500, 9300, 7250, 4
3375, 1960, and 200 years ago. In addition, 11 smal
events clustered near fold hinges. For five of the gr
earthquakes, the plate boundary ruptured in a series
events propagating from the trench toward the arc over
period of 50-175 years. Longer term deformation patte
within the Shumagin seismic gap agree geometrically
these recent data and indicate that the plate contact
beneath the Shumagin Islands and Alaska Peninsula is un
high stress and is about 60% coupled to the downgo
plate.

№ 23

SE-TERMINATION OF BUCKSKIN-BULLARD DETACHMENT FAUL WEST-CENTRAL ARIZONA: ONE VERSUS MANY NORMAL FAULT

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Extension accommodated almost entirely by 50 km (min.) slip on the
Buckskin-Bullard detachment fault system (BBDF) in the Harcuvar co
plex is transferred to slip on a series of smaller normal faults in the
adjacent Big Horn-Wickenburg extended terrane. Oligocene-E. Mioc
volcanic rocks overlie Proterozoic and Cretaceous crystalline rocks in
dipping tilt blocks across the 100 km wide extended terrane between
Pleasant and the Harquahala Plain. Cross sections were palinspasticall
reconstructed to determine amount of extension; the datum used was
base of the Tertiary section. The extended terrane is bounded on the S
the Eagletail and Little Harquahala Mtns.; geological ties between the
ranges indicate that no major fault separates them. Reconstruction of
of the present width of the extended terrane yields 20-22 km of exte
Extension is heterogeneously distributed. Extension magnitudes and
extension are: central Big Horn Mtns.: 3 to 5 km (20-40%); NE Vulture
Mtns.: 10 km (250%); Wickenburg Mtns.: 7 km (150%). Best guess ext
values for other areas along the transect yield another 21 km of exte
for a total of 41-43 km. At its SE termination, the BBDF trends NE, par
to the extension direction, and becomes a transfer zone separating a
rane to the SE in which crust extends along a series of large normal
from a terrane to the NW in which crust extends by slip on the BBDF.
the deformation becomes more distributed, maximum slip on any one
mal fault decreases to the point where no single fault exposes Tertiary
mylonitic rocks in its footwall. Thus, Tertiary mylonites are absent in
zone of distributed extension. The change in extension style coincide
with the intersection of the detachment terrane with a NE-trending
of voluminous Middle Tertiary volcanism.

№ 15

MAGNITUDE, TIMING, AND SIGNIFICANCE OF SLIP ON THE WATERMAN HILLS DETACHMENT FAULT, CENTRAL MOJAVE DESERT, CALIFORNIA

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The Waterman Hills detachment fault (WHDF) is a major Miocene low-angle normal faul
crops out in the central Mojave Desert near Barstow, California. A piercing-point offset
the WHDF may be provided by distinctive and similar intrusive complexes located 20 km
southwest in the Iron Mountains (footwall) and 20 km to the northeast near Lane Mo

(hanging wall). In each area, gabbroic plutons are cut by dikes of garnet-muscovite granite. Correlation of the intrusive complexes requires 40 km of slip along the azimuth (approximately N40°E) indicated by lower-plate mylonites in the Waterman Hills area.

Displacement along the WHDF has significantly altered the paleogeography and crustal structure of the central Mojave Desert. Restoring 40 km of slip on the WHDF (1) removes a prominent kink in the boundary between Paleozoic eugeoclinal and cratonal-miogeoclinal rocks, (2) places cratonal-miogeoclinal rocks structurally beneath eugeoclinal rocks, implying that the facies were stacked by thrusting, (3) straightens the western margins of the Late Jurassic Independence dike swarm and of the Late Triassic-Jurassic plutonic belt, and (4) explains the difference in metamorphic grade between footwall cratonal-miogeoclinal rocks (amphibolite facies) and hanging-wall eugeoclinal rocks (greenschist facies).

The WHDF roots to the northeast, beneath domino-faulted ranges of the central Mojave Desert and beneath the Colorado River trough. Movement on the WHDF occurred about 20 Ma ago and therefore was roughly coeval with large extension along the same azimuth in the Colorado River trough. Extended terranes of the central Mojave and Colorado River trough are separated by an area where early Miocene rocks are nearly flat-lying and little extended. Present geochronologic data do not resolve details of the timing of extension in the two highly extended areas, but field relations indicate that the ~18.3 Ma Peach Springs Tuff was emplaced after extension in the central Mojave Desert but during extension in the Colorado River trough. These spatial, temporal, and kinematic relationships support Davis and Lister's (1988, GSA Spec. Pap. 218) conceptual model of imbricate detachment systems.

№ 1305

MULTIPLE LOW-ANGLE FAULTS ATOP THE OROCOPIA SCHIST, SOUTHWESTERN ARIZONA AND SOUTHEASTERN CALIFORNIA

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The oceanic Orocopia, Pelona, and Rand Schists of S CA and SW AZ are exposed in some 15 tectonic windows through continental crust. The tectonic significance of these schists remains elusive. One problem is that all of the low-angle faults atop the schists have been considered thrust faults, that is, tectonic-burial faults. Recent studies in several areas, however, indicate that some of these low-angle faults actually are unroofing or uplift structures.

In the Picacho district and SE Trigo Mountains (along the lower Colorado River, ~35 km N of Yuma), the Orocopia Schist (OS) is overlain by three distinct low-angle faults. We infer that these faults record stages in the tectonic burial, metamorphism, and subsequent progressive unroofing of the schist. The oldest fault, the latest Cretaceous(?) Chocolate Mountains thrust, is marked by upper-plate mylonitic rocks that are synmetamorphic with respect to the prograde metamorphism of the underlying OS. This structure may be a remnant of the fault zone along which the oceanic supracrustal protolith of the OS was initially subducted beneath or overridden by continental crust. Hornblende compositions in OS metabasalt suggest metamorphism at depths of 20-30 km.

Two slightly younger, early Tertiary low-angle normal faults also overlie the OS. These two related faults are marked by or associated with alteration, retrograde metamorphism, or mylonitization of the OS, and evidently are unroofing or uplift faults. The structurally lower fault, the Arrastra Wash fault, juxtaposes the OS against a Jurassic kyanite-bearing granitoid terrane, which typically is not mylonitized along the fault. Some fault segments previously mapped as the Chocolate Mountains thrust may be parts of the Arrastra Wash fault. The structurally higher early Tertiary fault, the Sortan fault, places the OS beneath supracrustal rocks of low metamorphic grade, suggesting that the major uplift of the OS occurred during early Tertiary time. The Sortan fault apparently is of regional extent, because a similar fault crops out ~50 km to the E in the SE Castle Dome Mountains.

The youngest faults atop the OS are early Miocene detachment faults. Middle to late Tertiary crustal extension and erosion accomplished the final, though relatively minor, stages of exhumation of the Orocopia Schist.

№ 26065

THE LARAMIDE DECRETIONAL FOLD-THRUST REGIME, W.U.S.

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The onset and cessation of flat subduction brackets the Laramide orogeny. Flat subduction began at 87Ma and swept inland (cratonward) until 43Ma. Sublithospheric and subcrustal, shear-induced erosion (<u>decretion</u>) occurred in the overriding plate above the ever-lengthening flat- subduction segment. Decretional deformation produced abundant peraluminous plutons and trench-directed fold-thrust (FT) phenomenon on a scale unprecedented in Phanerozoic cordilleran geology. Decretional FT's are full-crust in scale and represent mega-accretionary prism analogues. Our proposed decretional FT zone largely correlates with the belt of 'metamorphic core complexes' (MCC). The supracrustal breakout zone of FT's commonly occurs west of the MCC's. Peraluminous magmatism is syn- to late kinematic with respect to the FT's. Where shear indicators are present (S-C fabrics, overturned folds, etc.), sense of shear is mainly trenchward. Typically, upper plate geology cannot be matched with lower plate geology. Minimal FT displacements required to restore observed overlap are on the order of mountain ranges (35-80km). FT overlap may easily exceed 200km when petrology of deep-seated peraluminous plutons is taken into account. Examples of paired peraluminous-FT zones include: 1) Kettle Falls shear zone and possibly a proto-Newport fault in nWA and nID; 2) Rapid River thrust system found along the western edge of the peraluminous Atlanta lobe of Idaho bath.; 3)the Mineral Ridge and Butte Valley FT's of NV; 4) Coast Range thrust of wCA; 5) Santa Rosa, Rand and Big Maria FT zones in sCA; 6) Harquahala and Catalina (Maricopa generic) FT zones in sAZ. Where interference relations exist the trench-directed FT's typically overprint earlier NE/SE directed FT's of Sevier or early Laramide age. Many of the FT zones have been re-utilized by subsequent MCC 'detachment' tectonism of mid-Cz age. The detachment overprint has partly obscured identification of former thrusts (e.g. Rand and Catalina FTs).

№ 27010

LATE MIOCENE GRANITE MAGMATISM AND DETACHMENT FAULTING IN THE KINGSTON RANGE, SOUTHERN DEATH VALLEY REGION, CALIFORNIA

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The Kingston Range in the southern Death Valley region consists of Proterozoic gneiss and gneissic granite unconformably overlain by the Late Proterozoic Pahrump Group and by approximately 2660 m of Late Proterozoic and Early Cambrian miogeoclinal deposits. These metamorphic and sedimentary rocks are intruded by the late Miocene Kingston Peak Granite (KPG). The KPG is divided into a margin facies of brown hornblende biotite granite porphyry, characterized by miarolitic cavities and by K-spar phenocrysts mantled by plagioclase, and an interior facies of white granite porphyry containing euhedral quartz phenocrysts. Basaltic xenoliths with crenulate chilled margins are common in both facies. Biotite and hornblende from the margin facies yield concordant K-Ar dates of 12.1 and 12.4 Ma, respectively.

The Kingston Range detachment fault (KRDF) dips 5° to 15° W and places the Pahrump Group and the miogeoclinal rocks, unconformably overlain by late Tertiary sedimentary and volcanic rocks, over Proterozoic basement rocks and folded Late Proterozoic and Early Cambrian sedimentary rocks. Rocks in the upper plate dip 25° to 50° NE, are cut by numerous closely spaced NNW-trending listric and planar normal faults and by NE-trending tear faults, and were transported 3 to 4 km southwest. The KRDF cuts 13.8- and 14.1-Ma tuffs that are interbedded with the late Tertiary sedimentary rocks and is cut by the KPG; these relations bracket an early period of crustal extension in the Kingston Range. Gravity and aeromagnetic data suggest that the KPG is about 6 km thick and has a flat floor. Paleomagnetic data suggest that the granite is tilted 30° E and is <u>not</u> rotated about a vertical axis. Combined, the geologic and geophysical data suggest that the KPG is cut and tilted by a flat fault(s) that postdates the KRDF.

№ 27231

EVIDENCE FOR DISTRIBUTIVE FAULTING AT YUCCA MOUNTAIN, NEVADA

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Yucca Mt. is the sole site being considered for underground storage of the nation's high-level nuclear waste. Low-sun-angle aerial photography indicates more widespread recent faulting than previously believed and suggests similar histories for the principal faults. Differing offsets of surfaces along the Solitario Canyon fault indicate multiple late Quaternary events; small vertical displacement (about 20 cm) of the youngest faulted surface suggests Holocene activity, similar to age-estimates from the Windy Wash fault (Whitney and others, 1986). Morphology of the Windy Wash scarp as defined on low-sun-angle photography supports the interpretation of a small Holocene displacement superimposed on a compound Quaternary scarp. Scarps along the Bow Ridge fault and at Busted Butte indicate more extensive and recent faulting than previous interpretations (e.g. Swadley and others, 1984). Morphology of the Fatigue Wash fault, which has received relatively little attention, indicates activity similar to the other principal faults in this area.

Complex seismic events involving several faults may be more characteristic of faulting at Yucca Mt. than simple, single-fault ruptures. Close spacing (<2 km) of Quaternary faults with similar morphology and the presence of basaltic ash from a local source in narrow fault fractures suggest the possibility of complex, large magnitude events. Such events would involve rifting and dike intrusion in the lower- to mid-crust and distributive rupture across several faults in the upper-crust and at the surface. Evidence of Holocene or latest-most Pleistocene ages of faulting and basaltic volcanism suggest such an event may be reasonably possible over the next 10,000 years.

№ 6950

LATE QUATERNARY VOLCANO-TECTONIC EVOLUTION OF THE MONO BASIN, EASTERN CALIFORNIA

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The Mono Basin of eastern California is an ideal area in which to study the interaction of active volcanic and tectonic processes. The record of activity over the past 100,000 years is relatively complete.

We measured fault scarp profiles on dated lateral moraine crests throughout the Mono Basin to determine fault slip rates. We compared these data with what can be deduced about extension rate due to dike intrusion underneath the Mono Craters. We then considered extension rates in the context of regional strain patterns to deduce the mode of deformation in the Mono Basin during late Quaternary time.

Extension rates indicate that dikes are being intruded underneath the Mono Craters in response to crustal stretching, and because of this, are now accommodating elastic strain that was once accommodated by range-front normal faulting. The section of the range front near the craters accommodated as much as 1 mm/yr of extension as recently as about 40,000 years ago. For the past 40,000 to 70,000 years, this section of range front has been inactive, even though the range front to north and south has continued extending at