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,

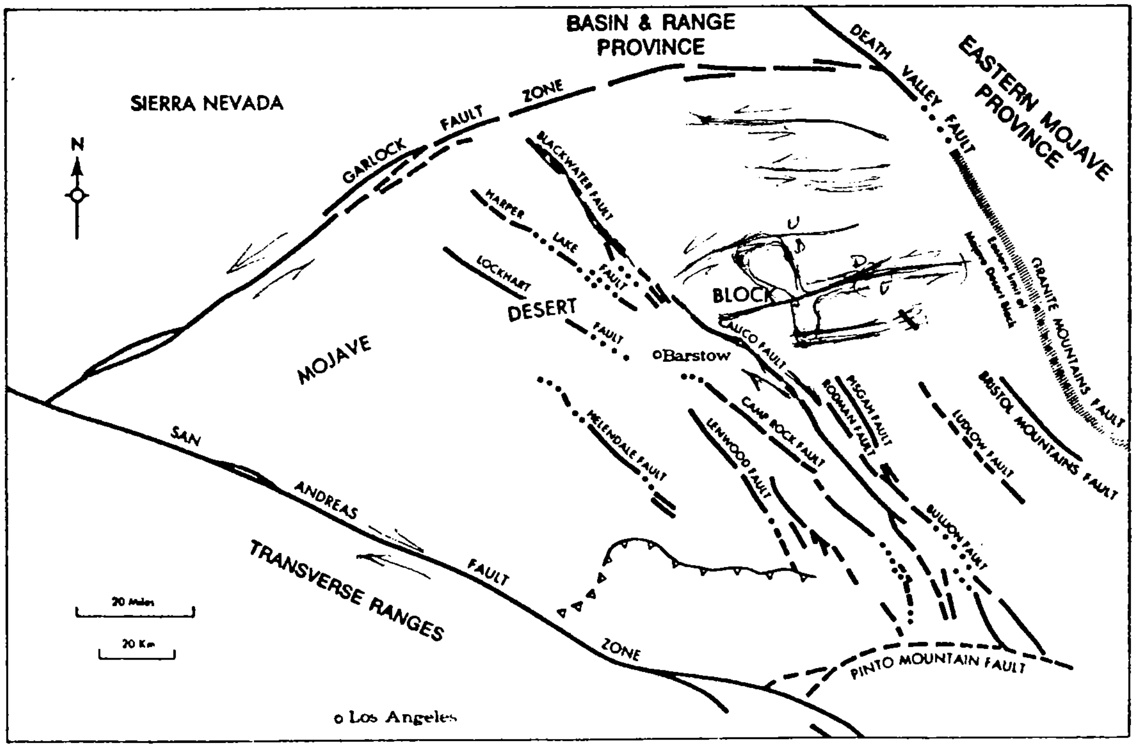

Figure 1. Index map for central Mojave Desert.

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

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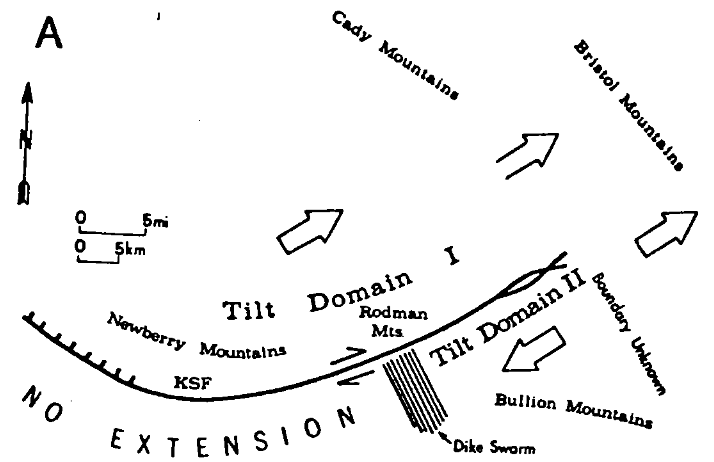
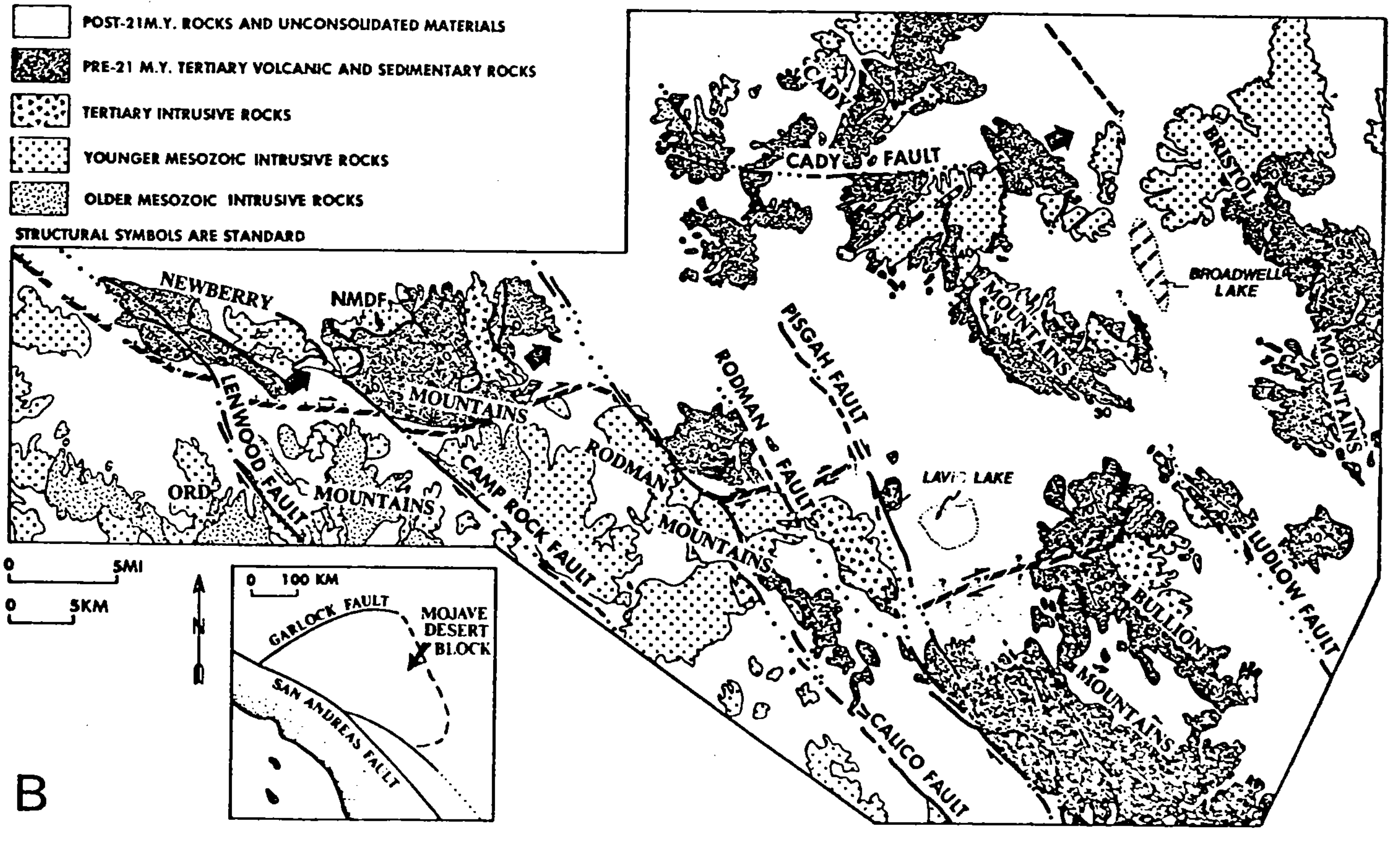


Figure 2. (A) Pre-strike-slip faulting (ca. 20 m.y. ago) configuration of central Mojave Desert. Structure symbols are standard. Kane Springs fault (KSF) is major accommodation structure that separates regions that extended differently during early Miocene detachment faulting interval. (B) Present-da, 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:

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

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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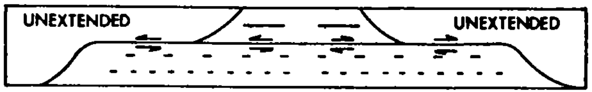
We propose a model to reconcile geophysical observations with field structural studies of ancient continental rifts. Extension develops in two major mechanical domains within the lithosphere. The upper domain (<15km) extends by brittle processes which are concentrated in a relatively narrow zone in comparison 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.

DAVID BLOOM

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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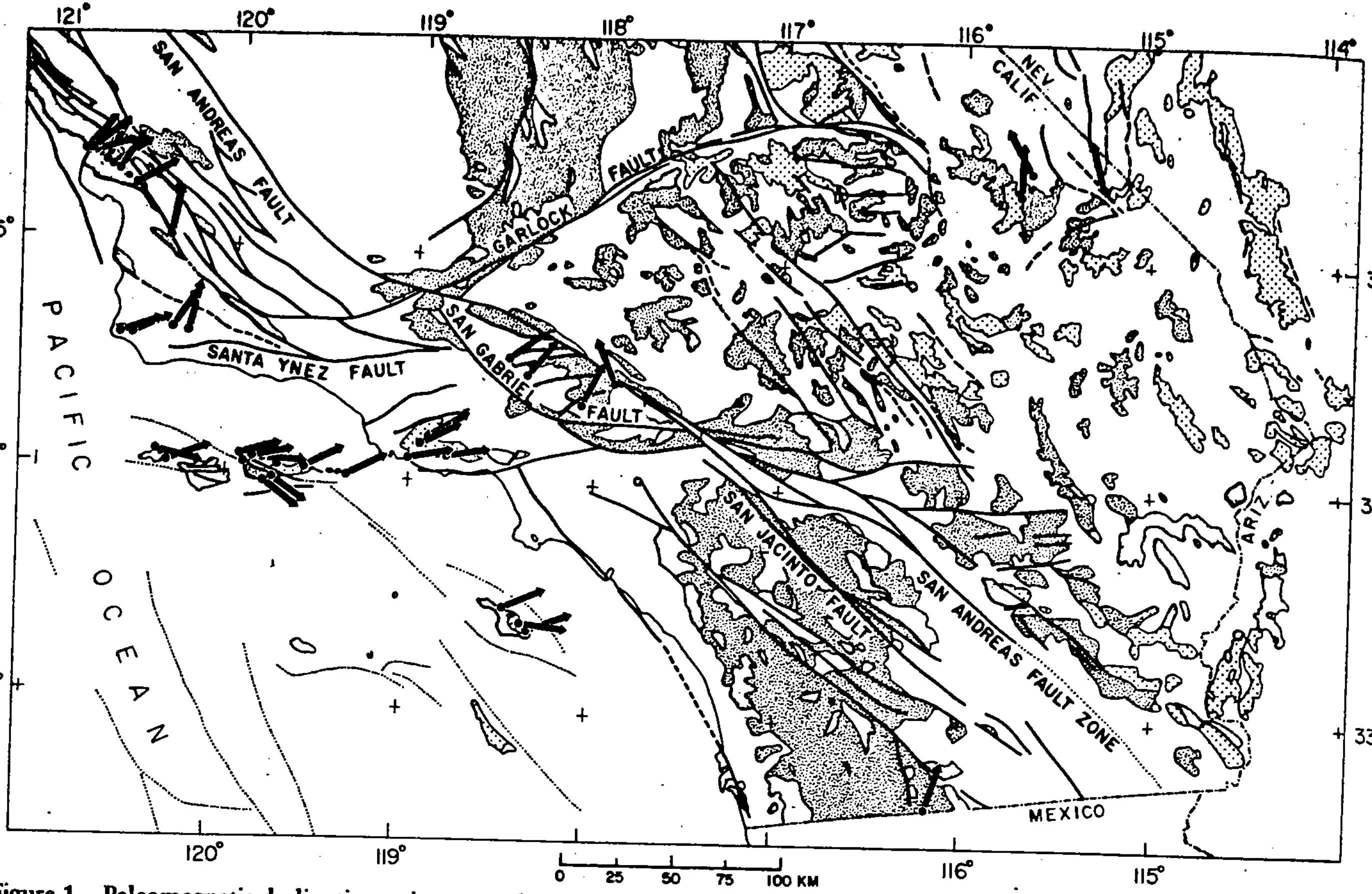


Figure 1. Paleomagnetic declination unit vectors determined at sites in southern California for Neogene rocks. Each vector represents determinations from one or more volcanic units and a dozen or more samples. Geology and faults from Jennings (1973).

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 =

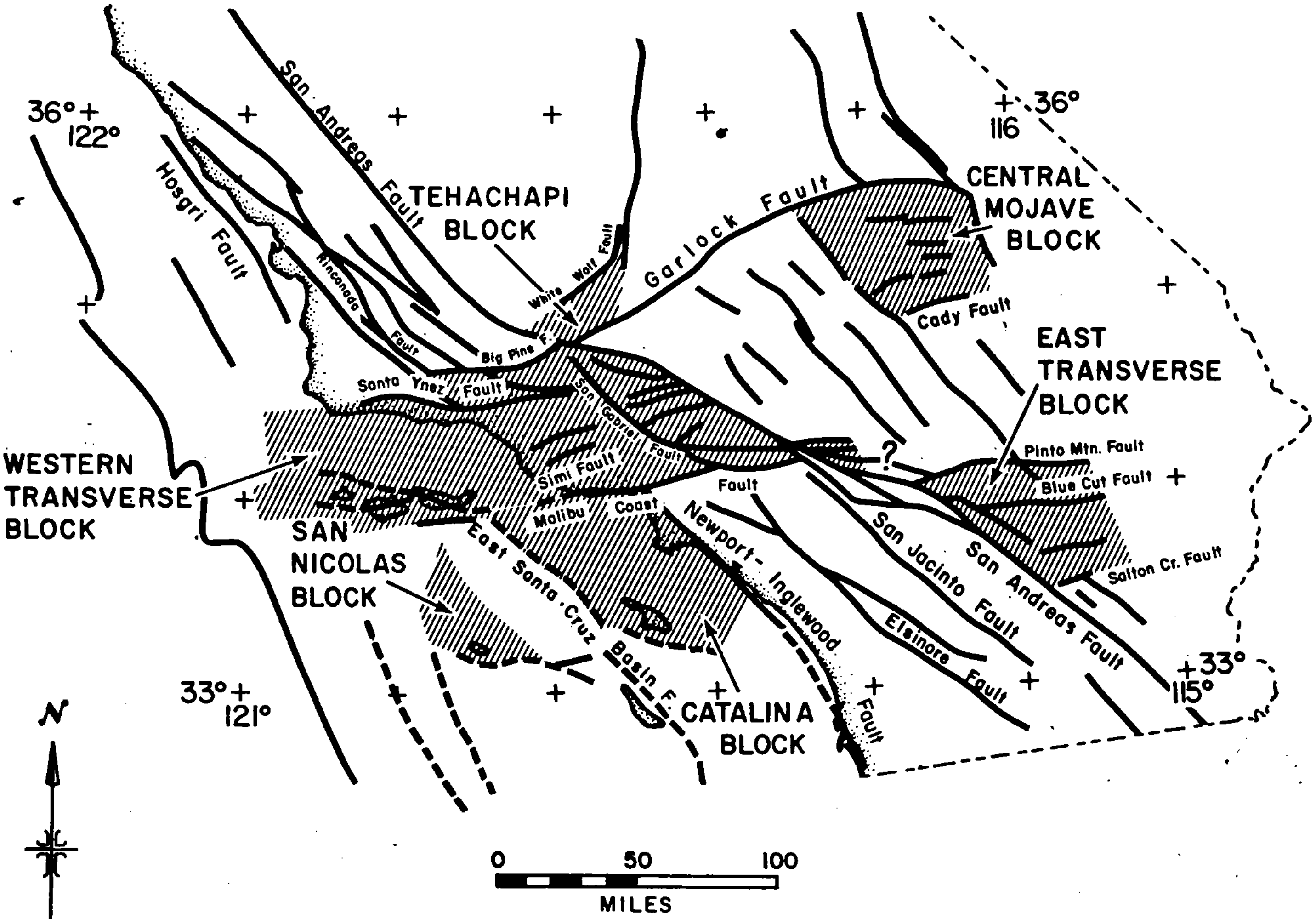


Figure 2. Areas in southern California (shaded) where apparent clockwise rotation is predicted from geometry or inferred from paleomagnetic data. All of the regions contain blocks bounded by sinistral faults. Geology and faults from Jennings (1973).

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**

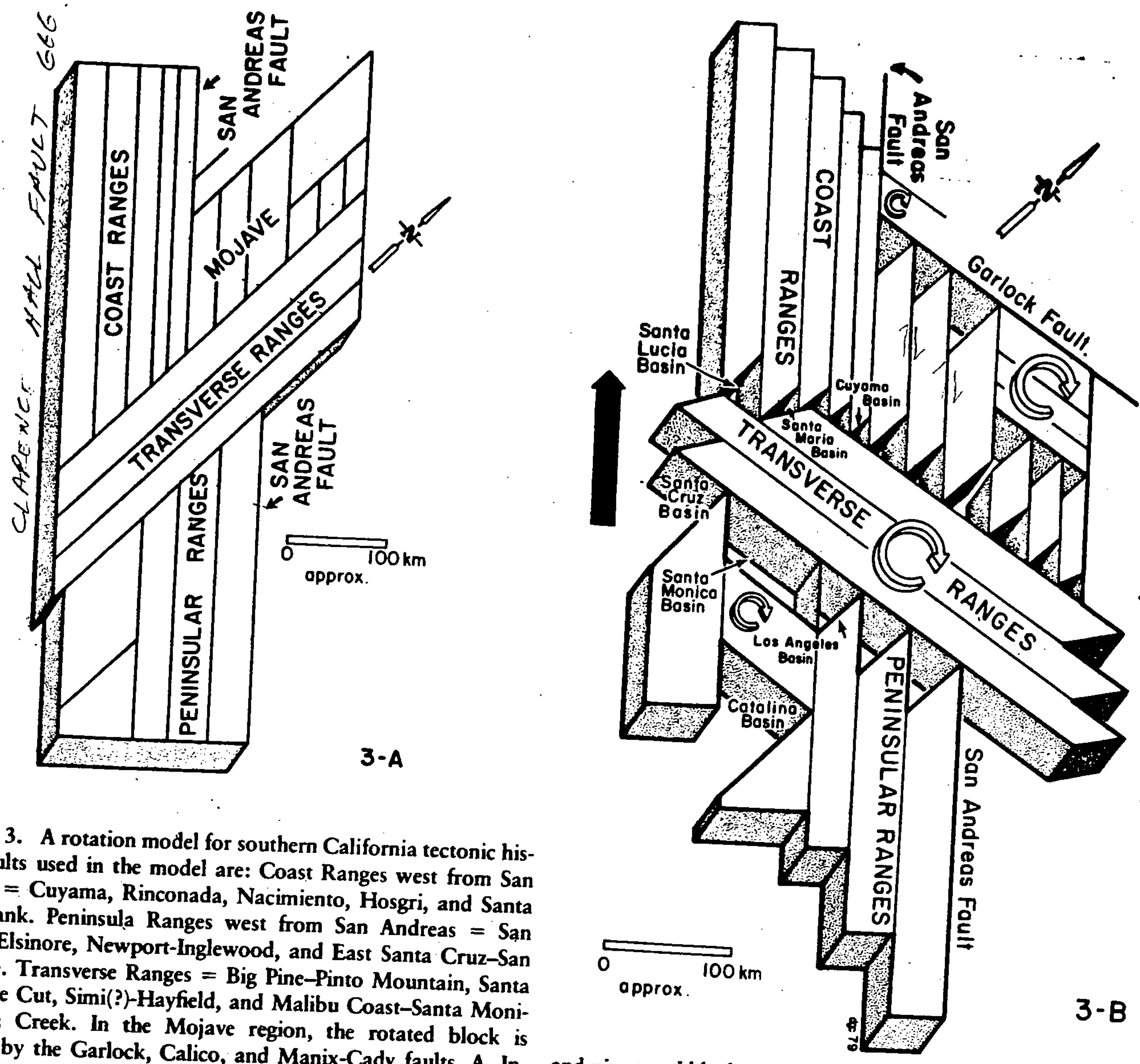


Figure 3. A rotation model for southern California tectonic history. Faults used in the model are: Coast Ranges west from San Andreas = Cuyama, Rinconada, Nacimiento, Hosgri, and Santa Lucia Bank. Peninsula Ranges west from San Andreas = San Jacinto, Elsinore, Newport-Inglewood, and East Santa Cruz–San 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.

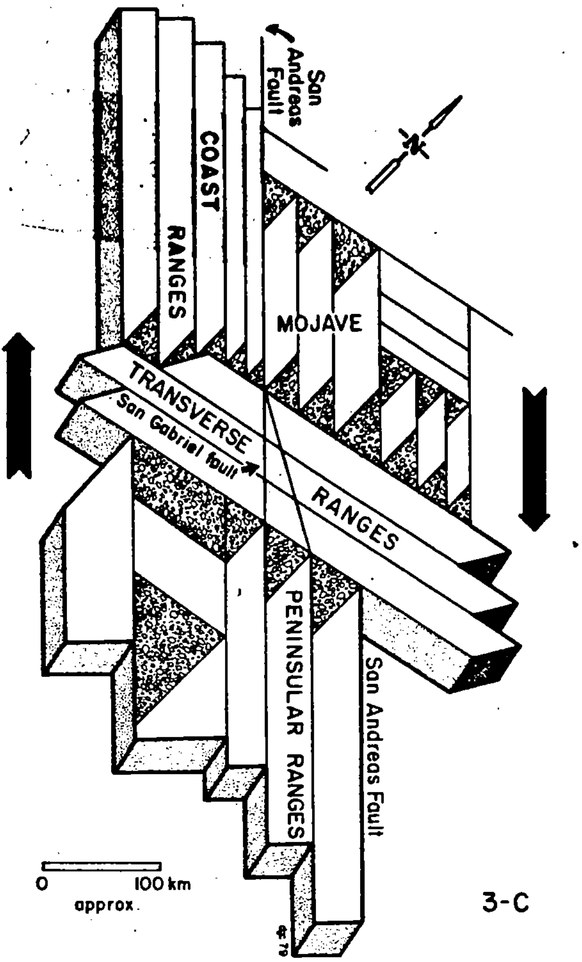
the Width of the Blocks (w), and the Amount of Rotation (r) (or vice-versa). This relationship may be expressed by

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

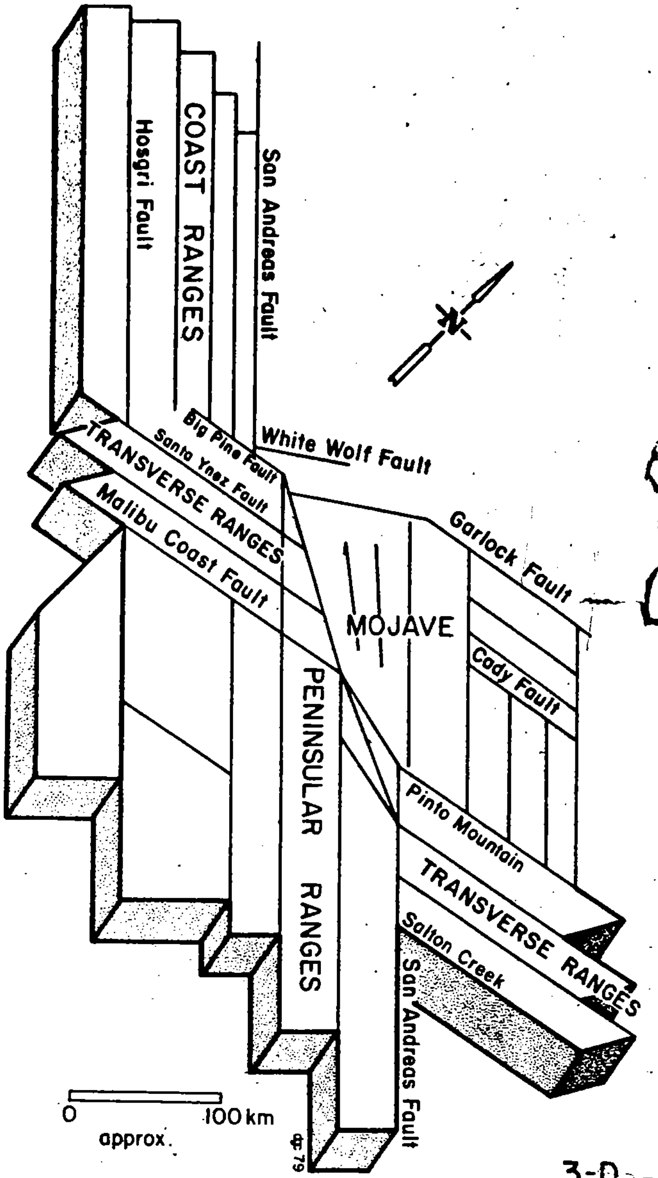
where s is one-half the angle between the original conjugate shears (23° to 28° in this case), and d is measured on the north side of the blocks.

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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