DAVID BLOOM

Model for the Late Cenozoic Tectonic History of the Mojave Desert, California, and for ts Relation to Adjacent Regions

I GARFUNKEL *Department of Geology, Hebrew University of Jerusalem, Jerusalem, Israel*

STRACT

he Mojave Desert region is crossed by ng northwest-striking right-slip faults. storation of their displacement indicates t the over-all shape of this region has n considerably distorted. The assump- n that the region was always in contact h the Sierra Nevada forms the basis for following conclusions: (1) The slices be- en the faults, and the faults themselves, e rotated counterclockwise, possibly by much as 30°; the precise magnitude and ing of the rotation can be checked by omagnetic studies. (2) Because of this ormation, the part of the San Andreas lt adjacent to the Mojave Desert was t; originally the fault was much ighter. (3) The major deformation of Mojave Desert was a west-trending left r that was supplemented by the left slip the Garlock fault. A similar deforma- n, without rotation of blocks, was omplished in the eastern Transverse nges by left slip on approximately west- king faults.

his crustal shearing resulted from the tion of the Mojave Desert between the ons of crustal spreading in the Great n and those in the continental border- d and the Salton Trough. The shearing e Mojave Desert accommodated lateral ations of crustal spreading.

hese deformations distorted the shape e margin of the North American plate ng Neogene and Quaternary time. They nly reflect movement normal to the e boundary, whereas much larger ement occurred contemporaneously llel to the plate boundary. *Key words:* *nics, late Cenozoic, Mojave, Califor- right-slip faults, model.*

RODUCTION

he Mojave Desert region of southern fornia (Jahns, 1954) has an anomalous structural position (Figs. 1 and 2): (1) it is associated with the Transverse Ranges and with the Garlock fault, which together cut across the regional northwest-trending structural grain; and (2) the neighboring segment of the San Andreas fault is bent. Understanding the structure and history of the Mojave Desert is expected, therefore, to clarify the regional structural relations.

This paper considers the wedge-shaped area (Figs. 1 and 2) delimited by the Garlock fault, a part of the San Andreas fault, and the San Bernardino and Little San Bernardino Mountains (that is, the eastern Transverse Ranges), which are geologically closely related to the area north of them. The eastern boundary is poorly defined, but the Soda-Avawatz fault zone and its southward projection may be used. This area will be referred to as the Mojave block.

The Mojave block is crossed by a somewhat irregular but prominent system of late Cenozoic faults that strike northwest. Faults with approximately west strikes are also common, especially in the northeast corner of the Mojave block.

This paper focuses attention on the young faults. Their effects on the deformation of the Mojave block and the relations with contemporaneous movements in the adjacent regions are analyzed. A detailed analysis of the structure of the Mojave block is not intended, however. The purpose is to discuss only the over-all late Cenozoic structural relations, whereas older tectonic events are not treated.

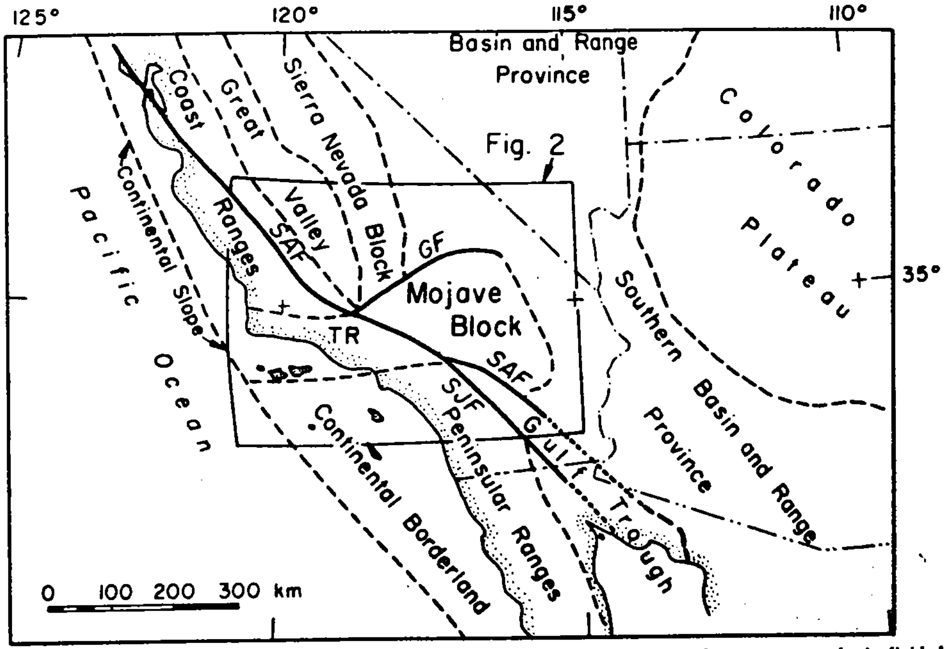

Figure 1. Mojave block and adjacent structural provinces. Region with basin and range topography is divided into Basin and Range province proper (roughly coinciding with Great Basin), Mojave block, and Southern Basin and Range province south of lat 34° N. SAF = San Andreas fault; GF = Garlock fault; SJF = San Jacinto fault; TR = Transverse Ranges.

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GENERAL GEOLOGIC FEATURES AND YOUNG STRUCTURE OF THE MOJAVE BLOCK

General accounts of the geologic history and structure of the Mojave block were given by Thompson (1929), Reed (1933), Hewett (1954a, 1954b), Bassett and Kupfer (1964), and Dibblee (1967a, and references therein); much of the knowledge is summarized by the 1:250,000 Trona, Needles, Salton Sea, San Bernardino, and Los Angeles sheets of the *Geologic Map of California* (Jennings and others, 1962; Bishop, 1963; Jennings, 1967; Rogers, 1967; Jennings and Strand, 1969).

The essentially pre-Tertiary basement complex consists of Precambrian crystalline rocks and of a variety of metamorphosed sedimentary and volcanic rocks, probably of Paleozoic to Jurassic age, that were strongly deformed and invaded by great volumes of granitic rocks of late Mesozoic to earliest Tertiary age. This area was a continental shelf that was involved in the late Paleozoic(?)–Mesozoic to early Tertiary Cordilleran orogeny (Hewett, 1954a; Dibblee, 1967a; King, 1969a, 1969b; Silver, 1971; Suppe and Armstrong, 1971; Burchfiel and Davis, 1972).

Paleocene to Oligocene sedimentary or volcanic rocks were not identified within the Mojave block, but continental sedimentary rocks of these ages are present north of the Garlock fault (Hewett, 1954a; Dibblee, 1967a; Woodburne, 1971). Marine Paleocene sedimentary rocks occur as slices along the San Andreas fault and southwest of it (Dibblee, 1967a), but they were probably juxtaposed with the Mojave block by large strike-slip movement.

Rocks of probably late Oligocene to Pliocene age are widespread. In the central and eastern parts of the Mojave block, a thick series of volcanic flows, pyroclastic rocks, and minor interbedded sedimentary rocks is developed; associated with these are hypabyssal bodies that often extend into basement rocks (Hewett, 1954a; Bassett and Kupfer, 1964; Dibblee, 1967a, 1971b; Jennings and others, 1962; Bishop, 1963; Rogers, 1967). The volcanic rocks cover a basement-rock surface of considerable relief and in many places dip steeply (as much as 45° or more); part of their disturbance may have resulted from emplacement of the hypabyssal intrusions.

These rocks are overlain unconformably by folded and tilted continental sedimentary rocks, which are interbedded with lesser volumes of pyroclastic and extrusive rocks. In places near Barstow, the sedimentary rocks yielded mammalian faunas of Hemingfordian and especially Barstovian ages (Dibblee, 1967a, 1968a), but sedimentary rocks in the Kramer Hills are somewhat older (Dibblee, 1967a, p. 82). Disturbed terrestrial sedimentary rocks of Clarendonian and Hemphilian ages are found in the Lava Mountains (Smith, 1964) and near the Avawatz Mountains (Grose, 1959). Contemporaneous fossiliferous continental sedimentary rocks occur also north of the Garlock fault (Dibblee, 1967a).

The younger rocks, of presumably (late?) Pliocene to Holocene age, include a variety of alluvial, fluvial, and lacustrine sequences as well as mainly basaltic volcanic flows. These rocks are separated by a marked unconformity from the older ones and are much less deformed; in most places, they are undisturbed. Unlike the older volcanic flows, the younger ones still preserve much of their original shape although they are quite dissected; in many places, they overlie a surface of considerable relief. Volcanism continued intermittently into Holocene time (Parker, 1963). Many valleys in the Mojave block were occupied by lakes during the Pleistocene pluvial ages (Blackwelder, 1954; Snyder and others, 1964); some valleys with internal drainage are still occasionally flooded.

The extensive alluvial plains in the western part of the Mojave block are underlain by a thick sedimentary series that is arched, folded, and exposed along the San Andreas fault. Here occur late Miocene marine sequences (in the extreme western part only), as well as continental clastic rocks ranging in age from Hemingfordian to Quaternary (Wiese, 1950; Crowell, 1952; Mabey, 1960; Dibblee, 1967a; Woodburne and Golz, 1971). This region apparently was depressed in relation to the rest of the Mojave block since middle Miocene time, and a relatively thick sedimentary sequence accumulated.

Northwest-striking faults dominate the late Cenozoic to Holocene structure of the Mojave block. The Garlock fault and other faults north of it also show evidence of activity during this time. In this paper, attention will be focused on these structures.

Hewett (1954a, 1954b) thought that the northwest-striking faults were of early Tertiary age and that they were intermittently active throughout the Neogene and until Quaternary and Holocene time. He also assumed a Pliocene orogeny to account for the disturbance of the Neogene sedimentary rocks and an early Pleistocene orogeny to account for the warping of some younger sedimentary rocks. Dibblee (1967a, 1968a) gave evidence for continuing Neogene, and possibly intensified Quaternary, diastrophism. However, the nature of the pre-Neogene structure of the Mojave block is obscure.

Hewett (1954b) interpreted the northwest-striking faults as having predominantly dip-slip movement, but Dibblee (1961) argued that they were strike-slip faults because: (1) The fault traces are rather straight, are tens of kilometers long, and are not associated with consistent topographic features in spite of their young age. (2) The downthrown sides alternate along the faults. (3) The fault surfaces seem to be vertical or very steep. (4) Along many faults, folds are developed that trend closer to due west than do the faults. These are drag folds that are expected along strike-slip faults. Some folds seem to be displaced right laterally by northwest-striking faults. Such folding affects sedimentary rocks of the Barstow Formation; Quaternary volcanic flows in the Gravel and Mud Hills along the Harper and Blackwater faults (Dibblee, 1961, 1968a); and alluvium south of Barstow (Dibblee, 1961, 1967a), along the West Calico fault around lat 34°34′ N., long 116°15′ W. (Dibblee, 1966a, 1967b), and in many other localities. The involvement of the Pleistocene alluvium and lava flows indicates that the faults are young. (5) Offsets of several hundreds of meters to a few kilometers were identified in basement terranes (Dibblee, 1961).

However, the distribution of the basement rocks and of the older Tertiary volcanic-sedimentary series suggests even larger slips on many of the northwest-striking faults. Several examples can be cited:

Large outcrops of older Neogene volcanic rocks, south of Interstate 40 and southeast of Barstow (Fig. 3) seem to be displaced right laterally: most noticeable is a right offset by the Pisgah and Calico faults along which volcanic rocks of the Bullion Mountains are displaced about 40 km from those in the Newberry Mountains (Fig. 3, A_1 and A_2). The southern boundaries of these volcanic units are buttress unconformities on old basement mountains (Dibblee, 1971b). If this boundary was originally a continuous west-trending line, it has been disrupted by right slip on the faults, as shown (Fig. 3, offsets A_1 through A_4). The original structure resembled, perhaps, that of the Cache Peak area (Dibblee, 1967a). Restoration of this slip aligns the body of metamorphic rocks around lat 34°25′ N., long 116°25′ W. with those near lat 34°15′ N., long 116°00′ W. Additional examples are shown in Figure 3. In the Sheep Hole Mountains, around lat 34°15′ N., long 115°45′ W., the southern boundary of Mesozoic granite seems to be offset about 15 km (Rogers, 1967).

These observations suggest that it is reasonable to assume strike slips of the order of 10 km or more on many northwest-striking faults in the Mojave block. The displacements of the Neogene volcanic rocks and of the basement terranes seem to be comparable; this suggests that a large part of, if not all, these offsets occurred since middle or late Miocene time.

Northeast of Barstow, major northwest-striking faults are absent, but approximately west-striking faults are present (Figs. 2 and 3). On one of them — the Manix fault (Fig. 3) — left slip occurred during the 1947 earthquake (Richter, 1958, p. 517–518), so it may be conjectured that the other faults of similar strike are also left-slip faults. The Garlock fault is the largest fault with such a strike, and on it about 60 to 65 km of left slip took place (Smith, 1962; Michael, 1966; Smith and Ketner, 1970). Left slip exceeding 5 km was recorded also on the roughly west-striking Pinto Mountain and Blue Cut faults in the Little San Bernardino Mountains (Dibblee, 1968b; Hope, 1969). The distribution of basement terranes (Jennings, 1967) suggests similar slip on other roughly west-trending faults in this region. The Pinto Mountain and Blue Cut displace alluvium; this indicates Quaternary activity, and they may have been active also in Neogene time.

The postulated predominance of strike-slip movement on the faults in the Mojave block can explain its rather "disorganized" relief: The faulting disrupted the preexisting relief, but the predominantly horizontal movements failed to produce well-defined linear ranges as did the predominantly vertical movements in the Great Basin farther north.

GEOMETRIC MODEL FOR DISTORTION OF MOJAVE BLOCK

To infer the effects of the northwest-trending strike-slip faults in the Mojave block, a simplified geometric model was used. A generalized palinspastic reconstruction of the region was derived and compared with the present structure to disclose the nature of the deformation. In the following section, the precision of this reconstruction is estimated and the simplifying assumptions are relaxed to better describe the real structure. Then the relations with the adjacent areas are examined.

For this purpose, we begin with the following simplifying assumptions: (1) The Mojave block is crossed diagonally by many right-slip faults (here the absence of such faults in the northeastern corner of the block is ignored; below it will be shown that this is permissible). (2) The slices between the strike-slip faults were rigid. (3) The displacements on the strike-slip faults were of the order of 2 to 40 km. (4) The ratio of the displacement on any fault at any time to the spacing between adjacent

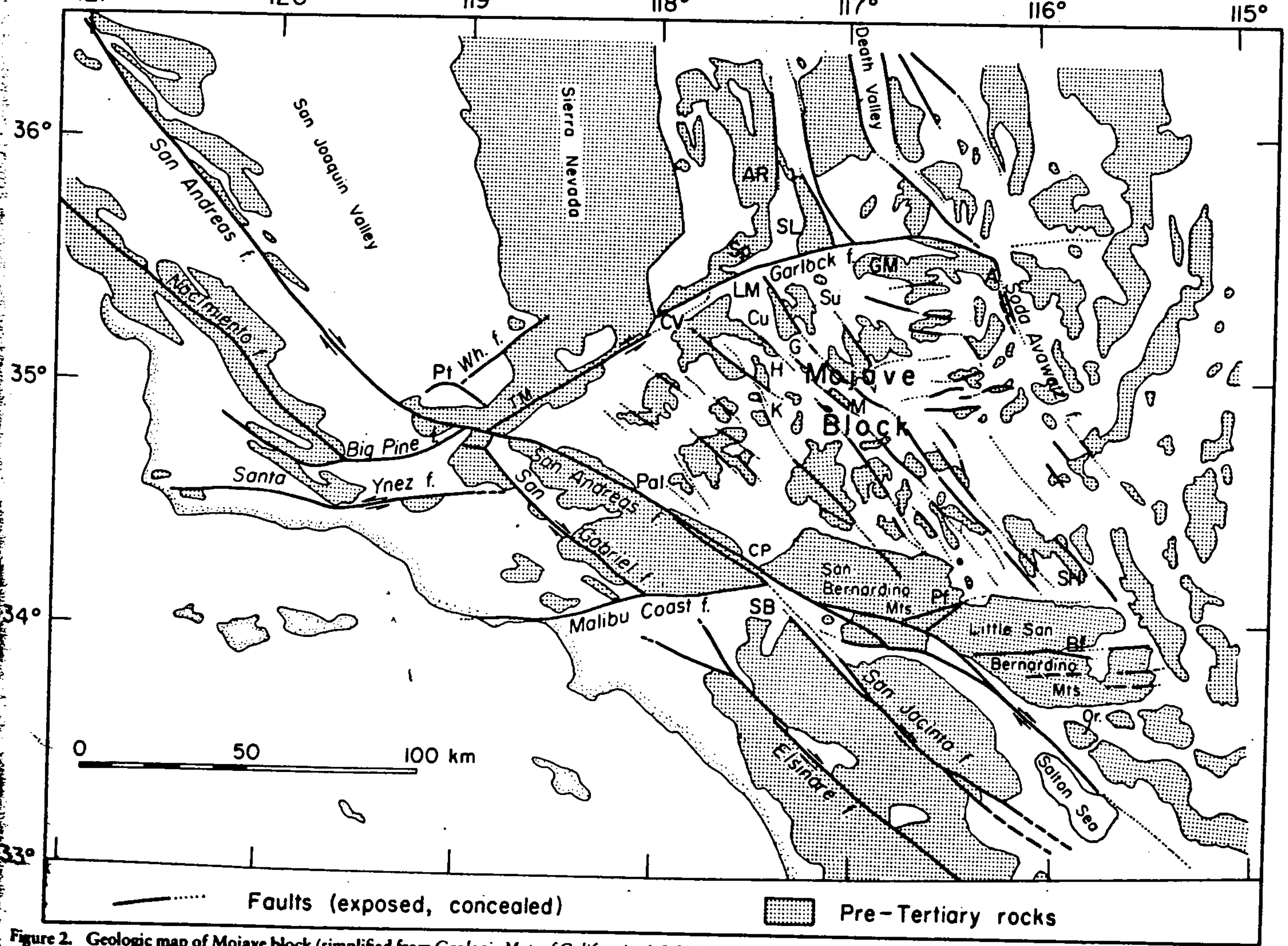

Figure 2. Geologic map of Mojave block (simplified from *Geologic Map of California*, 1:2,500,000, U.S. Geol. Survey and California Div. Mines and Geology). A = Avawatz Mountains; AR = Argus Range; Bf = Blue Cut fault; CP = Cajon Pass and Valley; Cu = Cuddeback Lake; CV = Cantil Valley; G = Gravel Hills; GM = Granite Mountains; H = Harper Lake; K = Kramer Hills; LM = Lava Mountains; M = Mudd Hills; Or. = Orocopia Mountains; Pal = Palmdale; Pf = Pinto Mountain fault; Pt = Pleito thrusts; SB = San Bernardino; SH = Sheep Hold Mountains; SL = Searles Lake; Sp = Spangler Hills; Su = Superior Valley; TM = Tehachapi Mountains; Wh. f. = White Wolf fault.

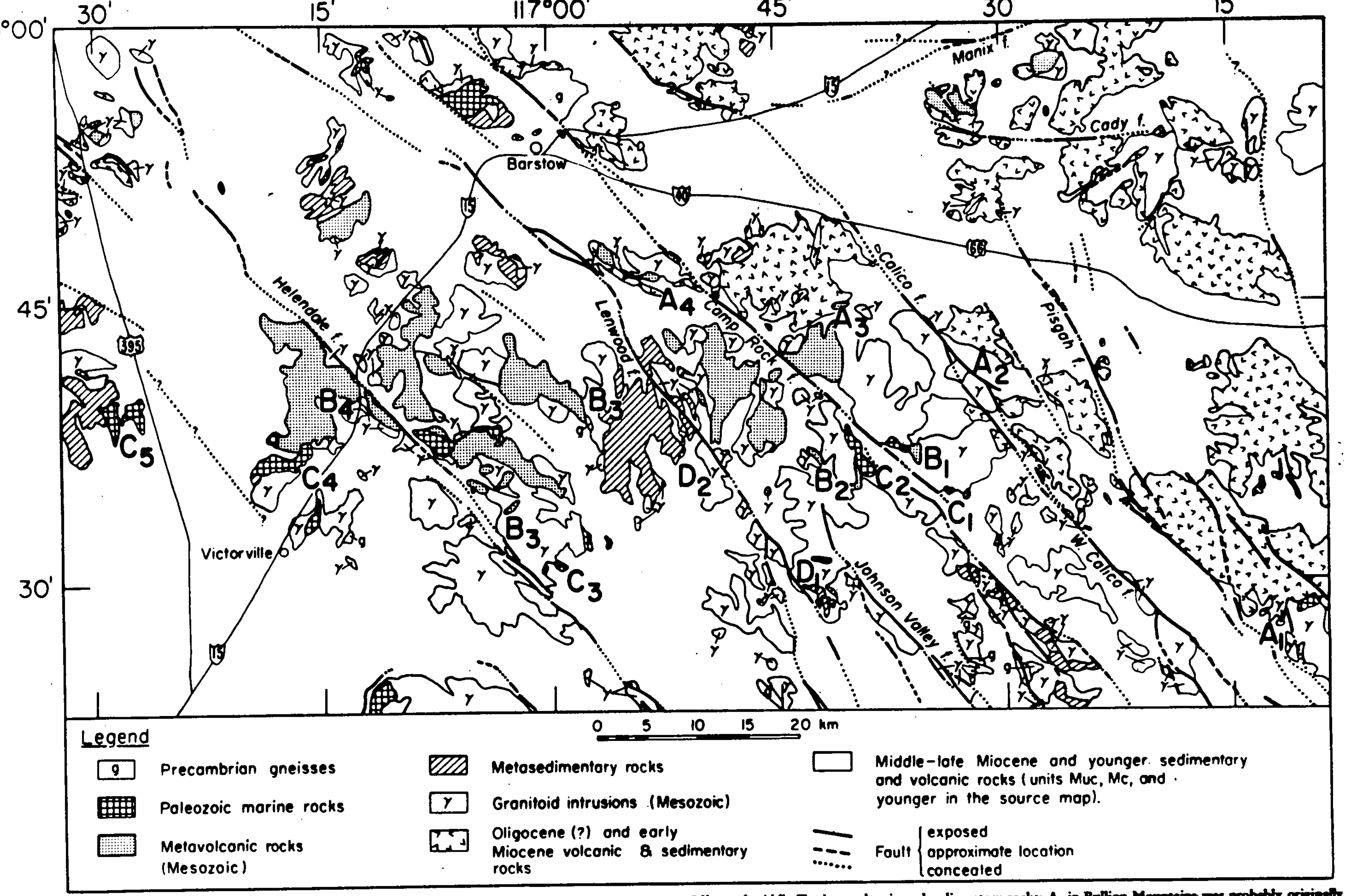

Figure 3. Geologic map of portion of Mojave block, showing possible strike slip. Simplified from Rogers, 1967. Offsets of middle Tertiary volcanic and sedimentary rocks: A_1 in Bullion Mountains was probably originally adjacent to A_2, which was probably offset from A_3, the Newberry Mountains; in all three, a volcanic-sedimentary series onlaps southward on granitic mountains. A_4 was possibly part of the same boundary. Offsets of the southern boundary of Mesozoic metavolcanic rocks: B_1 and B_2 probably originally aligned; now offset by same amount as A_3 and A_4. B_3 and B_4 are offset continuations of the same boundary of the metavolcanic rocks. Offsets of Paleozoic marine sedimentary rocks: Alignment of A_3 with A_4 and B_1 with B_2 aligns C_1 with C_2. Alignment of B_3 with B_4 aligns C_3 with C_4. The latter originally possibly aligned with C_5. Alignment of metasedimentary rocks at D_1 with D_2 requires same slip on the Lenwood fault as necessary to align B_2 with B_3. Proposed slips: Pisgah fault = 20 to 40 km; Calico fault = 10 to 20 km; Camp Rock fault = 10 km; Lenwood fault = 15 to 20 km; Helendale fault = 10 to 15 km.

faults was constant; that is, the over-all deformation was approximately homogeneous. (5) The San Andreas fault and the Garlock fault were the southwestern and northern boundaries of the Mojave block during the entire period of deformation here studied, and the northern boundary of the Mojave block remained adjacent to the southern part of the Sierra Nevada rigid block. Thus, although left slip occurred on the Garlock fault, it presumably did not rotate relative to the Sierra Nevada. From this, the internal strain of the Mojave block (which is defined by the previous assumptions) may be related to the surrounding regions and in particular to the Sierra Nevada, which is taken as a reference.

The geometric model, based on these assumptions, is shown in Figure 4. The eastern boundary is taken parallel to the northwest-striking faults and does not correspond to any definite geologic boundary. Average fault strikes were used.

To restore some of the fault movement, the slices between the strike-slip faults are shifted backward, that is, left laterally. Quantitatively, this may be best described by the parameter K, which is the ratio of slips on the faults to the distance between them. Thus, if the distance between point C and line AB (Fig. 4) is h, then point C is displaced in any given restoration over a distance $K \times h$ parallel to AB. K is a function of time. Increasing values of K describe progressively older situations, the original situation being described by some particular value, say K_0. The above estimates of the slips on the northwest-striking faults suggest K_0 values of 0.5 to 0.7 or more. Values of K from 0.2 to 0.4 may well describe the Pliocene to Quaternary movements.

A partial restoration with $K = 0.5$ is shown in Figure 4b. Other cases are shown in Figure 6a. The strike of the strike-slip faults is kept temporarily unchanged.

The most apparent effects of the reconstruction are changes in the angular relations within the distorted area. Thus, the angle between line BD (which is the restored northern boundary of the Mojave block) and the strike-slip faults has changed by γ. The lengths of the boundaries that are not parallel to the strike-slip faults change, but the area of the deformed region remains constant. The angle at the western apex of the distorted region also changes.

To facilitate calculations, the distortion of the Mojave block may be approximated by continuous and homogeneous shear strain in which K is the displacement gradient; thus quadrilateral BCEF in Figure 4a is transformed into BDHF in Figure 4b. Derivation of the relations given below is easier when the complete triangle ABC of Figure 4 is considered:

$$\sin \gamma = Kh \sin \beta \cdot (y^{-1}) = K(l/y) \cdot \sin^2\beta\,, \qquad (1)$$

$$l/y = (1 + K^2 \sin^2\beta - K \sin 2\beta)^{-\frac{1}{2}}\,, \qquad (2)$$

$$K = \frac{\sin \gamma}{\sin(\beta + \gamma) \cdot \sin \beta}\,, \qquad (3)$$

$$\cot \delta = \frac{(y/l) \cdot (\sin\theta/\sin\alpha) - \cos\xi}{\sin\xi}\,, \qquad (4)$$

where

$$\xi = 180^\circ - (\beta + \gamma)\,.$$

The values of γ and of δ as functions of K are shown in Figure 5.

Inaccuracies in the strikes chosen as averages for the faults amount to an error in the value of β or an error in that the initial configuration used is not the present one but is a past or future configuration. Thus, the origin in the graphs of Figure 5 may be somewhat misplaced. This is true because the various configurations are derived one from the other and because a small change of β will hardly affect the value of h or of the ratio y/l.

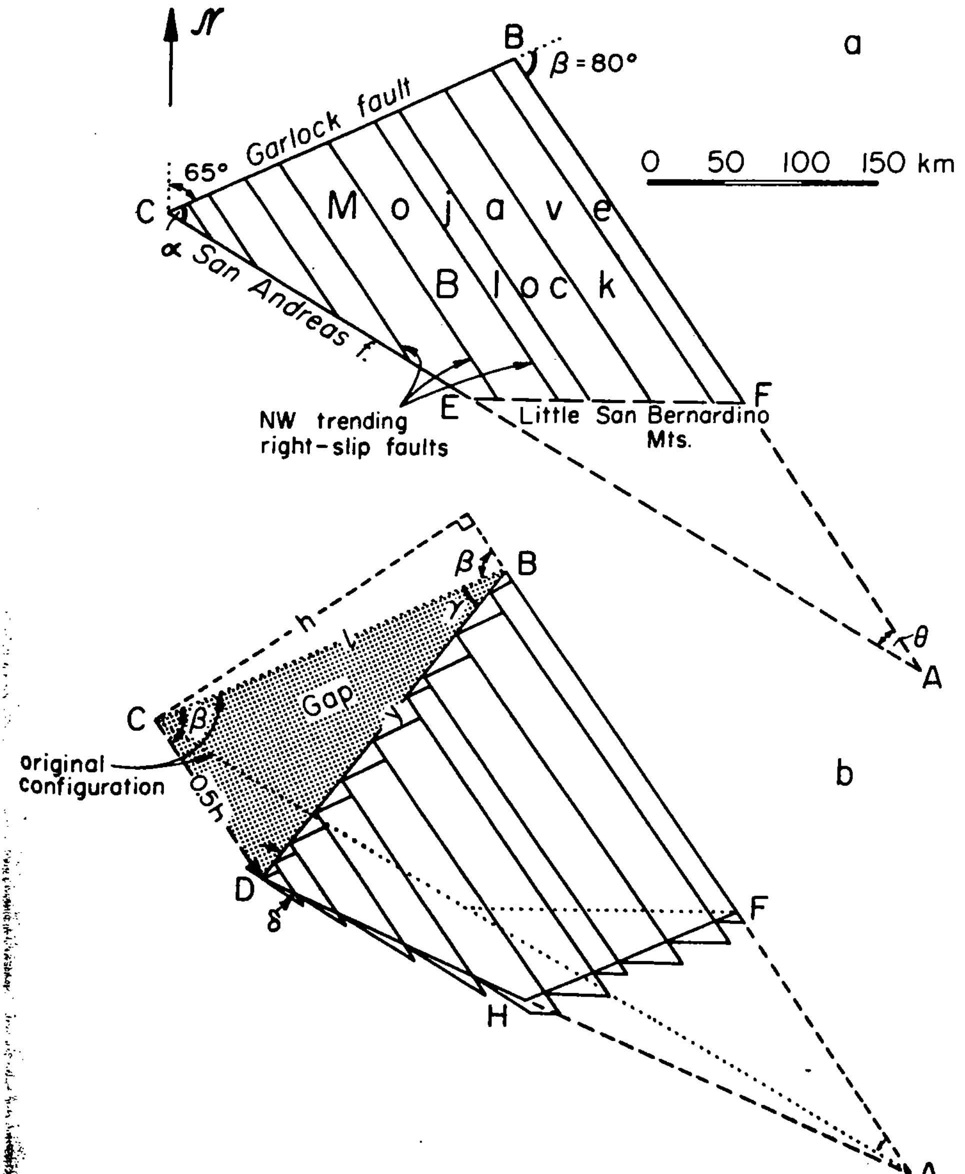

Figure 4. Geometric model of distortion of Mojave block; a, present situation simplified; b, restoration for $K = 0.5$, without rotation of faults within Mojave block (compare with Fig. 6). See text for details.

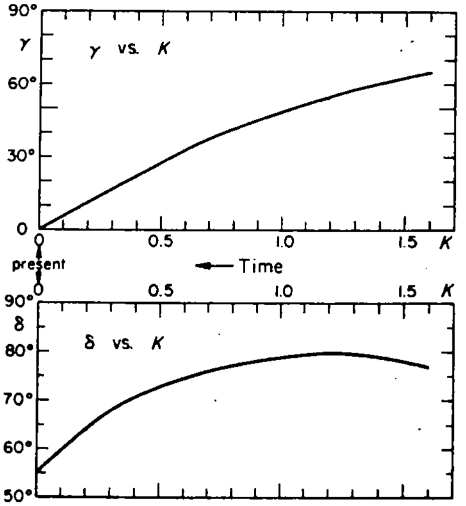

Figure 5. Magnitudes of deformation parameters for restorations to increasing antiquity. Upper graph gives angle γ as function of K. Lower graph gives angle δ as function of K. Angles γ and δ as in Figure 4.

The strike of the faults within the Mojave block was kept fixed in Figures 4b and 6a, but this requirement was not used in the calculations: only geometrical relations within the deformed area were studied, and these do not depend on its orientation relative to external regions. However, a fixed strike of the faults implies that the northern boundary of the Mojave block was formerly not in contact with the Sierra Nevada; that is, the two blocks originally were separated by a gap that has disappeared, or they overlapped in part. There is no evidence for either so that assumption (5) made above should be accepted.

This assumption implies that the past orientation of the Mojave block in relation to the neighboring regions is determined by the requirement that its northern boundary (not the faults within the Mojave block) did not rotate. To satisfy this, a rotation must be superimposed on the model illustrated in Figures 4b and 6a. This implies rotation of the northwest-striking faults, because they are merely boundaries of rock masses. Clearly, the rotation corresponding to internal deformation described by any particular value of K is through the angle γ.

The combined movements (Fig. 6b) are equivalent to approximately a left-lateral shear parallel to the northern boundary of the Mojave block. This resembles a stack of books that topples sidewise: the individual books rotate and also slip on each other so that their boundaries act as strike-slip faults. Obviously, the rotation of the blocks and the strike-slip movements are two different, contemporaneous aspects of a single process. The distinction between them is merely a convenient geometric device. Instead of using the parameter K, the deformation could have been described by the angle γ, which is constant for all slices (otherwise they would not remain in contact one with each other); equation (3) would give the corresponding value of K.

The over-all deformation envisaged here is a two-dimensional homogeneous shear in which surface area is preserved. This can be mathematically represented (Love, 1944; Jaeger, 1969) by a combination of either a simple or a pure shear with the appropriate rotations. The component of simple shear can be described as a displacement field, whose gradient is the parameter K (used above) on either one of two conjugate sets of slip lines. The lengths of the slip lines do not change during deformation, although their directions do. Each slip line consists of the same particles; that is, it is a "material line." The lengths of all other material lines change during deformation. Therefore, the mathematical representation as simple shear with rotation is an appropriate approximation of the actual discontinuous deformation of the Mojave block: in map view, the strike-slip faults could be taken as material lines of constant length, similar to the mathematical slip lines.

The above estimates of K_0 imply that the rotation of the slices, and of the faults which delimit them, might have reached 35° to 40°, so that originally their strike was close to due north. These faults possibly originated with similarly striking faults of the Basin and Range province north and east of the Mojave block. Later, the faults of the Mojave block were rotated to their present strike. The Pliocene to Quaternary rotation might have been 15° to 20°.

This conclusion provides a method of both *testing and refining* the geometric model: occurrence of rotation, as well as its rate (that is, the way K and γ depend on time) can be found in principle by paleomagnetic measurements on the abundant young volcanic rocks in the Mojave block and by comparing the data with that from regions farther north. The total rotation could be deduced from a comparison of paleomagnetic data from Mesozoic granite within the Mojave block with data from the Sierra Nevada (Grommé and others, 1967).

Rotation of blocks and of the faults that delimit them may be much commoner than this appears from the literature, in which only local deformations rather than relative orientations of deformed regions generally have been considered. Such rotations were, however, recorded in some cases (Freund, 1970, 1971; Freund and others, 1970; Garfunkel, 1970); they were also observed in experiments (Cloos, 1955).

APPLICATION OF THE GEOMETRIC MODEL TO THE MOJAVE BLOCK

After describing the idealized geometric model, the simple assumptions are now compared with the actual structure, and the effects of relaxing these assumptions so as to approach reality are examined. The purpose is to estimate the possible error in the quantitative relations presented above.

The assumption that the slices between the faults behaved as rigid blocks may apply to the Pliocene to Holocene deformation, because most rocks of this age in the Mojave region are hardly deformed, except in small areas near faults that probably can be neglected. This is not true for longer periods: the Miocene rocks are commonly folded and greatly tilted. However, the average dips are less than 30°; therefore, the shortening normal to strike is less than 15 percent. This might introduce an uncertainty of 2° to 5° in γ and an error of as much as 0.1 in K, which is not large if $K_0 \geq 0.5$. Furthermore, much of this shortening may be older than the deformation considered here.

Another simplifying assumption was that the faults are straight and go from boundary to boundary of the block so that surface area is preserved. In fact, the faults have somewhat irregular strikes, and none is known to cross the entire Mojave block. Such an arrangement should produce compressional and (or) dilatational structures that change the surface area (Fig. 7). Many closed depressions in the Mojave block could have resulted from strike-slip on en-echelon faults. An idealized situation is shown in Figure 8; the addition of surface area lengthens only the north-south dimension of the block, whereas the length of its northern boundary does not change. The total area of depressions is only a fraction of the area of the Mojave block; apparently, the effect of right-slip on en-echelon

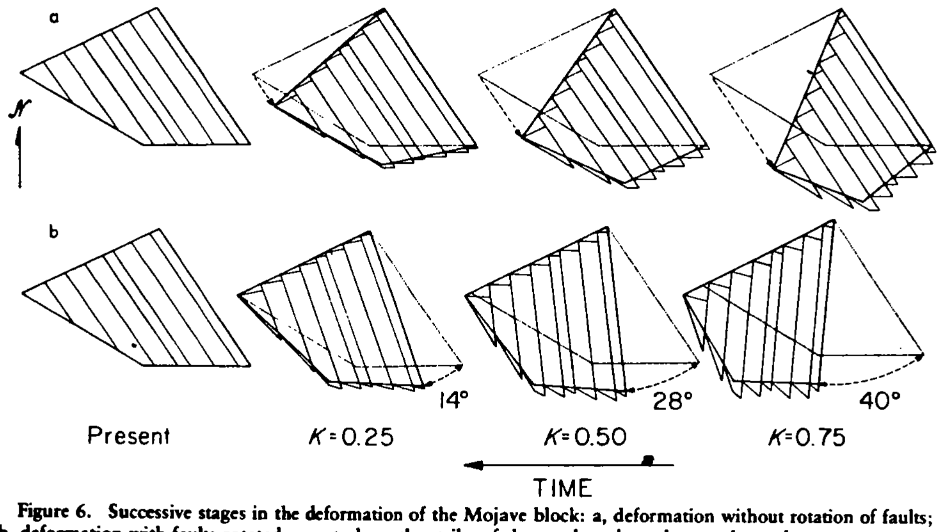

Figure 6. Successive stages in the deformation of the Mojave block: a, deformation without rotation of faults; b, deformation with faults rotated so as to keep the strike of the northern boundary unchanged.

faults is probably not large and may be offset in part by compressional structures. Therefore, these complexities are assumed not to introduce significant errors in the model.

By far, the most inaccurate assumptions are those about the homogeneity of the deformation and the nature of the northern boundary of the Mojave block. The Garlock fault (which delimits the block on the north) is not straight, and large strike slip occurred on it. Furthermore, the region north of it (that is, the southern part of the Sierra Nevada block and the Tehachapi Mountains) is not rigid (Buwalda, 1954), and neither is the area farther east. It will now be shown that this does not significantly change the main features of the model when $K_0 \geqslant 0.20$ to 0.25.

Left slip on the curved Garlock fault must rotate the Mojave block clockwise in relation to the Sierra Nevada, which is opposite to the rotation envisaged in the model. The rotation resulting from the approximately 60 km of slip on the somewhat irregularly curved Garlock fault is difficult to estimate, but it would not exceed 5° and was probably less.

The structure north of the Garlock fault strongly suggests that the curvature of the fault has somewhat increased in the geologically recent past, which would decrease the above effect. At present, the western extremity of the Garlock fault strikes closer to due west than the part of the fault farther east. However, restoration of the compressional structures in the southern end of the San Joaquin Valley (see below) would rotate this segment of the Garlock fault and better align it with the rest of the fault.

The segment of the Garlock fault east of Searles Lake is conspicuously arcuate. North of the fault, northwest-trending to north-northwest–trending strike-slip faults and north-trending normal faults were active in the geologically recent past (Burchfiel and Stewart, 1966; Wright and Troxel, 1969). Right slip on these faults should rotate the southwestern boundary of the Great Basin, which is here delimited by the arcuate segment of the Garlock fault. Thus, in late Neogene time, this eastern segment was probably more in line with the rest of the Garlock fault.

The main deviations from rigidity immediately north of the Garlock fault are along the southern margins of the San Joaquin Valley. The recent tectonic activity in this region was manifested during the 1952 Arvin-Tehachapi earthquake (Buwalda, 1954; Oakeshott, 1955; Richter, 1958), and recent deformation occurred also on and near the Pleito thrusts (Crowell, 1964). As all these structures are compressional, their restoration requires a relatively southward shift of the Tehachapi Mountains. These mountains have risen, relative to the floor of the adjacent San Joaquin Valley, by possibly as much as 10 km since Miocene time (Hoots and others, 1954; Hackel, 1966). If this structural relief was created by movement on one or several thrusts dipping 30°, then a horizontal displacement of about 17 km occurred; if the thrusts dip 45°, the horizontal displacement was about 10 km. The White Wolf fault, on which the 1952 earthquake originated, dips about 30° to 45° south-southeast (Buwalda and St. Amand, 1955), but the earthquake mechanism of the main shock in 1952 suggests a steeper dip (Gutenberg, 1955). The distance between the surface traces of the White Wolf fault and the Garlock fault is about 35 km. The above estimates suggest that half of this figure is probably a reasonable estimate of the shortening normal to these faults and may be too high. Restoration of this deformation would decrease the size of the gap in this region in the reconstructions shown in Figures 4 and 6a. However, when $K = 0.25$, this gap becomes about 60 km wide, which is considerably larger than the shortening estimated above. Thus, the effect of the deformation north of the Garlock fault is to reduce the value of γ by possibly as much as 5°, which is not very large when $K_0 \geqslant 0.25$ (for which $\gamma \geqslant 15°$).

Because the shape of the northern boundary of the Mojave block changed, the assumption of the over-all homogeneity of deformation must also be relaxed: if the slices were to remain in contact with the curved and distorted northern boundary of the Mojave block, then the slip between them could not have been always proportional to their widths. Therefore, K and K_0 vary locally, and their values used in the geometric model are only average slip gradients over the entire Mojave block. On the other hand, γ is expected to be the same for all slices: if it varied from one slice to another (that is, if adjacent slices rotated differently), then wedge-shaped gaps or overlaps should have developed, but such structures have not been identified. The angle γ, which in principle can be determined by paleomagnetic measurements, may be used to calculate a corresponding average value of K.

The way that the northwest-striking faults and slabs between them terminate deserves special attention. In the reconstructions of Figure 6, the rotation of the slabs leaves triangular gaps along the unfaulted adjacent regions. The size of these gaps depends on the width of the slabs and the amount of rotation. Some structural depressions along the northern boundary of the Mojave block might have resulted in this manner, for instance Harper Lake, Cuddeback Lake, Superior Valley (Jennings and others, 1962), and the Pliocene basin of the Lava Mountains (Smith, 1964). If the faults splay before reaching the boundaries of the Mojave block, then small depressions will form. Additional field studies are required to test this interpretation.

Slip on the irregularly curved Garlock fault should produce local deformation in addition to that resulting from the terminations of the northwest-striking fault slices. The most obvious structure of this type is Cantil Valley. Gravity anomalies (Mabey, 1960) and young fault traces (Clark, 1971) indicate that this valley is a graben and that it was formed between left-stepped en-echelon segments of the left-slip Garlock

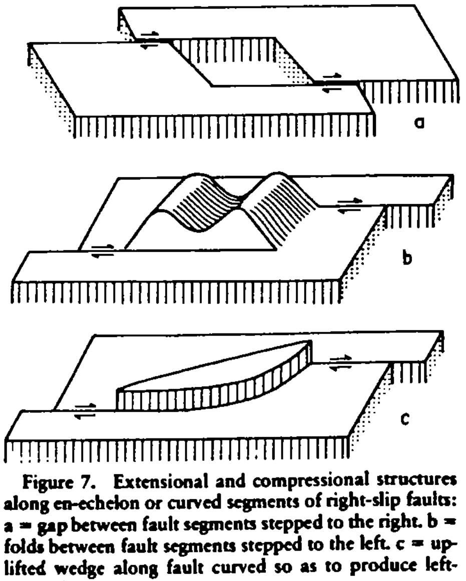

Figure 7. Extensional and compressional structures along en-echelon or curved segments of right-slip faults: a = gap between fault segments stepped to the right. b = folds between fault segments stepped to the left. c = uplifted wedge along fault curved so as to produce left-stepped segments.

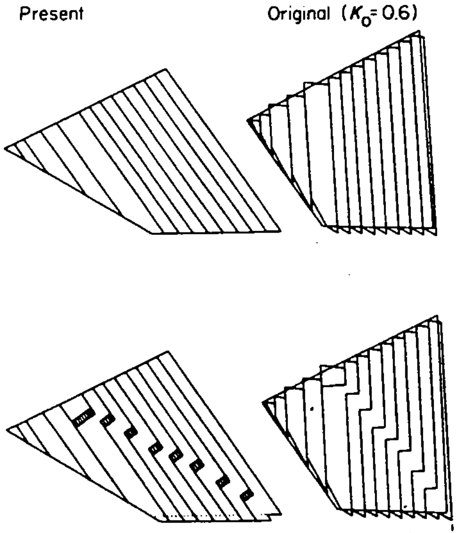

Figure 8. Example of increase in area by right slip on en-echelon faults. Over-all deformation as in Figures 4 and 6.

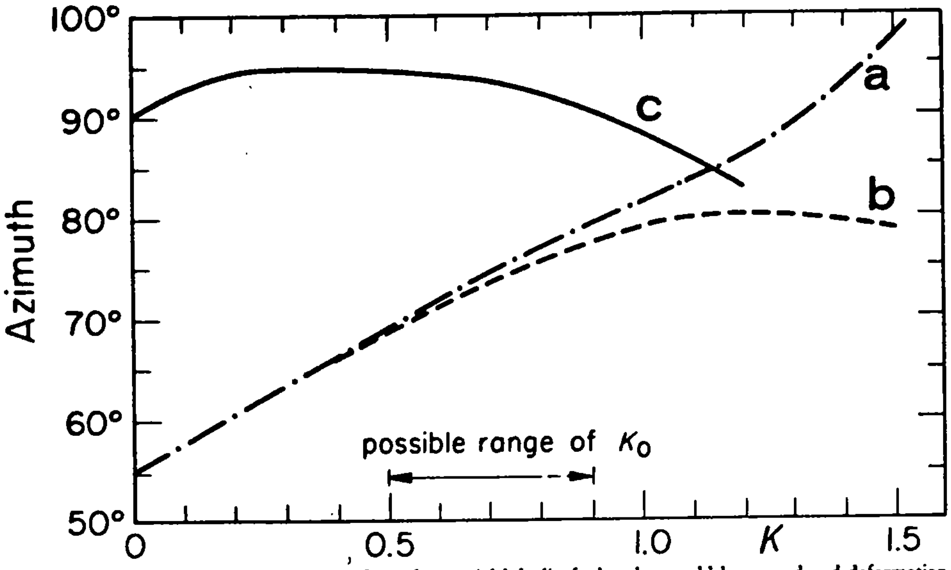

Figure 9. Orientations, as a function of K, of potential left-slip faults, that could have produced deformation shown in Figure 6b: a = original strike of left-slip faults; b = final strike of same faults; c = original strike of lines that finally strike due west.

fault. The structure is a mirror image of the one shown in Figure 7a.

ROLE OF APPROXIMATELY WEST-STRIKING LEFT-SLIP FAULTS

The reconstructions of Figures 4 and 6 incorrectly show the northwest-striking right-slip faults traversing the northeastern corner of the Mojave block, whereas this area is cut by west-striking to west-southwest–striking faults similar to the Manix fault. Young faults of this type also occur in the Little San Bernardino Mountains (Fig. 2). The Garlock fault itself belongs to this fault system. These left-slip faults were active contemporaneously with the right-slip faults discussed above, and the relations between them must now be discussed. It will also be shown that the approximation used in Figures 4 and 6 is permissible.

The role of the left-slip faults is explained by the theory of homogeneous, continuous shear: identical effects can be produced by either right slip on one, or left slip on the other of two conjugate sets of slip lines, combined with appropriate rotations. The two cases are distinct in the corresponding discontinuous case.

Figure 9 shows the original and final directions of possible sets of left-slip faults that could have produced the same deformation as that envisaged in Figure 6b. For K_0 in the range 0.5 to 0.7, such faults strike slightly north of east and do not rotate much. Therefore, it is justified to divide the Mojave block into domains crossed by either one of the two possible sets of conjugate faults. During deformation, these domains remain in contact with each other because their over-all deformations are identical (Figure 10). This justifies the approximation of Figures 4 and 6.

Ideally, the rotation of the domain of left-slip faults should be very small and clockwise. However, the domain of the northeastern corner of the Mojave block is adjacent to the eastern part of the Garlock fault that probably was, as discussed above, bent clockwise; it seems that the latter rotation dominated quantitatively. Such an extra rotation is suggested also by the differences in strike of the dike swarm in the Argus Range and Spangler Hills from that of its offset continuation in the Granite Mountains on the other side of the Garlock fault (Smith, 1962). This extra rotation implies a local deviation from homogeneous shear.

Left slip on west-striking faults also occurred in the Little San Bernardino Mountains, and it can be described by values of K_0 in the range of 0.6 to 0.8. The deformation of this domain may be quite similar to that of the Mojave block, but here the rotation was probably quite small.

Hence, the two fault systems — right-slip, northwest-striking and left-slip, west-striking faults — combine to produce a similar over-all effect that is roughly a west shear, and this is supplemented by the left slip on the Garlock fault. The circumstance that a large area was deformed in a generally uniform manner, although this was achieved in different ways in various domains, strongly suggests that rather uniform stresses acted over the entire region. The differences between the surficial structures probably reflect local variations of mechanical properties and of prefaulting history rather than variations in the driving forces. The latter impose quite uniform boundary conditions of strain that the surface deformations will satisfy by the type of reaction that is mechanically most easily achieved.

This agrees with the mechanical theory of faulting (Anderson, 1951) that predicts that, in any given stress state, two conjugate fault systems can be developed. The two fault systems considered here are such conjugate systems, each one developed in a different region or domain and probably the result of local factors.

BENDING OF THE SAN ANDREAS FAULT

The distortion of the Mojave block should deflect the adjacent segment of the San Andreas fault: Figures 5 and 6 show that, as distortion progresses, the angle δ between the Garlock fault and the San Andreas fault, south of where they meet, decreases. Therefore, here the San Andreas fault should be rotated counterclockwise so as to strike closer to due west (Fig. 10). This is actually observed.

It is proposed, therefore, that the bent shape of the San Andreas fault in the Transverse Ranges is not an original feature, but that it was acquired contemporaneously with the distortion of the Mojave block, perhaps as late as Pliocene and Quaternary time. In the Coast Ranges, the fault strikes N. 40° to 44° W. If $K_0 = 0.5$, then δ changes by 18°, so a strike of N. 58° to 62° W. can be expected adjacent to the Mojave block, which is close to the trend of the San Andreas fault between Palmdale and San Bernardino.

Possible significant rotation of the straight segment of the San Andreas fault in the Coast Ranges in relation to the Sierra Nevada reference block must be checked. This might have occurred in view of the young folding along the western margin of the Great Valley. If the 250-km-long fault segment between Hollister and the Carrizo Plain rotated 1°, then one end of this fault segment should have moved about 4 km east or west in relation to the other end; that is, there should be a corresponding notable difference between the shortening normal to the fault in the two regions. A considerable change of strike of the San Andreas in relation to the Sierra Nevada would require, therefore, considerable differences in east-west shortening; this is not observed in the folds along the west margin of the Great Valley. Hence, the calculated bending of the San Andreas fault should be correct within 3° to 5°.

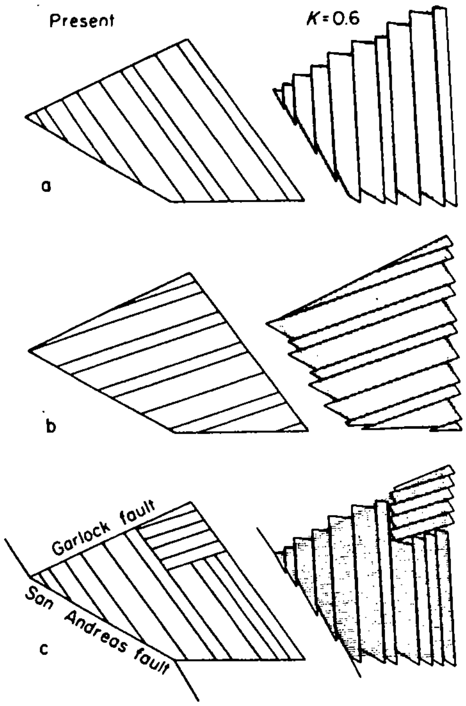

Figure 10. Identical deformation resulting from right and (or) left slip on conjugate fault systems. a = right slip only, with proper rotation. b = left slip only, with proper rotation (which is quite small). c = model of Mojave block consisting of two domains, each with only one of the conjugate fault systems; also shows bending of San Andreas fault.

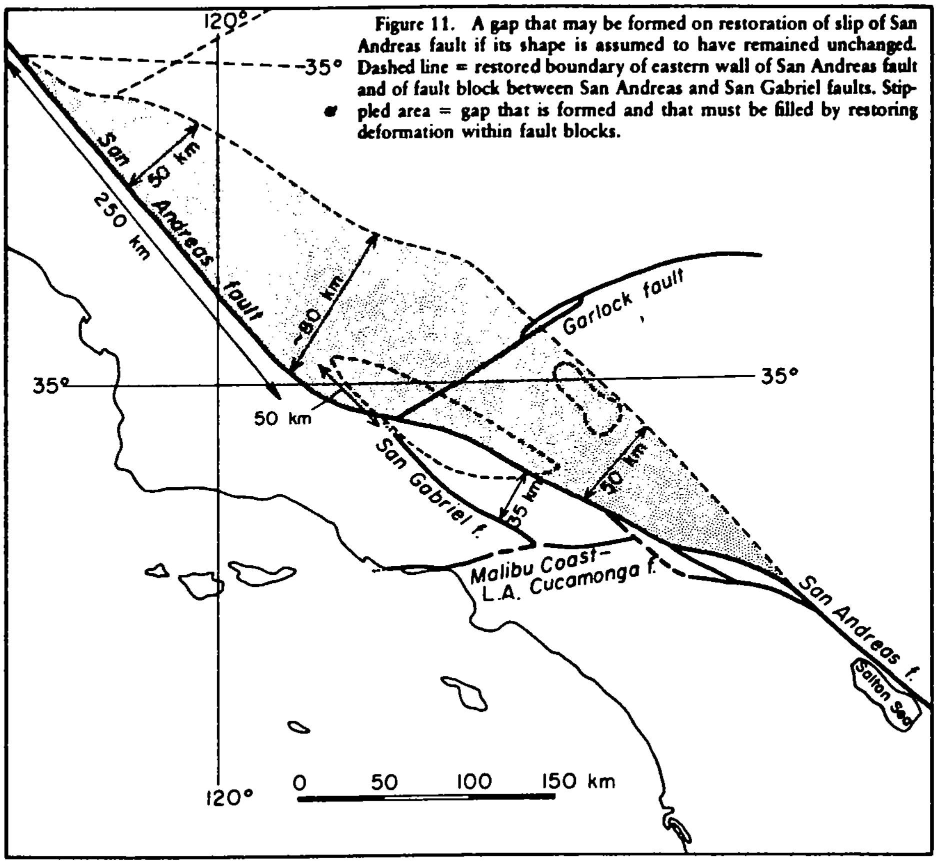

Figure 11. A gap that may be formed on restoration of slip of San Andreas fault if its shape is assumed to have remained unchanged. Dashed line = restored boundary of eastern wall of San Andreas fault and of fault block between San Andreas and San Gabriel faults. Stippled area = gap that is formed and that must be filled by restoring deformation within fault blocks.

The postulated bending of the San Andreas fault should produce progressively intensified compression normal to the fault in the region adjacent to the distorted segment, which is an obstacle for strike-slip movement. The structure of this region bears much evidence for such compression (Hill, 1954). Although the compression, especially in the Transverse Ranges, is only partly related to the bending of the San Andreas fault, this hypothesis can, however, explain the following tectonic relations in this region:

1. Based on the assumption that the shape of the San Andreas fault did not change, Figure 11 shows a restoration of 250 km of slip on the fault; this amount is somewhat less than the slip since the end of the Oligocene Epoch (Addicot, 1968; Turner, 1969). In this reconstruction, a gap as much as 80 km wide is formed so that a comparable shortening normal to the fault should have taken place when this slip occurred. This seems to exceed considerably the shortening apparent in the Neogene rocks. Furthermore, parts of the Coast Ranges would have had to be greatly distorted when passing around the curvature of the fault, but no such effects have been recognized. These difficulties do not arise if the bent shape of the San Andreas fault is a young feature, because then little compression normal to the fault is required to allow strike-slip movement.

2. Until late Pliocene time, the San Gabriel fault was an active strike-slip fault. Later, however, strike slip ceased, and the fault was disrupted by thrusts: the Frazier thrusts in the north (Crowell, 1964, 1968) and the San Fernando fault (or fault zone) in the south. The February 9, 1971, San Fernando earthquake originated on the latter (Wentworth and others, 1971; Kamb and others, 1971; Proctor and others, 1972). This tectonic development suggests intensified north-south compression during Quaternary time, which is expected to result from the proposed progressive bending of the San Andreas fault.

3. The late Pliocene or early Quaternary Crowder Formation and older Neogene sedimentary rocks north of the San Andreas fault in the Cajon Valley and farther west were derived essentially from the Mojave block; the younger sedimentary rocks were derived, however, from the opposite direction while the older ones were uparched and deformed (Dibblee, 1967a; Pelka, 1971; Sharp and Silver, 1971; Woodburne and Golz, 1971). This agrees with intensified compression normal to the San Andreas fault in Quaternary time and is compatible with its late bending.

4. The uplifting of the San Bernardino Mountains resulted from compression generated by strike slip on the bent segment of the San Andreas fault. This uplifting is quite young (Dibblee, 1971a), which again is compatible with the proposed late bending of the fault.

5. The San Jacinto fault is a young member of the San Andreas fault system: most of its 25 km of total right slip was achieved during Quaternary time (Sharp, 1967). The current seismicity indicates a slip rate of about 1.5 cm per year (Brune, 1968), which could produce the total displacement in less than 2 m.y. It may be conjectured that, as the main strand of the San Andreas fault was bent, a new and more favorably oriented fault — the San Jacinto fault — was formed and part of the slip was shunted to it.

6. In the northern part of the Coachella Valley, late Quaternary sediments are folded (Dibblee, 1954; Allen, 1957; Proctor, 1968). Such compression within a subsiding trough is remarkable, and in fact the uplifting of the folded sediments leads to local cessation of sedimentation. It is

must be compatible. The advantage of using the Mojave block rather than the regional approach is that the model presented herein can in principle be tested quantitatively by paleomagnetic studies, and unambiguous results can be expected. A complete regional analysis is beyond the scope of this paper, but several points must be noted.

The discussion above suggests that the Mojave block was affected by a left shear that was supplemented by left slip on the Garlock fault. If $K_0 = 0.5$, then the rotation of the fault slices within the Mojave block was about 30°. Thus, if the eastern boundary of the block originally trended close to due north and was about 200 km long, then the northeastern corner of the block moved westward by about 100 km (= 200 km × sin 30°) in relation to its southeastern corner. The Sierra Nevada moved farther west by about 60 km as a result of the slip on the Garlock fault. Altogether, in relation to the Colorado Plateau (or any other part of the continental interior), the westward movement of the Sierra Nevada was greater by 160 km or more than that of the Little San Bernardino Mountains (Fig. 12). Hence, the distortion of the Mojave block and the left slip on the Garlock fault accommodate changes in the east-west stretching or crustal spreading in the Basin and Range province: at lat 36° N., the stretching was at least 160 km greater than at lat 34° N.; in the north, the area affected by normal faulting is wide, exceeding 500 km at lat 40° N., but is much narrower east of the Mojave block. A complete treatment should consider also right-slip faults such as the Furnace Creek fault, but since their displacement is perhaps not very large (Wright and Troxel, 1970), they are ignored in the first approximation.

The role of the Garlock fault as accommodating by left slip some of the spreading in the Basin and Range province deserves attention. This fault does not obviously extend east of the Avawatz Mountains where it is bent and disrupted by the Death Valley fault. However, its extension probably continues some distance eastward. Normal faulting and tilting of blocks extended the region north of this fault line by at least 30 percent in the late Neogene and Quaternary (Wright and Troxel, 1971). There is no comparable extension south of this fault line; left slip is required to accommodate this extension whose magnitude is adequate to account for most, if not all, of the left slip of the Garlock fault. This was discussed by Troxel and others (1972) and by Davis and Burchfiel (1973) and need not be further discussed here.

The estimate of the extension in the Basin and Range province given here is high. However, extreme extension occurred on the flat-lying normal faults that were recognized in many areas adjacent to the Mojave block (Longwell, 1945; Anderson, 1971; Wright and Troxel, 1971). This should be added to the extension due to the formation of horsts and grabens that dominate the relief: extension affected also the interior of horsts. Stewart (1971) estimated that the first effect accommodated about 50 to 100 km of spreading so that when the additional internal extension of the horsts is added, the estimate presented here seems reasonable.

South of lat 34° N. and of the Mojave block, crustal extension occurs in two structural provinces:

1. The continental borderland (Figs. 1 and 12). The physiography of this region is similar to that of the Basin and Range province, and the region possibly has a similar structure dominated by east-west extension (Emery, 1960; Krause, 1965; Moore, 1969). Seismicity (Allen and others, 1965; Barazangi and Dorman, 1969) suggests recent activity, although perhaps most of the deformation occurred in late Miocene and Pliocene time, as suggested by the history of the Los Angeles basin at the northeastern corner of this province (Yerkes and others, 1965).
2. The Gulf of California and its northern extension into the Salton Trough. Here, the slip is at an angle to the general trend of the gulf and of the continental margin, so that the component normal to these produces the opening of the gulf while Baja California drifts away from the mainland; the component of slip normal to the continental margin was active mainly during the most recent 4 m.y. (Hamilton, 1961; Larson and others, 1968; Moore and Buffington, 1968).

The Mojave block separates these two southern regions of crustal extension from the Basin and Range province. Such an arrangement requires east-west left shear in the Mojave block (Fig. 12). When the young slip on the San Andreas fault is restored, this is even more obvious than at present. In the south, the crustal extension is mainly near the continental margin; whereas north of the Mojave block, the extension occurs far inland. Thus, the continental margin is distorted at the latitude of the Mojave block and the Transverse Ranges. The left shear in the latter two regions fits, therefore, into a regional pattern (the north-south shortening in the Transverse Ranges may be kinematically independent, reflecting irregularities in the north-south component of movement of the continental sliver west of the San Andreas fault system).

This discussion did not consider the southern Basin and Range province (Fig. 1). This area was active in late Tertiary and Quaternary time, although its recent activity was probably not very great (King, 1965). Some recent activity is indicated by surface faulting during the 1887 earthquake in Sonora (Richter, 1958, p. 594) and by seismicity, especially in the related Rio Grande rift. However, the tectonic relation of this province to the area considered above is not clear.

In the context of plate tectonics, the deformation considered here records the nonrigidity of the margins of the Pacific and North American plates. The best estimate of the slip rate between these plates is about 6 cm/yr (Atwater, 1970). The deformation normal to the plate boundary, which was considered above, is much smaller and slower and is therefore merely a second-order effect.

Thus, here the movement between the two plates is resolved into two components: the larger is parallel to the plate margin and is concentrated on a single strike-slip fault or fault zone — the San Andreas — which therefore defines the local plate boundary. The smaller component, normal to the plate margin, is accommodated by quite irregular deformation in a wide zone (Fig. 12). This leads to the peculiar deformation of the Mojave block and distorts locally the shape of the plate margin.

Such complex plate interactions cannot be predicted from the movement of plates. A local cause, probably related to the mechanism which drives the plates, is called for. This is corroborated by the observation that the spreading in the Basin and Range province exceeded the space which was "allocated" for it between the adjacent rigid parts of the plates: contemporaneously with this spreading, there was roughly east-west compression in the California Coast Ranges which allowed, or resulted from, the extra spreading inland (Eaton, 1932). These phenomena can best be explained as surface manifestations of active mantle processes below the studied region and not just a result of interaction between margins of moving plates.

SUMMARY

The late structure of the Mojave block is dominated by roughly northwest-striking right-slip faults that do not extend beyond its boundaries. Reconstruction of the slip on them shows that the Mojave block was considerably distorted and that the angular relations inside this block changed. In order to maintain contact with the adjacent regions, rotation must have occurred. The magnitude of the rotation depends on the offset of the faults and may have been as large as 30° or more. Its magnitude and timing can be checked in principle by

paleomagnetic measurements. The over-all distortion of the Mojave block was approximately an east-west shear. In one subdomain of the block, this was achieved by left-slip on west-trending faults. A similar deformation apparently occurred also in the eastern Transverse Ranges.

The model presented is quite simplistic, but it is not fundamentally changed by introducing into it some of the actual complexities. This is so only if the slip on the northwest-trending faults and the rotation are as large as suggested herein. The various other complications simply introduce a small, but not negligible, uncertainty into the geometric model.

The distortion of the Mojave block and slip on the Garlock fault are geometrically and temporally related to irregularities in the magnitude and location of crustal spreading of the adjacent regions: as they are all in contact with each other, their deformations should be compatible. Here, a small component of the slip normal to the boundary between the Pacific and North American plates is accommodated by deformation in a wide region. Irregularities in this deformation locally distort the plate boundary. This is most evident in the case of the Garlock fault that locally distorts the San Andreas fault at the point where the two meet. The shearing of the Mojave block, on the other hand, is more diffuse but is much more important, and it bent considerably the San Andreas fault, which represents the plate boundary. The major component of plate slip is parallel to the plate boundary.

These irregularities reflect local complexities in the interaction between the Pacific and North American plates. Here, their margins deviate considerably from rigid behavior. This probably results from the activity of the underlying mantle, especially in the Basin and Range province, that generates local crustal spreading normal to the dominant slip between the plates.

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