TECTONICS, VOL.9, NO. 2, PAGES 311-340, FEBRUARY 1990

# LATE CENOZOIC STRIKE-SLIP FAULTING IN THE MOJAVE DESERT, CALIFORNIA

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*Abstract.* Recent tectonic models for southern California treat the entire Mojave Desert Block as the site of distributed simple shear during late Cenozoic time. These models consider that much of the region is composed of a series of narrow blocks, bounded by active NW striking, right-slip faults that have facilitated the distortion and rotation of the region about vertical axes during translations. As much as 100 km of cumulative right slip is predicted for these faults by some of these models. These kinematic models require that the faults of the Mojave Desert Block merge with the Garlock fault, which is viewed as the intact northern boundary that served to accommodate the distortion of the Mojave Desert Block by simple shear. Map-scale structural relations are used to test explicit and implicit features of kinematic models proposed for the region. These relationships indicate that late Cenozoic NW striking, right-slip faults of the Mojave Desert Block possess the following characteristics: (1) the faults are discontinuous, with only the Calico-Blackwater fault spanning the entire Mojave Desert; (2) the faults terminate before reaching the Garlock fault; (3) faults south of an irregular line extending from near Barstow eastward to Ludlow and to Soda Lake are continuous and well developed and have a cumulative net slip of >40 km, whereas faults to the north are discontinuous and display <12 km of right slip; and (4) there is a northwestward decrease in net slip along most of the faults. A new kinematic model is proposed to reconcile these new observations with existing data. We assert that integrated strain within the province since middle Miocene time is not regionally homogeneous as predicted by simple shear models but is instead partitioned into six major domains. The domains probably have deformed and rotated about vertical axes independently of each other and are separated by zones of shortening or extension or by strike-slip faults. Strike-slip faults and folding have likely accommodated internal deformation and rotation of some of the domains. The model predicts that the Mojave Desert has been the site of ~65 km of right shear since middle Miocene time. The broad network of faults of the Mojave Desert Block along with similar strike-slip faults of the Death Valley region constitute a regional zone of right shear, named here, the Eastern California shear zone. Because of its probable physical connection to the San Andreas fault system, the Eastern California shear zone may have accommodated a significant portion of Pacific-North American transform motion. The Eastern California shear zone accounts for 9-14% of the total shear, predicted from plate tectonic reconstructions, along the Pacific-North American transform boundary since ~10.6 Ma. The kinematic connection of the normal faults of the Death Valley region, with the San Andreas fault system via the faults of the Mojave Desert accords with the deduction of Atwater (1970) that late Cenozoic extension in portions of the Basin and Range province is related to Pacific-North American transform shear. Finally, the present arcuate trace of the Garlock fault is ascribed to oroclinal folding within the broad zone of distributed shear of the Eastern California shear zone.



Paper number 89TC02945
0278-7407/90/89TC-02945$10.00

## INTRODUCTION

Recent studies of the Mojave Desert Block (Figure 1) have demonstrated that the region was affected by two, major, nonsynchronous tectonic regimes in late Cenozoic time. The western and central portions of the Mojave were the site of major, detachment fault-dominated extension during early Miocene time (22-17 Ma)[Dokka, 1980, 1986, 1989ab]. Deformation was concentrated within the generally east trending Mojave Extensional Belt [Dokka, 1986, 1989a; Dokka and Woodburne, 1986; Dokka et al., 1988]. This belt originally opened in an approximately N-S direction but was subsequently rotated 30°-50° clockwise about vertical axes between ~20 and ~18 Ma [Dokka, 1989a; Ross et al., 1987, 1988, 1989; Golombek and Brown, 1988]. These events were followed by post-13 Ma deformation and rotation facilitated by right-slip faulting along dominantly NW striking faults [Dibblee, 1961; Dokka, 1983, this paper]. These faults are important because of their role in establishing the current structural grain and physiography of the region as well as for the seismic hazard that they pose to the ever expanding metropolitan areas of southern California [e.g., Wesnousky, 1986].

Hewett [1954] was the first to note the regional extent and pattern of late Cenozoic faults in the Mojave Desert Block, but he reckoned that their motions were mainly dip-slip. Dibblee [1961] recognized the right-slip character of the dominant NW striking faults and thought that they were related to the nearby San Andreas fault system. Subsequent workers have corroborated this observation and have recognized transpressional and transtensional structures [Dokka, 1976; Morton et al., 1980; Dokka, 1983] and strike-slip earthquakes [Hill and Beeby, 1977; Sauber et al., 1986]. Figure 2 shows the location of late Cenozoic strike-slip faults and associated structures of the Mojave Desert Block.

Several models have been set forth to explain the tectonic setting of strike-slip faults of the Mojave Desert Block. Garfunkel [1974] proposed that the Mojave Desert Block has been the site of regional simple shear during late Cenozoic time and that the NW striking faults facilitated the strain (Figure 3). About 100 km of distributed dextral shear and 30°-40° of regional counterclockwise rotation about a vertical axis of much of the Mojave Desert Block were predicted by his model. Carter et al. [1987] also embraced the regional simple shear concept and predicted, based on paleomagnetic measurements in other parts of southern California, that the western and southern Mojave was rotated 15° in a counterclockwise sense (Figure 3), that the northeastern Mojave was rotated clockwise ~40°, and that total distributed dextral shear across the region was ~100 km.

In this paper, kilometer-scale structural relationships are presented to more completely document the geometry and kinematics of the late Cenozoic, NW striking, right-slip faults of the Mojave Desert Block. These data are used to test explicit and implicit features of published kinematic models and form the basis of a new hypothesis proposed here for the late Cenozoic tectonic evolution of the Mojave Desert Block.

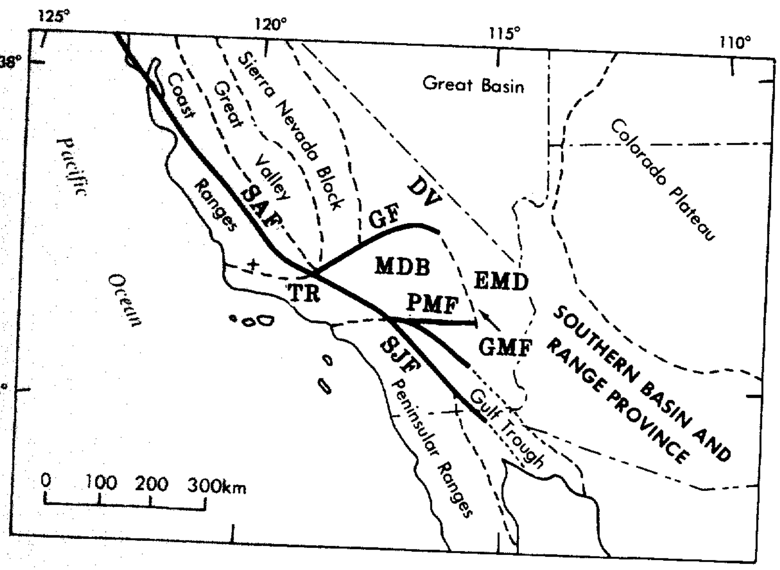



Fig. 1. Index map to the Mojave Desert region. DV, Death Valley; EMD, Eastern Mojave Desert Province; GF, Garlock fault; GMF, Granite Mountains fault; MDB, Mojave Desert Block; PMF, Pinto Mountain fault; SAF, San Andreas fault; SJF, San Jacinto fault; TR, Transverse Ranges.

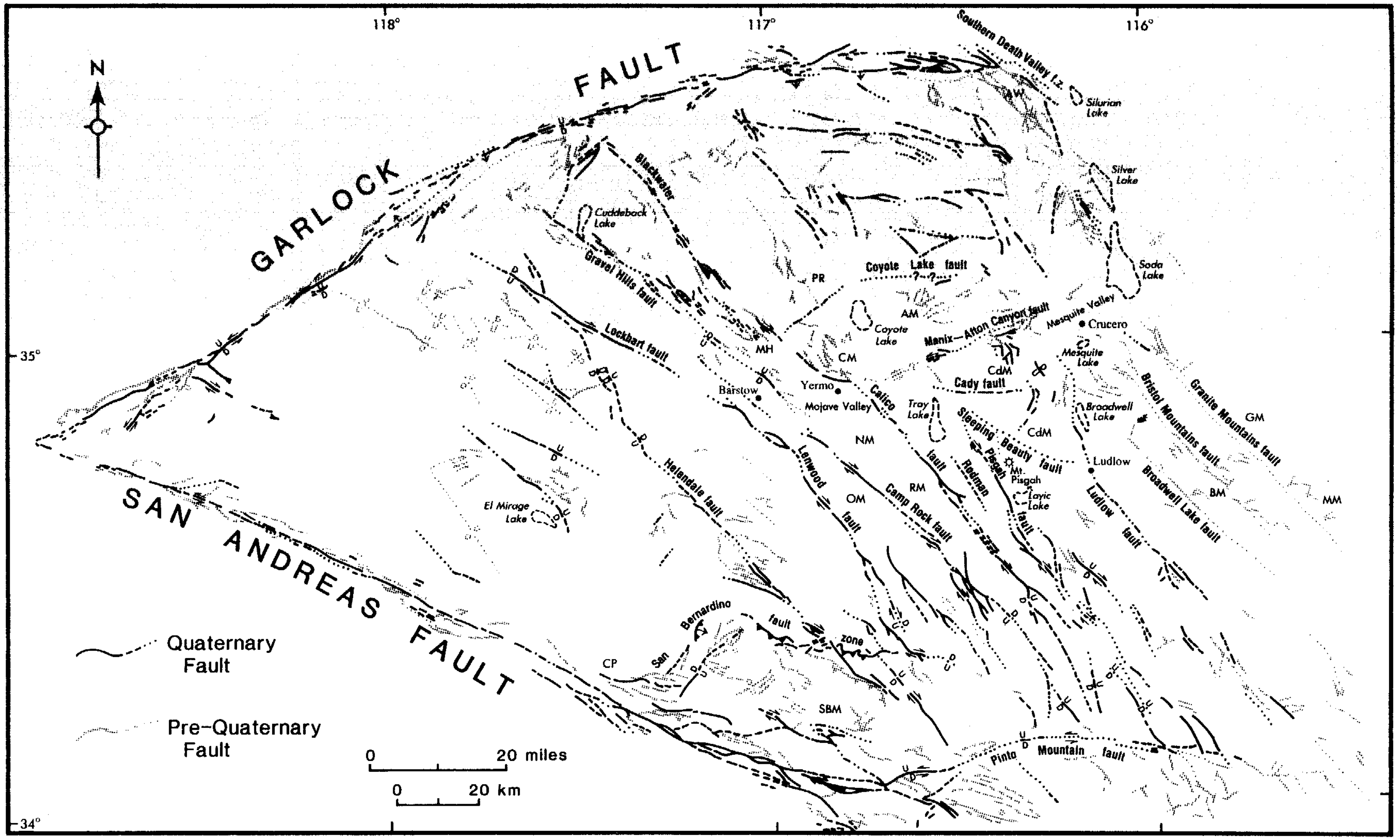



Fig. 2. Fault map of the Mojave Desert highlighting the location of late Cenozoic faults and associated features. AM, Alvord Mountains; AW, Avawatz Mountains; BM, Bristol Mountains; CM, Calico Mountains; CdM, Cady Mountains; CP, Cajon Pass; GM, Granite Mountains; MH, Mud Hills; MM, Marble Mountains; NM, Newberry Mountains; OM, Ord Mountain; PR, Paradise Range; RM, Rodman Mountains; SBM, San Bernardino Mountains.

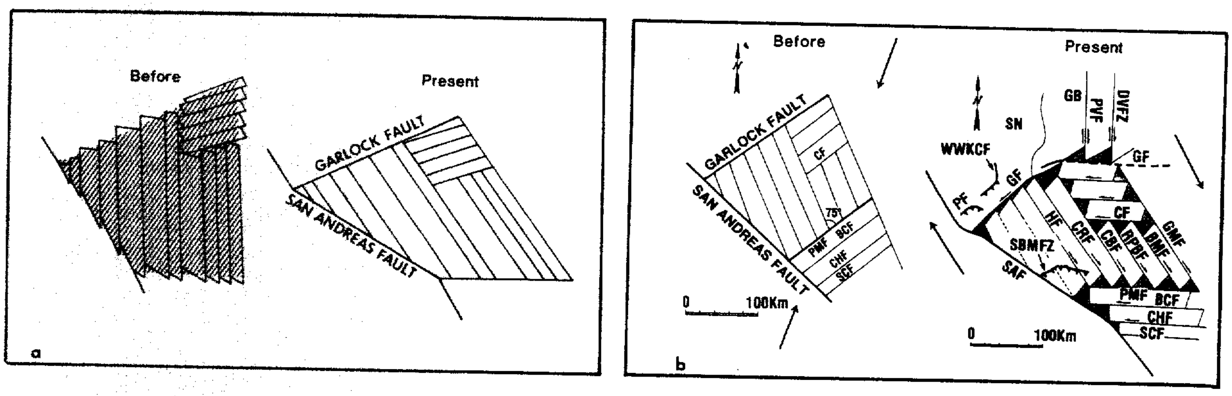



Fig. 3. Models for the late Cenozoic tectonic evolution of the Mojave Desert Block. (a) Garfunkel [1974]. (b) Carter et al. [1987]. PMF, Pinto Mountain fault; BCF, Blue Cut fault; CHF, Chiriaco fault; SCF, Salton Creek fault; GMF, Granite Mountains fault; BMF, Bristol Mountains fault; RPBF, Rodman/Pisgah/Bullion fault system; CBF, Blackwater/Calico fault system; CRF, Camp Rock fault; HF, Helendale fault; SAF, San Andreas fault; SBMFZ, San Bernardino Mountains fault zone; PF, Pleito thrust system; WWKCF, White Wolf-Kern Canyon fault; GF, Garlock fault; DVFZ, Death Valley fault zone; PVF, Panamint Valley fault; CF, Cady fault; SN, Sierra Nevada batholith; GB, Great Basin.

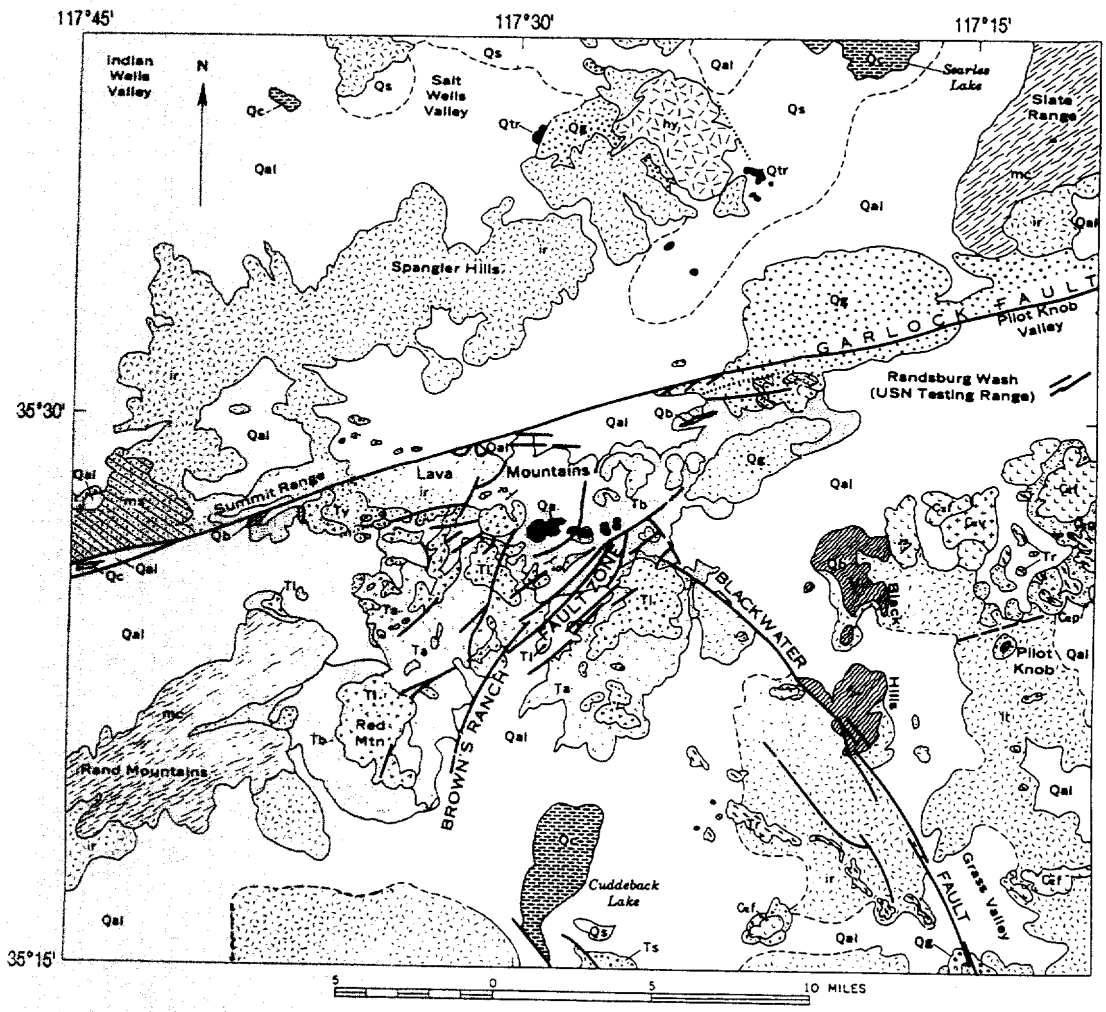



Fig. 4. Geologic map of the northern Lava Mountains [after Smith, 1964] showing the northern termination of the Blackwater fault.

## GEOLOGIC CONSTRAINTS

### *Continuity of NW Striking Faults and Relationship to the Garlock Fault*

A critical feature of simple shear-based models for the Mojave is that all NW striking right-slip faults must span the entire province and merge to the north with the Garlock fault (Figure 3). In order that simple shear occur, the NW striking faults must be able to freely slip and rotate between intact northern (Garlock fault) and southern (Pinto Mountain fault) boundaries. Field mapping indicates, however, that most NW striking faults lack lateral continuity and that only the Calico fault and its possible northwestern continuation, the Blackwater fault, can be argued to cross the entire region (Figure 2). Although a Calico-Blackwater connection beneath Mojave Valley is strongly suspected [Dibblee, 1970; Morton et al., 1980], the Blackwater fault ends a few kilometers short of the Garlock fault. The north end of the Blackwater is cut by WSW striking faults that are in turn buried by older Quaternary alluvium (Figure 4)[Smith, 1964]. These relations suggest that the Calico-Blackwater fault once spanned the entire region but is no longer active at all points along its trace or, alternatively, that strain is transferred to the Garlock fault in some complex fashion.

Perusal of regional geologic maps [Dibblee, 1967a; Jennings, 1977] and Landsat Thematic Mapper imagery of the areas south of the Garlock indicates that none of the other NW striking right-slip faults of the Mojave Desert Block continue to and merge with the Garlock fault. The other recently active fault of the northwestern Mojave, the Gravel Hills-Harper Lake fault, apparently terminates in a zone of extension in Cuddeback Lake (Figure 2).

### *Fault Slip*

Measurements of fault slip permit testing of predicted and implied kinematic features of simple shear models proposed for the Mojave Desert Block. In this analysis, both individual net slips and combined regional slip are compared. These data allow us to see whether the individual faults that are thought to facilitate simple shear display homogeneous slip along strike. Such uniformity of movement is an inherent property of materials deformed in simple shear [e.g., Ramsay and Huber, 1983].

Structures of the now disrupted early Miocene Mojave Extensional Belt provide regional markers with which to measure the net slip on many faults of the central Mojave Desert. Dokka [1983] used offset segments of the early Miocene Kane Spring transfer fault to determine displacements on NW striking faults south of Barstow. These data as well as other published displacement data on faults north of Barstow are given in Table 1. Net slip values of zero

Fig. 4. (continued)

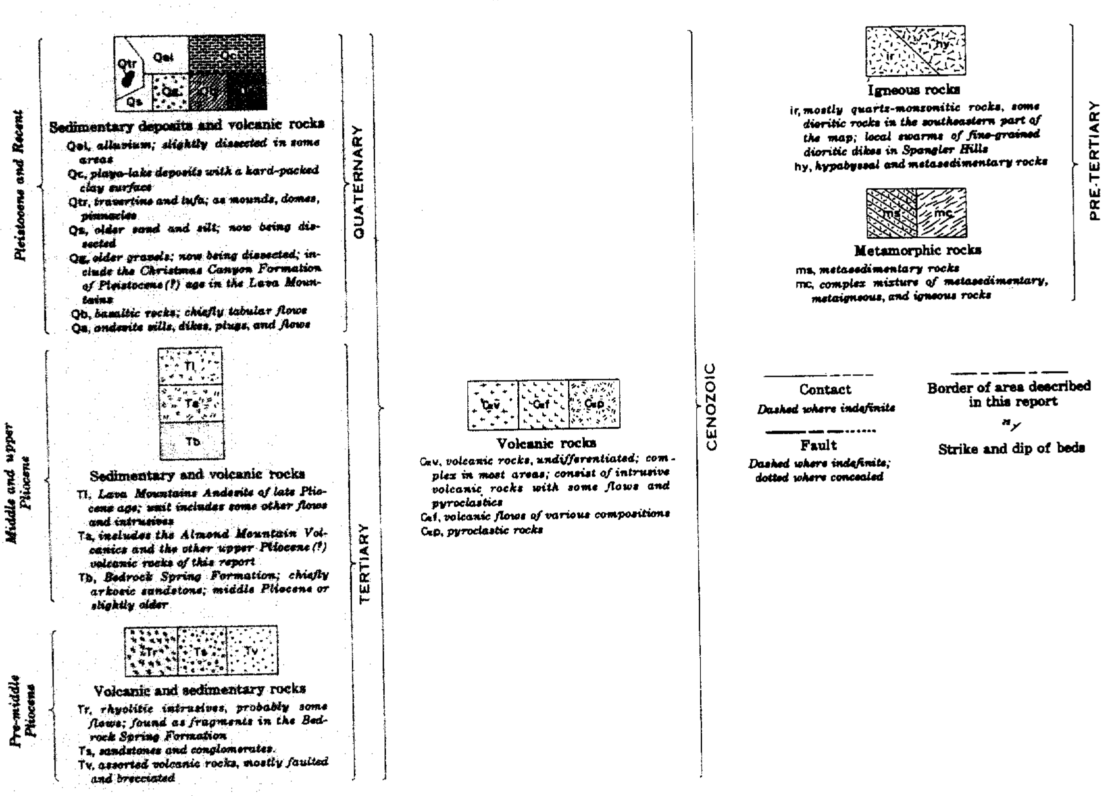


TABLE 1. Observed and Predicted Net Slip Values for Late Cenozoic Strike-Slip Faults of the Mojave Desert Block

| Fault | Observed | Simple Shear Model [a] | This Paper |
|---|---|---|---|
| NW Striking Faults | | | |
| Faults south of Barstow | | | |
| Helendale | 3.0[b] | 10-15 | 2.5 |
| Lenwood | 1.5-3.0[c] | 15-20 | 1.5 |
| Camp Rock | 1.6-4.0[c] | 10 | 3.0 |
| Calico-Blackwater | 9.6[c,d] | 10-20 | 10.0 |
| Rodman-Pisgah | 6.4-14.4[c] | 20-40 | 10.5 |
| Ludlow | small?[c] | 0 | 2.0 |
| Broadwell Lake | ? | 0 | 0.5 |
| Bristol Mountains | >6.0[e] | 0 | 13.5 |
| Granite Mountains | ? | 0 | 21.5 |
| Cumulative Net Slip | 28.1-40.0+? | 65-105 | 65.0 |
| Faults north of Barstow | | | |
| Calico-Blackwater | 8.5[f] | 10-20 | 10.0 |
| Gravel Hills-Harper Lake | <3.2[g] | 10 | 0 |
| Lockhart | >0[h] | 15-20 | 0 |
| Cumulative Net Slip | >11.7 | 35-50 | 10.0 |
| Faults near the Garlock fault | | | |
| Calico-Blackwater | ≤1.6[g] | 10-20 | 0 |
| Gravel Hills-Harper Lake | 0[h] | 10 | 0 |
| Lockhart | 0[h] | 15-20 | 0 |
| Cumulative Net Slip | ≤1.6 | 35-50 | 0.0 |
| Other Faults [i] | | | |
| Cady | <1 | large | <1 |
| Manix | | | 12.5 |
| Coyote Lake | | | 12.5 |

All values are kilometers.

[a] Garfunkel [1974].

[b] Miller and Morton [1980].

[c] Dokka [1983].

[d] Includes 1.4 km of right shear expressed as strain.

[e] Miller et al. [1982] documented >6 km of right separation.

[f] Dokka [1989] documents 8-9 km of right separation in the Calico Mountains-Mud Hills.

[g] Estimate of right-lateral displacement by Dibblee [1968].

[h] R. Dokka [unpublished data, 1988].

[i] Left-slip faults.

are assigned to the ends of all faults that terminate within the Mojave Desert Block.

Three important relationships are revealed by the data in Table 1. There is a significant difference in the combined amount of slip between the faults south of Barstow and their projected counterparts in the northwestern Mojave. The combined net slip for the southern faults (Helendale to Ludlow) is 22-34 km [Dokka, 1983], whereas the sum of slips on northern faults is only ~12 km. Further to the north in the area just west of the Blackwater fault and south of the Garlock fault, the combined net slip is <2 km. There is also a major discrepancy of net slip values on individual southern faults and their projected counterparts in the north. The most striking example is the large displacement Rodman-Pisgah fault, which has no counterpart north of Troy Lake (Figure 2). Finally, only the Calico-Blackwater fault shows similar net slip values along most of its length. This fault, however, also apparently ends near the Garlock fault. The data above indicate that all of the NW striking faults of the Mojave do not display uniform slip along their strike as required by simple shear models.

The precise timing of the onset of right-shear across the Mojave Desert Block is difficult to ascertain but can be constrained by cross cutting relations exposed in the province and in surrounding areas. All late Cenozoic strike-slip faults of the central and eastern Mojave truncate 20 Ma or older rocks and structures of the Mojave Extensional Belt [Dokka, 1983, 1989a]. Exposed geologic markers of appropriate ages (i.e., Miocene and younger sediments deposited just before faulting) are few or as yet unrecognized in the region. The best evidence available for the age of initiation of faulting in the central Mojave is in the Calico Mountains-Mud Hills area along the Calico-Blackwater fault [Dokka, 1989a, Figure 8c], where the youngest dated rocks that are displaced the full amount belong to the lower and middle Miocene Barstow Formation. Dating of a tuff from near the top of this unit yielded an $^{40}Ar$-$^{39}Ar$ single-crystal fusion date on biotite of 13.4±0.2 Ma [MacFadden et al., 1990], which establishes an upper limit on the age of movement on the Calico-Blackwater fault. Cross cutting relations in the San Bernardino Mountains suggest that shears belonging to the currently active family of NW right-slip faults of the Mojave Desert Block were initiated between 1.5 and 0.7 Ma [Meisling and Weldon, 1989]. Carter et al. [1987] inferred that shearing of the Mojave is late Miocene or younger based on the age of the youngest rocks (10.2±2.0 Ma) involved in shear-related rotation of the eastern Transverse Ranges. Age relations established on NW striking, right-slip faults of the adjacent Death Valley region [Stewart, 1983] suggest that faulting in the Mojave may have begun as recently as late Miocene (~6 Ma). In summary, regional right shear across the Mojave Desert Block was most likely imposed in late

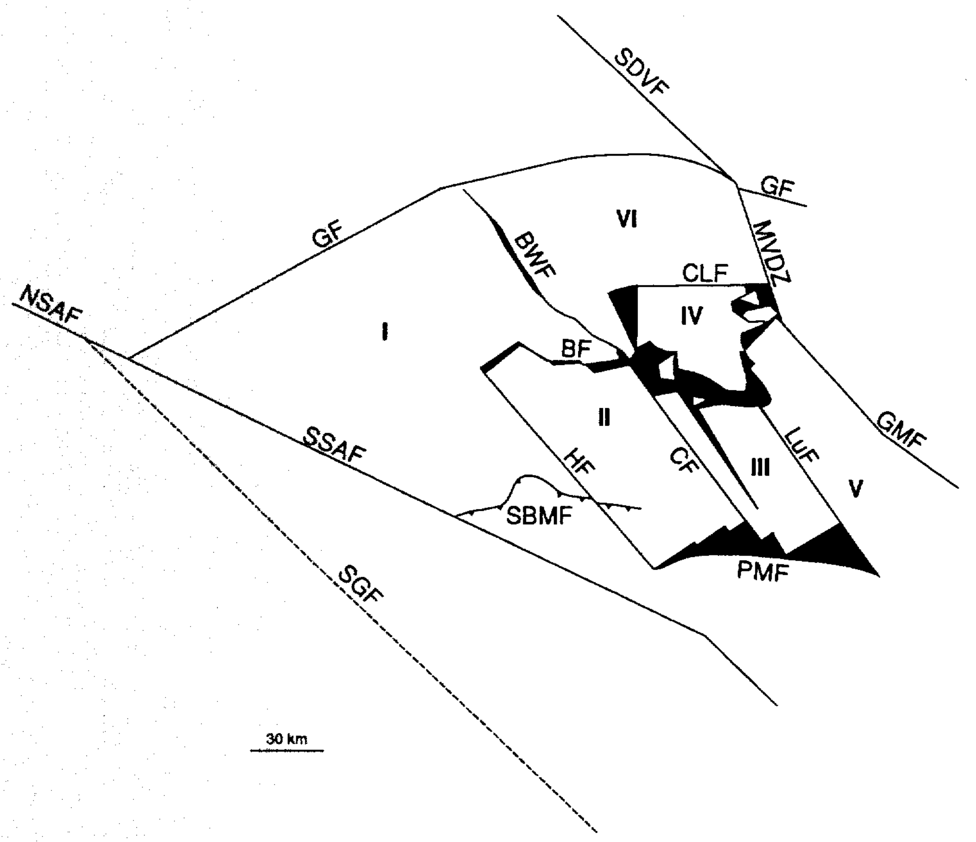



Fig. 5. Domain map. NSAF, northern San Andreas fault; SGF, San Gabriel fault; SSAF, southern San Andreas fault; GF, Garlock fault; HF, Helendale fault; BF, Barstow fault; BWF, Blackwater fault; CF, Calico fault; PMF, Pinto Mountain fault; CLF, Coyote Lake fault; SBF, Sleeping Beauty fault; LuF, Ludlow fault; GMF, Granite Mountain fault; MVDZ, Mesquite Valley disturbed zone; SDVF, Southern Death Valley fault zone. Shaded areas are zones of extension created by fault motions and block rotations.

Miocene time (~10-6 Ma); movement along the presently active faults of the south-central Mojave was initiated between 1.5 and 0.7 Ma.

*Faulting and Regional Strain Pattern*

Geologic and historic deformation indices suggest that late Cenozoic strain in the Mojave Desert Block is not concentrated in two major zones as predicted by Garfunkel [1974] and Carter et al. [1987](Figure 3) but is instead partitioned into six smaller domains. Each domain is defined on the basis of geometry and style of faulting, rotational history, and timing of tectonic activity. The characteristics of these domains are discussed below. The locations of these domains and major boundary fault zones of the Mojave Desert Block are shown in Figure 5.

Field mapping shows that all major NW striking fault zones of the Mojave Desert Block except the Calico-Blackwater fault terminate or become discontinuous in the central part of the province north of an irregular line extending eastward from near Barstow to near Ludlow and continuing north-northeast to Soda Lake (Figure 2). Domain I includes the area north of this line and west of the Calico-Blackwater and Helendale faults (Figure 5). The NW striking faults of Domain I are most continuous along their southern segments but gradually become less ordered and eventually die out to the north (Figure 2). The paucity of earthquakes (Figure 6; C. H. Jones, written communication, 1989) and the lack of horizontal deformation of the Barstow regional strain network during the period 1979-1983 [King, 1985], argue that present-day lateral movements along faults of Domain I are small or nonexistent. We conclude, therefore, that this domain has not been significantly deformed nor is it involved in a major way in the present-day deformation of the Mojave Desert Block.

In contrast, fault zones lying south of the Barstow-Ludlow-Soda Lake line are well developed and can be traced southward to the San Bernardino Mountains [Dibblee, 1982; Sadler, 1982; Meisling and Weldon, 1989] and to near the Pinto Mountain fault [Jennings, 1977; Morton et al., 1980]. These faults are included in Domains II, III, and V. Earthquake activity (Figure 6; C. H. Jones, written communication, 1989), ground rupture along the faults [Hill and Beeby, 1977; Morton et al., 1980; Dokka and Woodburne, 1986], and distortion of the Mojave regional strain network [Sauber et al., 1986] indicate that faults of Domains II and III are currently active. Faults of Domain V are overlain by undated (probable late Quaternary) alluvium and are thus dead or have very long recurrence intervals [Davis, 1977; Miller et al., 1982; Brady, 1988; Brady and Dokka, 1989; Ford et al., 1989].

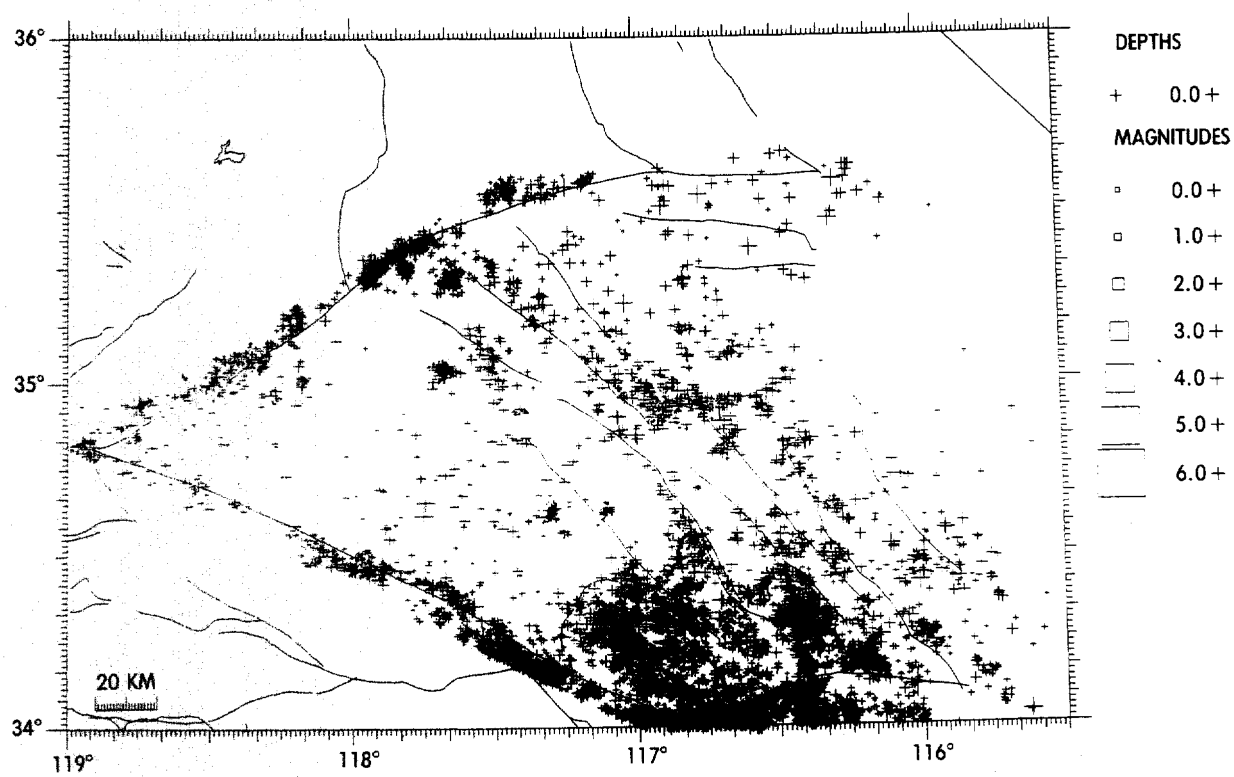



Fig. 6. Seismicity in the Mojave Desert during the period 1977-July 1989 (event qualities A, B, C) [C. H. Jones, written communication, 1989].

Domains II, III, and V are dominated by NW striking, right-slip faults (Figure 2) and are differentiated on the basis of the magnitude of strain and by the age of faulting. Domain II is located in the southern portion of the Mojave Desert Block and includes the area between the Helendale and Calico faults (Figure 5). The northern boundary of Domain II is marked by a series of young basins along the valley of the Mojave River. These basins are separated by zones of shortening which occur at the northern terminations of NW striking faults. For example, in the northern Newberry Mountains the Camp Rock fault changes from NW striking to WNW striking and becomes an oblique slip fault with dominantly reverse displacement (Figure 7a). Mesozoic crystalline basement rocks are thrust to the north over middle Miocene Barstow Formation (Figure 7b). Similarly, the Lenwood fault apparently ends in a zone of shortening near the Lenwood anticline, an east trending arch that contains folded strata as young as Quaternary (Figure 8)[Dibblee, 1967a]. Significant Quaternary or older alluvial deposition has occurred between the areas of shortening. Evidence for this can best be seen along the northern flank of the Newberry Mountains where several generations of Holocene and older alluvial fans have built northward away from the range (Figures 7 and 9). Multiple phases of relative uplift and denudation must have occurred judging from the presence of outliers of fan material in higher parts of the range that consist of clasts exotic to the area [Dokka, 1980]. The older fans contain gravels of pre-Tertiary marble, schist, and granitic rocks that are similar to outcrops found in the Ord Mountain district, located ~20 km to the south (Figure 2). Dissected older fans and an exhumed pediment (Figure 9) are consistent with relative uplift along the range front. The southern boundary of Domain II with the eastern Transverse Ranges is characterized by a series of triangular-shaped basins along the Pinto Mountain fault (Figure 2).

Faults of Domain II are active and accommodate much of the current shear strain ($0.16\pm0.03 \times 10^{-6}$ $yr^{-1}$) across the Mojave Desert Block [Sauber et al., 1986]. Shear across this domain accounts for ~12% of the 56 mm $yr^{-1}$ of present-day relative motion between the Pacific and North American plates [Sauber et al., 1986]. The integrated slip across Domain II is ~7 km (not including Calico fault; Table 1).

Relationships in the San Bernardino Mountains summarized by Meisling and Weldon [1989] provide an important clue on the timing of deformation of Domain II. The northern range front thrusts of this area both truncate [Shreve, 1968; Sadler, 1981] and are cut by NW striking, vertical, right-slip faults of the Mojave Desert [Sadler, 1981; Meisling, 1984]. Meisling and Weldon [1989] conclude that the Sky High Ranch fault and, by inference, the Helendale fault and the Old Women Springs strand of the Lenwood fault were initiated between ~1.5 Ma and 0.7 Ma (Pleistocene) and have continued to be active up to the present. These relations are illustrated on Figure 10.

The throughgoing Calico-Blackwater fault separates Domains II and III. The northern boundary of Domain III is marked by Troy Lake, a large basin located between the Cady Mountains and Newberry Mountains [Groat, 1967](Figure 2), and by several other Quaternary basins along Interstate 40 (Lavic Lake, Hector, Argos). These basins are the site of several Quaternary volcanic centers, the most recent of which is the Pisgah basanitic basalt shield volcano (Figures 2 and 11)[Wise, 1969]. The NW-striking faults of Domain III, such as the Rodman-Pisgah fault system, cannot be traced into or beyond these bounding basins. The southern boundary, like that of Domain II, is marked by triangle-shaped depressions adjacent to the Pinto Mountain fault. Domain III is currently active and has been the site of 16-24 km of right slip (Table 1).

Reconnaissance paleomagnetic declination studies by Wells and Hillhouse [1989] imply that rocks of Domains II and III have rotated by a small amount since 19 Ma. Declination anomalies range from $13.1°\pm5.0°$ (clockwise) to $10.1°\pm3.7°$ (counterclockwise). Carter et al. [1987] produced a summary declination vector for this region using data from Burke et al. [1982] and J. Morton and J. Hillhouse (unpublished data, 1987) that suggests $15°\pm11°$ net counterclockwise rotation of the southern Mojave Desert Block since middle Miocene time. These data are in clear conflict with the model of Garfunkel [1974] that predicted a large (30°-40°) counterclockwise rotation of the area of Domains II and III.

Domain IV includes the Cady Mountains-Alvord Mountains vicinity and is bounded by the Coyote Lake fault on the north, Troy Lake on the west, by the proposed Mesquite Valley disturbed zone (described below) on the east, and by a suspected WNW trending fault south of the Sleeping Beauty area of the southern Cady Mountains (Figures 2 and 11). The domain is cross cut by the currently active left-slip Manix-Afton Canyon fault zone [Bulwalda and Richter, 1948; Richter, 1949; Keaton and Keaton, 1977; Weldon, 1982, McGill et al., 1988] and the Pleistocene Cady fault (Figures 2, 11, and 12). Richter [1949] produced a focal plane solution for the 1947 Manix earthquake ($M = 6.2$) indicating either left-slip on an ENE striking vertical fault (Manix fault) or right-slip on a hypothetical, buried NNW shear. Left-slip (<1 km) is also suspected on the Cady fault based on the offset of rock bodies and by the arrangement of faults and associated topographic character (Figures 11 and 12).

Paleomagnetic declination data from the Cady Mountains [MacFadden et al., 1990b] suggest that Domain IV has rotated 26° in a clockwise sense in the past ~16 Ma. In contrast, paleomagnetic studies of ~18-19 Ma tuffs in the southern tail of the Cady a)

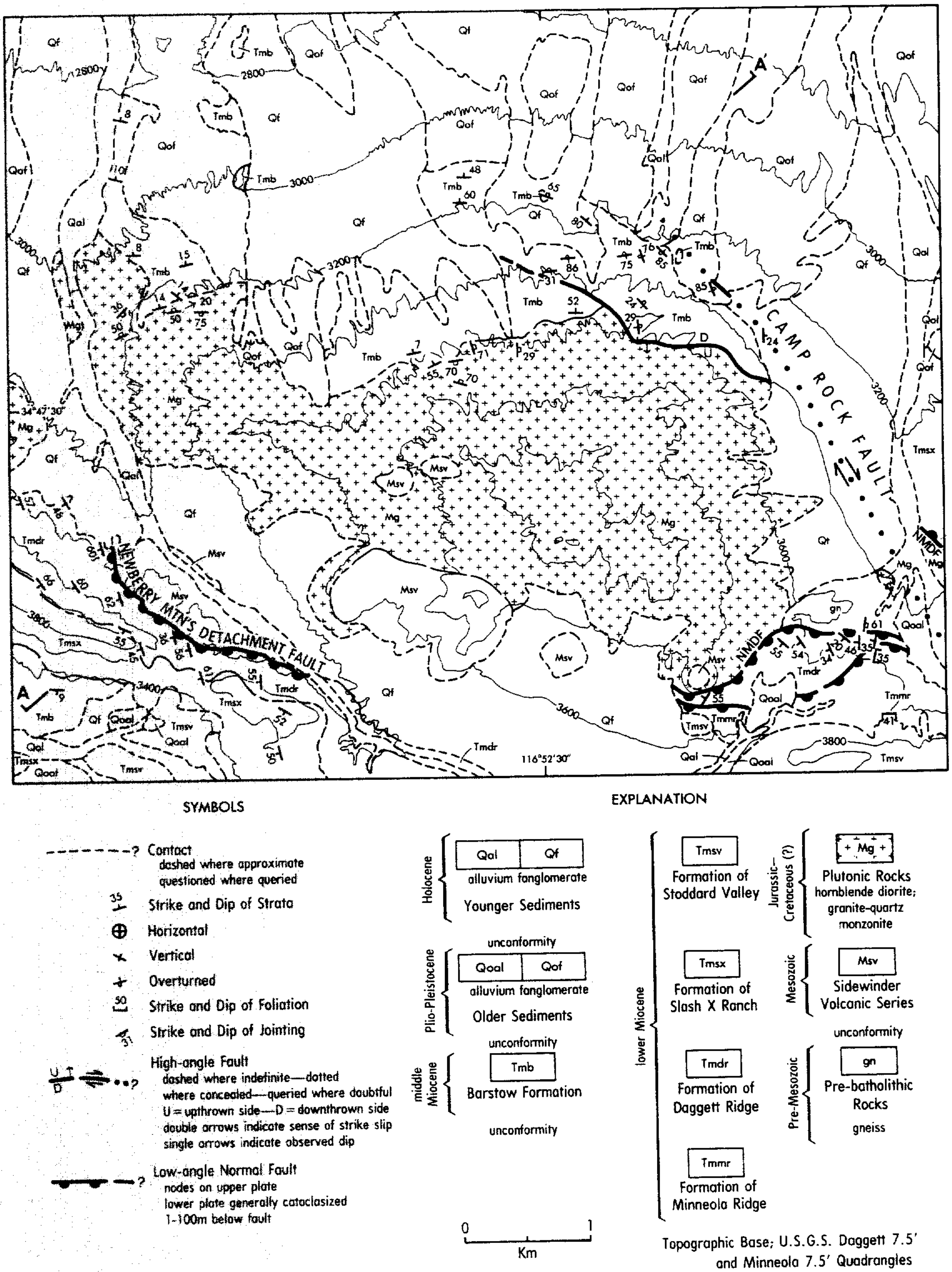



Fig. 7. (a) Geologic map and (b) structure section of the western Newberry Mountains. The Newberry Mountains detachment (NMDF) is a low-angle normal fault that was active between ~22 and 20 Ma [Dokka, 1986, 1989ab]. Middle Miocene (16-13 Ma) Barstow Formation unconformably overlies the detachment and lower plate rocks. The Camp Rock fault is a later structure that cuts rocks and sediments as young as late Quaternary along its trace. Note the dissected Quaternary older fans along the northern flank of the range.

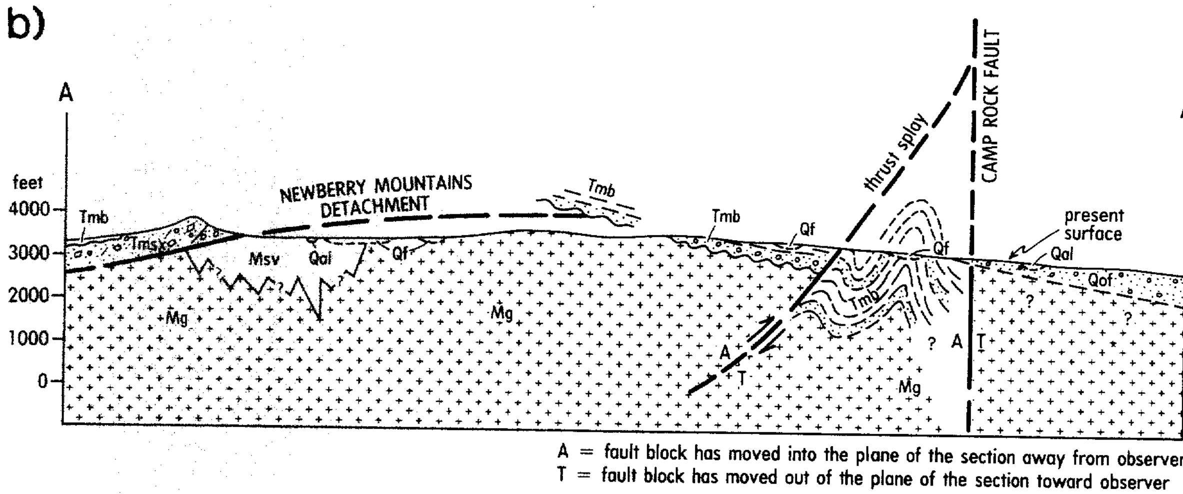



Fig. 7 (continued)

Mountains by Wells and Hillhouse [1989] yielded a post-early Miocene declination anomaly of only 11.6°±4.2° (clockwise). We attribute this difference to drag effects along the proposed left slip Sleeping Beauty fault. As Domain IV rotated ~26° clockwise, its southern boundary (Sleeping Beauty fault) experienced left shear, resulting in local counterclockwise rotation near the fault. Field evidence for the existence of the proposed Sleeping Beauty fault includes the alignment of truncated spurs (Bassett and Kupfer [1964] and this paper, Figures 11 and 13) and the occurrence of associated shortening structures developed in Miocene through Quaternary strata along the southern Cady Mountains. The arrangement of these faults and folds relative to the WNW trending line of truncated spurs are reminiscent of a left-slip fault zone. For example, Durrell [1953], mapped a family of N40°W striking, SW dipping reverse faults and NW trending folds along the southernmost portion of the Cady Mountains; these faults die out to the northwest [Dibblee and Bassett, 1966a b; Dibblee, 1967b; Glazner, 1981]. The gradual deflection of strikes of lower Miocene strata from NW to WNW on approach to the Sleeping Beauty fault is consistent with local counterclockwise rotation associated with left shear (Figure 13).

Domain V lies between the Ludlow and Granite Mountains faults and south of the proposed Mesquite Valley disturbed zone (Figure 5). The locations of mapped faults of Domain V, as well as the newly discovered Broadwell Lake fault [Ford et al., 1989], are shown on Figures 2 and 11. Neither the Ludlow fault nor the Broadwell Lake fault can be traced through Broadwell Lake, whereas the Granite Mountains and Bristol Mountains faults end north of the Bristol Mountains in the Mesquite Valley disturbed zone (Figures 5 and 11). Paleomagnetic declination vector studies on ~18.6 My Peach Springs tuff by Wells and Hillhouse [1989] suggest that Domain V is not rotated.

The Mesquite Valley disturbed zone is a sinuous belt of basins that occurs between Ludlow and Soda Lake (Figure 2). Some of the depressions, such as Broadwell Lake, Soda Lake, and Mesquite Lake, are associated with active or recently active east to NE striking, normal faults and/or NW striking, strike-slip faults [Brady, 1988; Dibblee, 1967b; Ford et al., 1989]. Other NE and NW trending lineaments interpreted as faults can also be seen in the Crucero area on Landsat thematic mapper imagery [Ford et al., 1989]. The Mesquite Valley disturbed zone coincides with a major topographic trough and hence perhaps with a region of thinned crust. This trough includes Soda Lake (bolson of the Mojave drainage system [Blackwelder, 1954; Weldon, 1982]), the Mojave River Sink, Mesquite Lake, and Broadwell Lake; the surface elevations of these basins are 282, 338, 340, and 399 m, respectively. This sinuous depression is about 0.5 km lower than the average elevation of the surrounding Mojave Desert [Strange and Wollard, 1964]. The Mesquite Valley disturbed zone also correlates with a portion of the surface trace of a ridge or hinge on the Moho which has a relief of ~2.5 km [Fuis, 1981]. The association of a shallow Moho, topographic depression, and normal faulting suggests an extensional or transtensional origin for the Mesquite Valley disturbed zone.

Domain VI occupies the extreme northeastern corner of the Mojave Desert Block between the Garlock, Calico-Blackwater, Coyote Lake, and Southern Death Valley fault zones (Figure 5). The structure of the area is poorly known because much of it lies within the Fort Irwin Military Reservation and the Goldstone Deep Space Communications Complex. Previous workers have emphasized the role played by a family of approximately east striking, left-slip faults in the deformation and

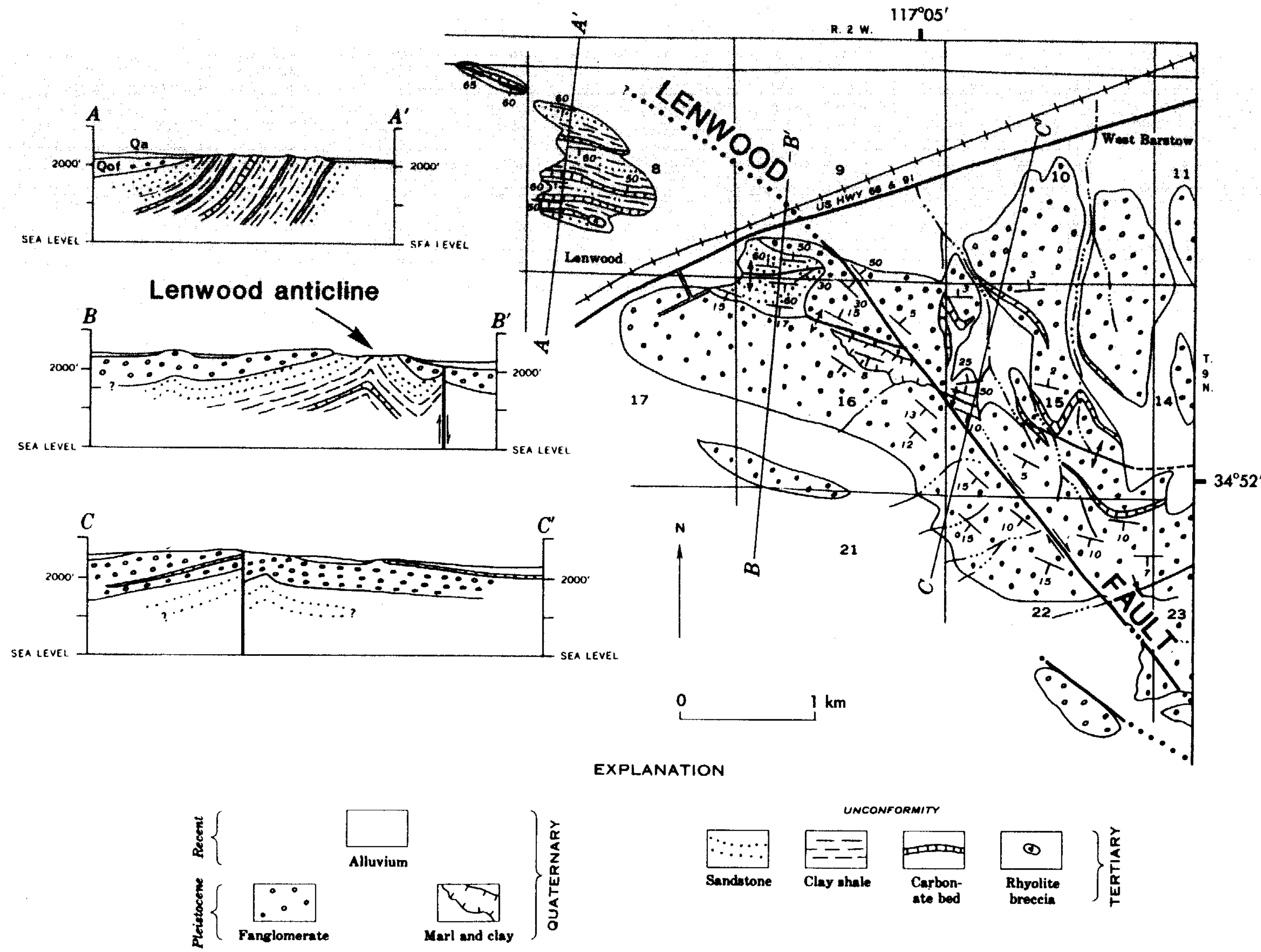



Fig. 8. Geologic map of the northern part of the Lenwood fault near Barstow [after Dibblee, 1967a].

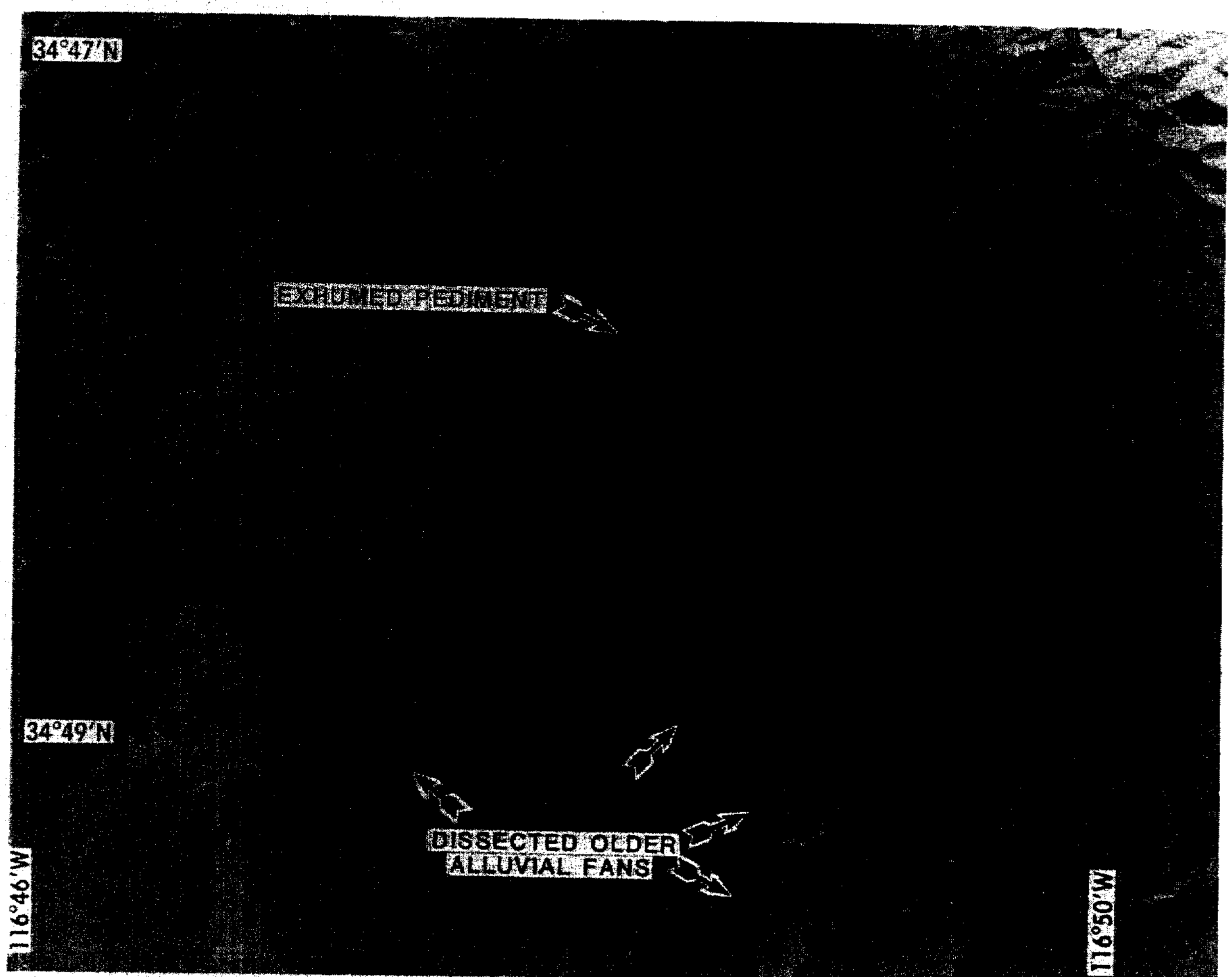



Fig. 9. Aerial photograph illustrating late Cenozoic alluvial fan formation and dissection along the northern flank of the Newberry Mountains.

rotation of the area [Garfunkel, 1974; Jennings, 1977; Luyendyk et al., 1980; Carter et al., 1987]. Garfunkel [1974], followed by Carter et al. [1987], assumed that these faults spanned the entire domain, from the Calico-Blackwater fault to the Silurian Valley-Soda Lake district (Figure 3). According to Jennings [1977], however, these faults cut only the central part of the domain. Garfunkel [1974] assumed that the faults were left-slip based on geometric similarities with the Manix fault. Our own field studies, augmented by Landsat Thematic Mapper and radar imagery, confirm the location and nature of these faults but suggest that numerous but previously unreported right-slip faults may be more important to the overall deformation [R. Dokka, J. Ford, R. Blom, R. Crippen, 1990, manuscript in preparation]. Right shear along NW striking faults subparallel to the Southern Death Valley fault zone is also suspected in the eastern half of the domain [Brady, 1988; Brady and Dokka, 1989]. The northern boundary of the domain, the eastern Garlock fault, has been dominated in late Cenozoic time by left shear [Smith, 1962; Davis and Burchfiel, 1973]. Late Miocene to Holocene ~N-S shortening and uplift has occurred near the intersection of the Garlock and the Southern Death Valley fault zone in the Avawatz Mountains [Troxel, 1970; Spencer, 1981, 1990; Brady, 1984; Brady and Verosub, 1984].

## DISCUSSION

Kilometer-scale structural relations presented above invalidate the models advanced by Garfunkel [1974] and Carter et al. [1987], who advocate regionally distributed simple shear for the development of the Mojave Desert Block during late Cenozoic time. Although there can be no doubt that

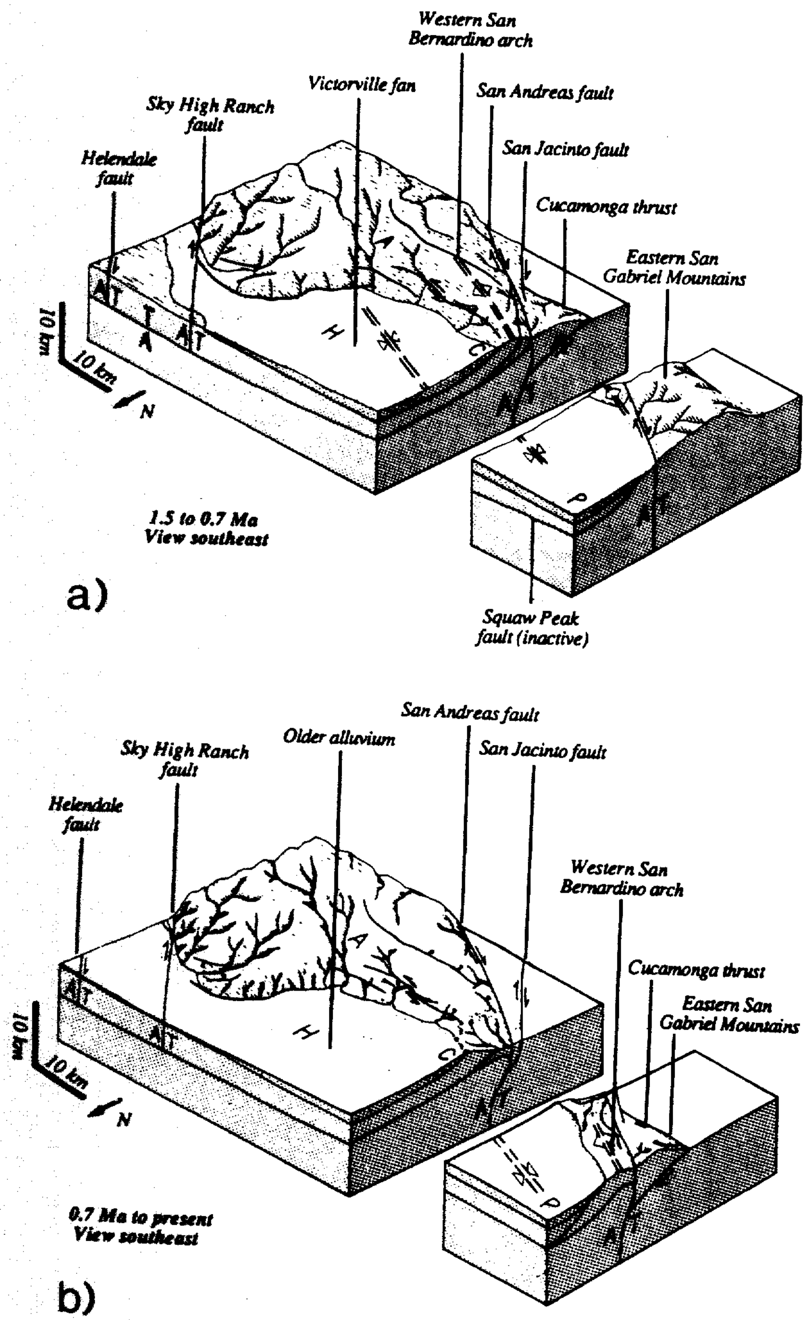



Fig. 10. Paleotectonic block diagrams illustrating the relationship of late Cenozoic shortening-related structures of the San Bernardino Mountains and strike-slip faults of the adjacent Mojave Desert Block [from Meisling and Weldon, 1989]. (a) 1.5-0.7 Ma. (b) 0.7 Ma to present. A, Arrowhead; C, Cajon; H, Hesperia; P, Phelan.

much of the Mojave has been the site of significant NW-SE right shear, long-term and historic strain indices show that deformation has not been homogeneous as required by simple shear but instead suggest that strain is regionally heterogeneous and is partitioned into six smaller domains. Previous models also fail to correctly predict observed fault geometries and net slip values on individual faults. Garfunkel [1974] and Carter et al. [1987] predicted correctly, however, the general amount and sense of

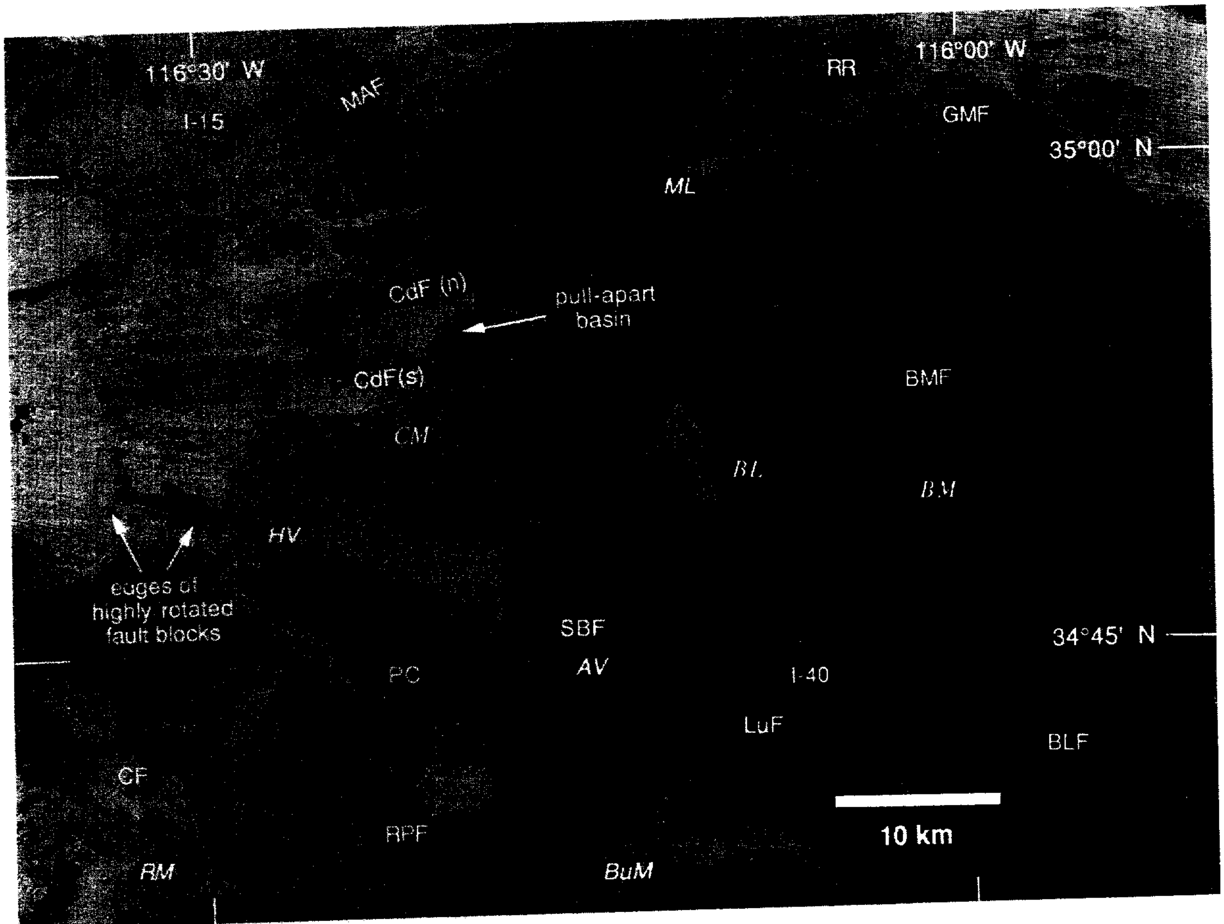



Fig. 11. Landsat thematic mapper image of the Cady Mountains and surrounding areas highlighting the locations of known and newly recognized strike-slip faults and related structures. Light, east trending streaks on west central portion of image are aeolian sand deposits. AV, Argos Valley; BL, Broadwell Lake; BLF, Broadwell Lake fault; BM, Bristol Mountains; BMF, Bristol Mountains fault; BuM, Bullion Mountains; Cdf(n), north strand of Cady fault; Cdf(s), south strand of Cady fault; CF, Calico fault; CM, Cady Mountains; GMF, Granite Mountains fault; HV, Hector Valley; LuF, Ludlow fault; MAF, Manix-Afton Canyon fault; ML. Mesquite Lake; PC, Pisgah Crater; RM, Rodman Mountains; SBF, Sleeping Beauty fault. Other features: I-15, Interstate 15; I-40, Interstate 40; RR, railroad.

rotation about vertical axes of most crustal blocks and thus have provided important insights into the overall tectonic setting of the Mojave Desert Block.

We present an alternative model to explain the geological relations outlined above as well as other geologic and geophysical data. Our model seeks only to explain strains of the upper crust and does not address how deeper levels have behaved during deformation. We consider the Mojave Desert Block to be composed of six structural domains that have deformed and rotated in response to regional right shear. Each domain consists of one or more fault-bounded blocks. Individual blocks are defined by the faults described above. The proposed model is constrained by fault locations, fault net slips, apparent rotation of paleomagnetic declination vectors, present-day topography, and the position of rock units.

We first restored the blocks to prefaulting and prerotation positions using fault slip and paleomagnetic vector constraints. The geometry of and motion along unconstrained boundaries was then adjusted to eliminate geologically unexplained overlaps or gaps. Next, we ran the model forward to test how well it could predict topography, present-day deformation patterns, and geologic map relationships. Successive iterations of this procedure were performed to obtain a geometric best fit to observed relationships. Figure 14 illustrates the geometric and kinematic features of our model and

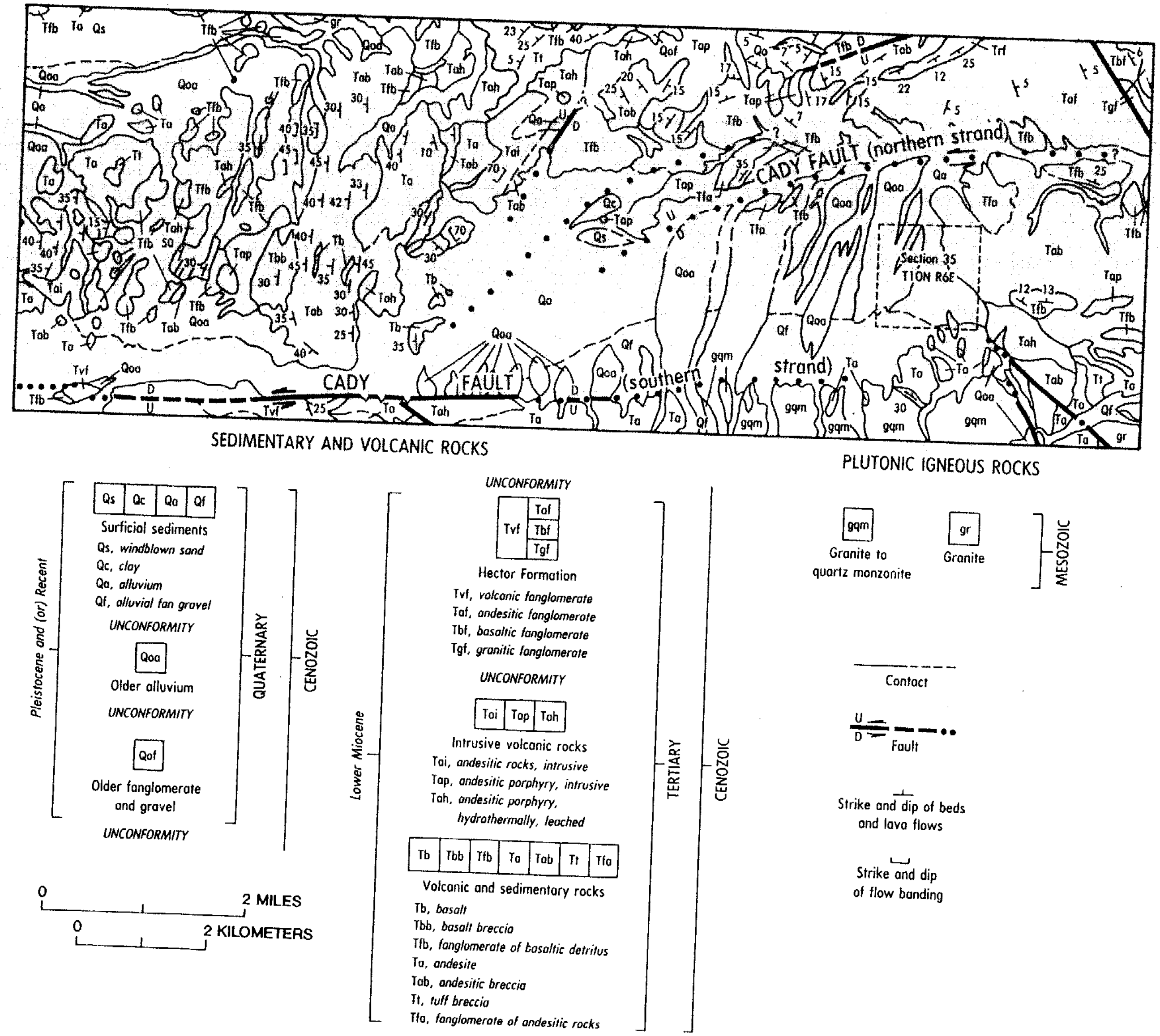



Fig. 12. Geologic map of the central Cady Mountains highlighting the left-slip Cady fault (modified from Dibblee and Bassett [1966a]). Compare with Fig. 11. Section 35 shown for location purposes.

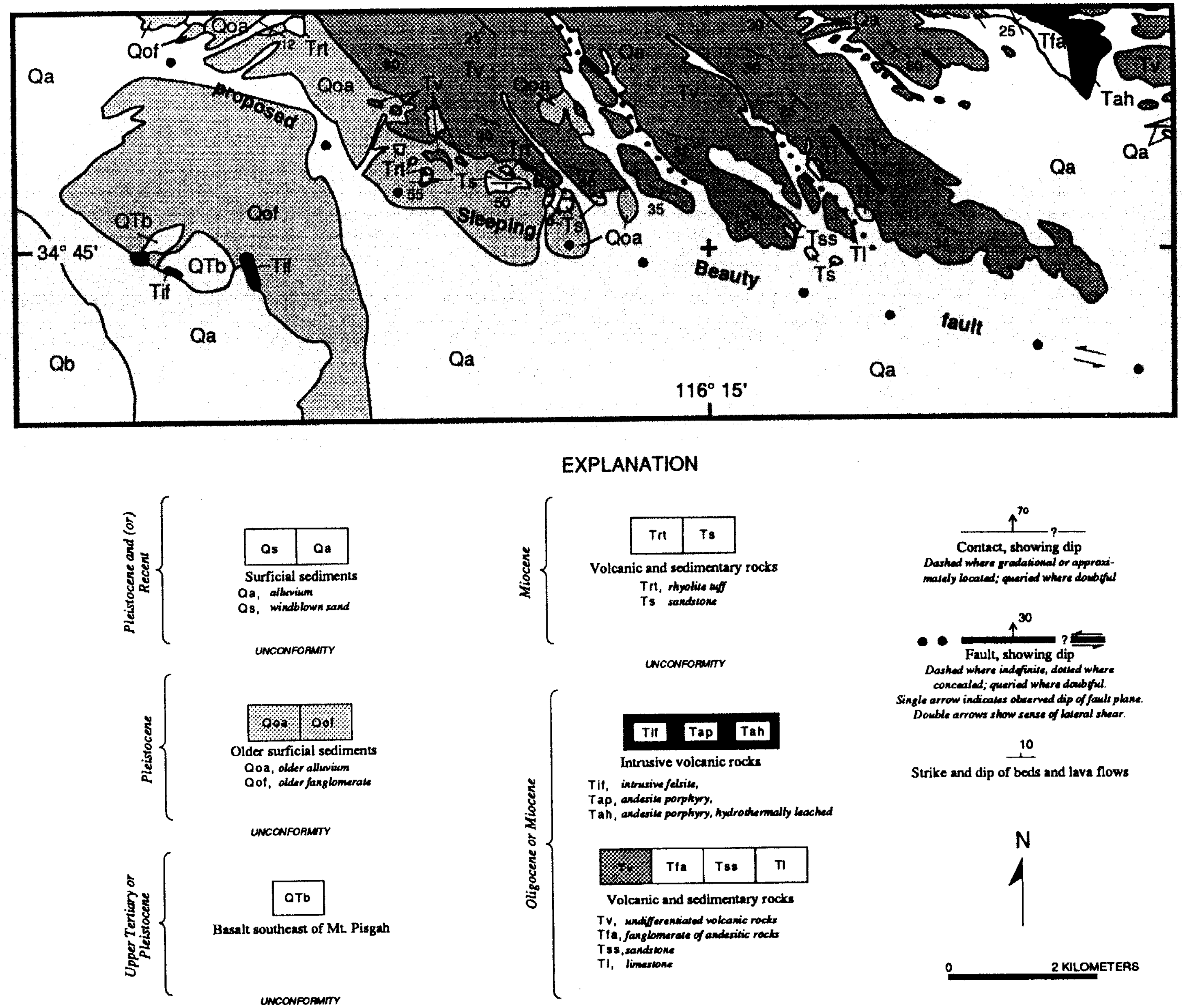



Fig. 13. Geologic map of the southern Cady Mountains showing the location of the proposed Sleeping Beauty fault and associated structures (modified from Dibblee [1966, 1967b, 1967c] and Dibblee and Bassett [1966b]).

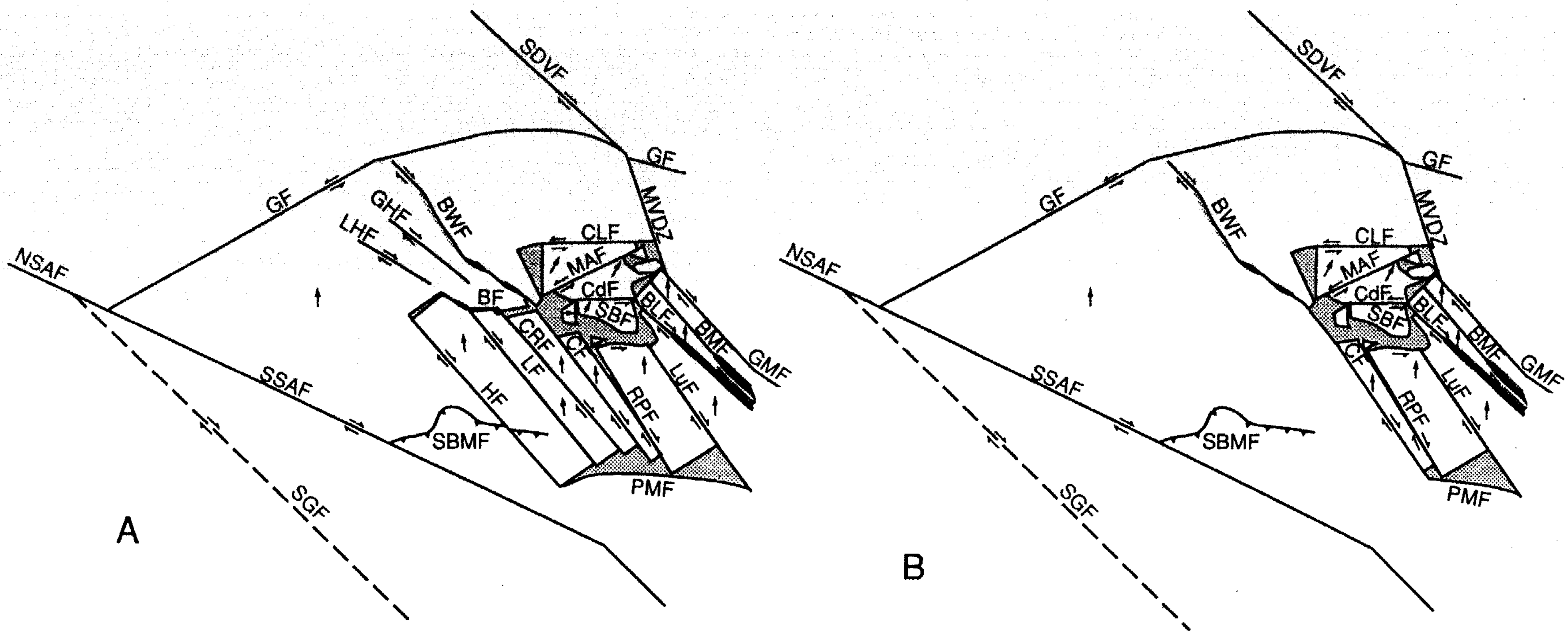



Fig. 14. Proposed kinematic model for the late Cenozoic evolution of the Mojave Desert. (a) Present-day configuration showing all late Cenozoic faults. (b) Intermediate step showing all faults active near 1.5 Ma. (c) Prefaulting (late Miocene) restoration of structural blocks. Solid black indicates areas of extension and stippled pattern areas of shortening. BF Barstow fault; BLF, Broadwell Lake fault; BMF, Bristol Mountains fault; BWF, Blackwater fault; CdF, Cady fault; CF, Calico fault; CLF, Coyote Lake fault; CRF, Camp Rock fault; GF, Garlock fault; GHF, Gravel Hills fault; GMF, Granite Mountains fault; HF, Helendale fault; LF, Lenwood fault; LhF, Lockhart fault; LuF, Ludlow fault; MF, Manix fault; MVDZ, Mesquite Valley disturbed zone; NSAF, northern San Andreas fault; PMF, Pinto Mountain fault; RPF Rodman-Pisgah fault; SBF, Sleeping Beauty fault; SBMF, San Bernardino Mountains fault; SDVF, Southern Death Valley fault zone; SGF, San Gabriel fault; SSAF, northern San Andreas fault. Internal structure of Domain VI not shown; see Figure 17 for speculative restoration.

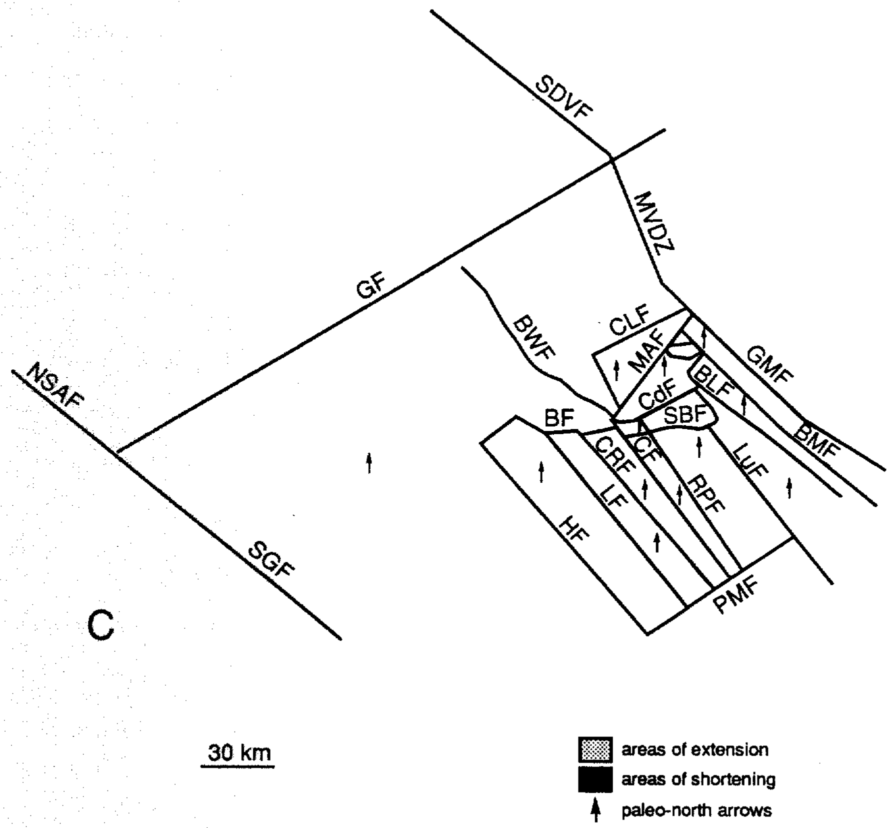



Fig. 14. (continued)

provides a time sequence of events. The behavior of each of the structural domains is described in the following sections.

All of Domain I, except for the San Bernardino Mountains at the southern boundary with the San Andreas fault, is treated as a nonrotated, intact block. The notion that much of this domain is not rotated is consistent with published paleomagnetic data for the region. Weldon et al. [1984] showed that the middle Miocene Crowder Formation at Cajon Pass (southern part of Domain I) has rotated no more than 4° since middle Miocene time. Data presented by MacFadden et al. [1990a] suggest that the Mud Hills (near Barstow, Figure 2) has not rotated since ~19 Ma. These data are in line with those reported in the reconnaissance studies of Burke et al. [1982], who concluded that rocks of the central and northern parts of Domain I have suffered negligible or possibly slight (<15°) counterclockwise rotation since ~18 Ma. Studies by Valentine et al. [1989] also show that the Barstow area has not been rotated significantly since 16 Ma.

Although the eastern boundary of Domain I is depicted as a single line (Calico-Blackwater fault), it is probably gradational. Recent activity on the Gravel Hills-Harper Lake fault zone suggests that shear may be broadly distributed along this boundary and that local strains associated with small strike-slip faults are to be expected. Other faults in this domain are either inactive or have long (>historic) recurrence intervals.

Domain II deforms by simple shear in response to right-slip movements along the Helendale, Lenwood, and Camp Rock faults according to values given in Table 1. Faulting begins between 1.5 and 0.7 Ma and continues to the present in accordance with relations set forth by Meisling and Weldon [1989]. Long-term rates of movement calculated from timing relations and the 7 km of cumulative right-slip across the domain, are consistent with the present-day shear rate (~7 mm $yr^{-1}$ [Sauber et al., 1986]. We conservatively assign a value of 5° counterclockwise rotation to Domains II and III. This rotation is sufficient to produce the N-S shortening and uplift observed at the northern boundary of Domain II (northern flank of the Newberry Mountains) and to satisfy regional paleomagnetic constraints, yet not so much as to require large amounts of shortening between Domains III and V (Figure 14a). The northern boundary of Domain II lies south of Barstow between Lenwood and Newberry Springs and is named here the Barstow fault (Figure 14a). It is an irregular and structurally complex zone of extension, local shortening, and left slip caused by the collision of Domains I and II. Extension is the result of southeastward relative motion of Domain II fault blocks relative to Domain I. Local shortening of the northernmost tips of Domain II fault blocks has apparently occurred in response to counterclockwise rotation (Figure 14a). The concentration of stresses at this irregular boundary may also be contributing to the small amount of right shear observed on the faults north of Barstow.

The small counterclockwise rotation of Domains II and III and the southernmost portion of Domain I is not easily explained in a right slip regime such as the Mojave. We speculate that this anomalous rotation may be superimposed on the general pattern of right shear in the Mojave and is related to transpression along the adjacent "Big Bend" segment of the San Andreas fault. Creation of the transpressive Big Bend near 4 Ma resulted in a zone of ~N-S shortening that is expressed in the San Bernardino Mountains by late Cenozoic thrusting, and folding [Sadler, 1981; Meisling and Weldon, 1989]. Such N-S shortening would also have tended to reorient adjacent NW trending features such as fault blocks of the southern Mojave in a counterclockwise manner.

Following the argument above, Domain III is rotated 5° in a counterclockwise sense. Blocks that constitute the domain are translated in accordance with net slips presented in Table 1. Southward translation of fault blocks of the domain, coupled with rotation of Domain V, creates a large triangular extensional gap between the Cady Mountains and the northern Bullion Mountains and Rodman Mountains (Figure 14a). The occurrence of modern basins and the recently active Pisgah volcano at the predicted locations of these voids accords with this feature of the model (Figures 2 and 14a). The model also predicts that a small amount of left-slip should occur early along the boundary between Domains III and V. This explains the evidence for left shear observed north of the proposed Sleeping Beauty fault in the southern Cady Mountains. According to the model, the Sleeping Beauty fault was originally oriented ENE but was subsequently rotated ~26° clockwise during regional strain to its present orientation (Figure 14a). In a similar fashion, the model predicts that the southern boundary of Domains II and III (Pinto Mountain fault) originated as a NE striking fault that has been rotated 40° clockwise. Rotation of the Pinto Mountain fault implies that the Little San Bernardino Mountains (eastern Transverse Ranges) and proximal areas to the south have been rotated in a like manner; this notion was originally proposed by Carter et al. [1987] based on paleomagnetic studies. The model also predicts that motions along faults of Domains II and III result in the formation of large triangular basins north of the Pinto Mountain fault (e.g., Dale Lake; Figure 2; cf. Figure 14a).

Domain IV is rotated 26° clockwise in accordance with the paleomagnetic data of MacFadden et al. [1990b]. Internal deformation of the domain during rotation occurs by left-slip motions along the Coyote Lake, Manix-Afton Canyon, and Cady faults. The model predicts 13 km, 12 km and <1 km of left-slip, respectively, on these faults. As shown in Figure 14a, a consequence of this motion is the creation of a triangular zone of extension west of the Cady Mountains, which corresponds to and explains the structural origin of Troy Lake basin. Similarly, eastward translation of the Alvord Mountains block along the Coyote Lake fault creates an extensional basin beneath Coyote Lake. Restoration of the Alvord Mountains against the northern flank of the Calico Mountains and Paradise Range results in a reasonable geological match of pre-Tertiary igneous and metamorphic rocks [cf. McCulloh, 1952; Byers, 1960].

Because the behavior of the blocks that comprise Domains V and VI is poorly constrained, the model assumes that their movements are a consequence of the motions of the other domains. Figure 15 illustrates the room problems encountered during modeling and their solutions. We emphasize that Figures 15a and b are intermediate modeling steps and not stages in a time sequence. The first iteration of modeling resulted in a satisfactory reconstruction of Domains I, II, III, and part of IV but created an unacceptably large misfit between Domains III-IV and Domain V (Figure 15a). The misfit was eliminated by moving Domains I-IV 37.5 km to the southeast and by lesser southeastward translations of blocks of Domain V (Figure 15b). A geometric best fit was achieved with 2.0, 0.5, 13.5, and 21.5 km of right-slip on the Ludlow, Broadwell Lake, Bristol Mountains, and Granite Mountains faults, respectively (Figure 14a). The unrotated character of Domain V predicted by the model accords well with the paleomagnetic data presented by Wells and Hillhouse [1989]. Palinspastic reconstruction of these fault blocks in this manner seems reasonable because it results in alignment of similar Mesozoic basement rocks as well as middle Tertiary volcanic rocks of the Granite Mountains, Marble Mountains, and Bristol Mountains (Figure 16). We are currently testing this predicted feature through net slip analysis of these faults.

Palinspastic translation of the Mojave Desert Block to the southeast with respect to stable North America created, however, an unacceptably large overlap in the area adjacent to Domain VI (Silver Lake-Soda Lake-Devil's Playground area; Figure 15b). We reduced this overlap by moving eastern portions of Domain VI to the northwest (Figure 15b). Regional geologic relations discussed below suggest that this solution is plausible.

Figure 17 illustrates the details of our highly speculative hypothesis for the deformation of Domain

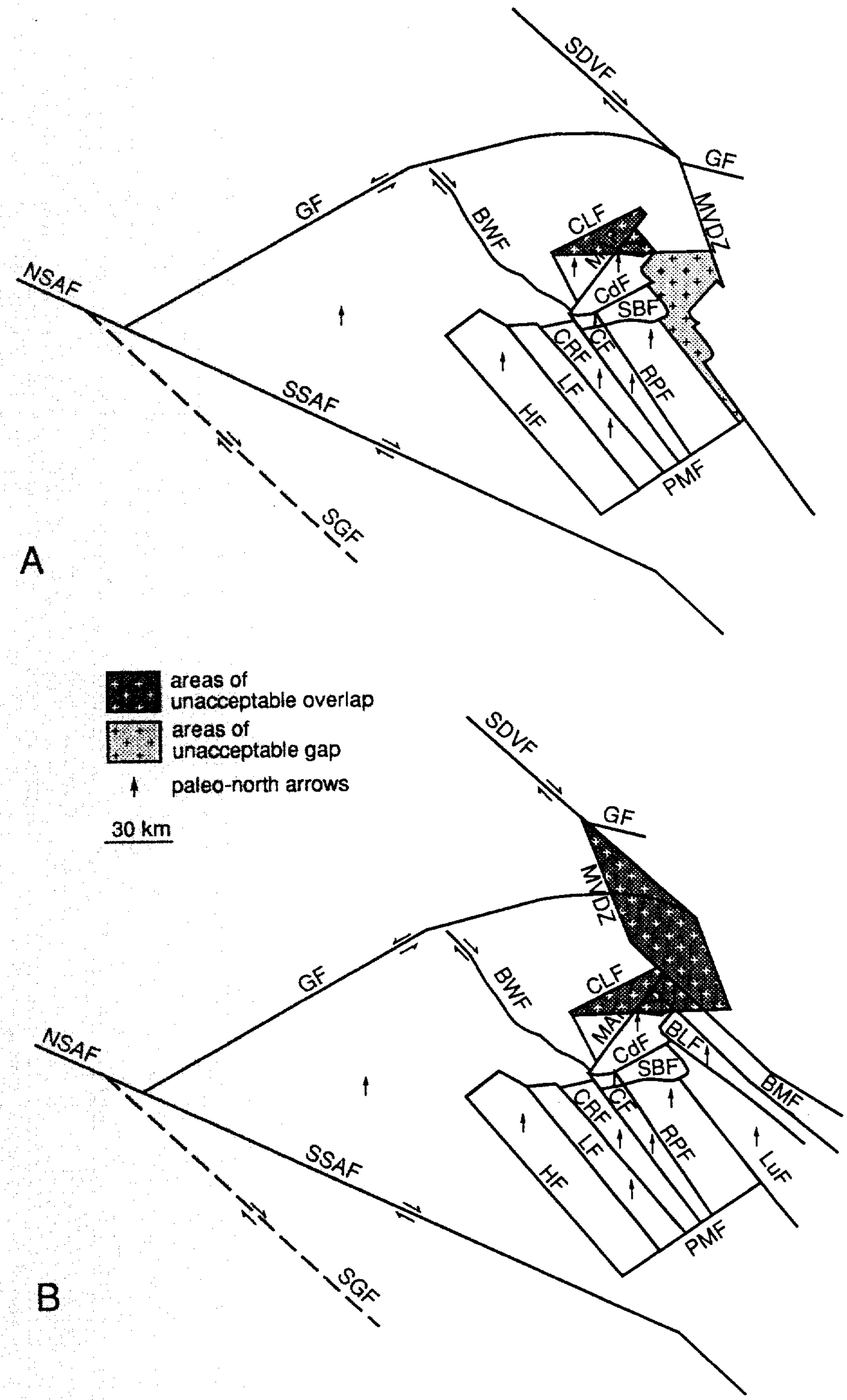
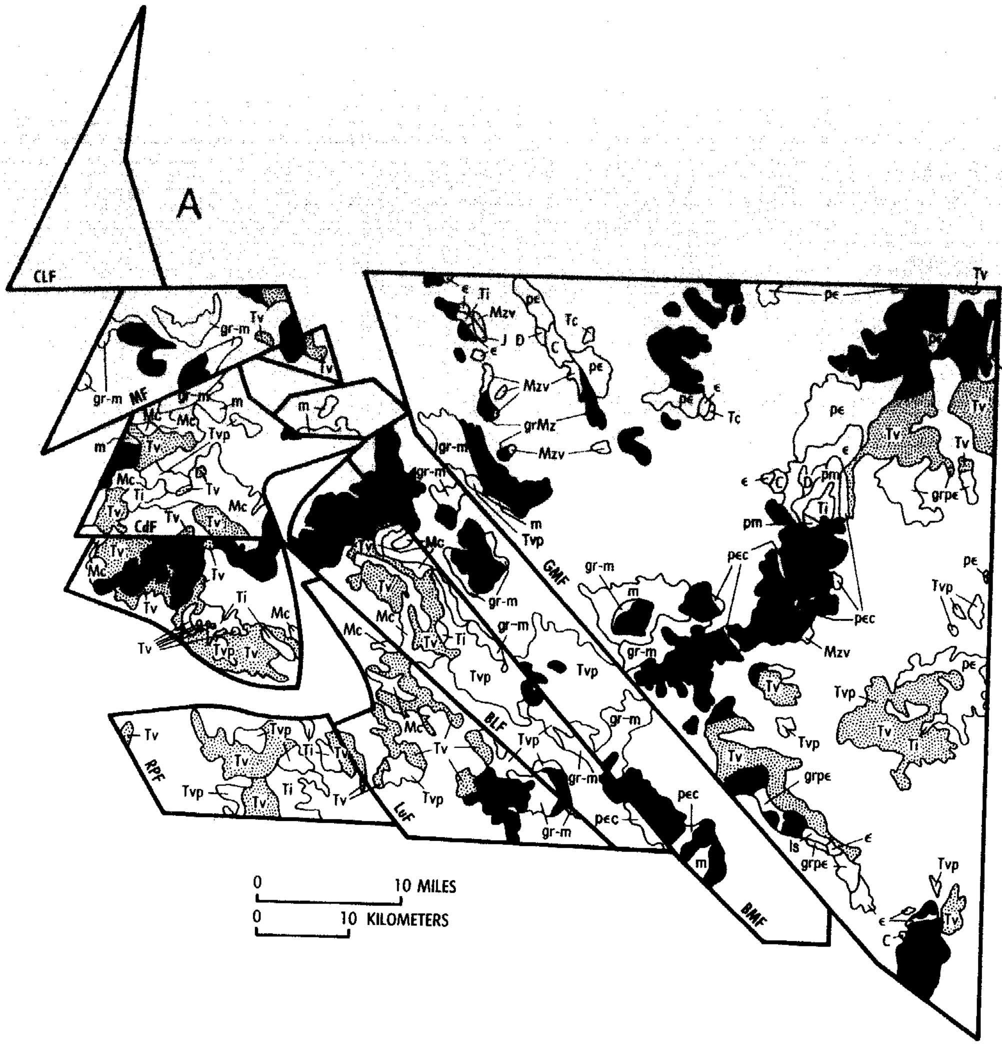



Fig. 15. Intermediate modeling steps. Note that these steps do not represent individual time slices but instead are meant to depict the stages in modeling that led to a geometric best fit. See text for discussion. See Figure 14 for key to abbreviations.



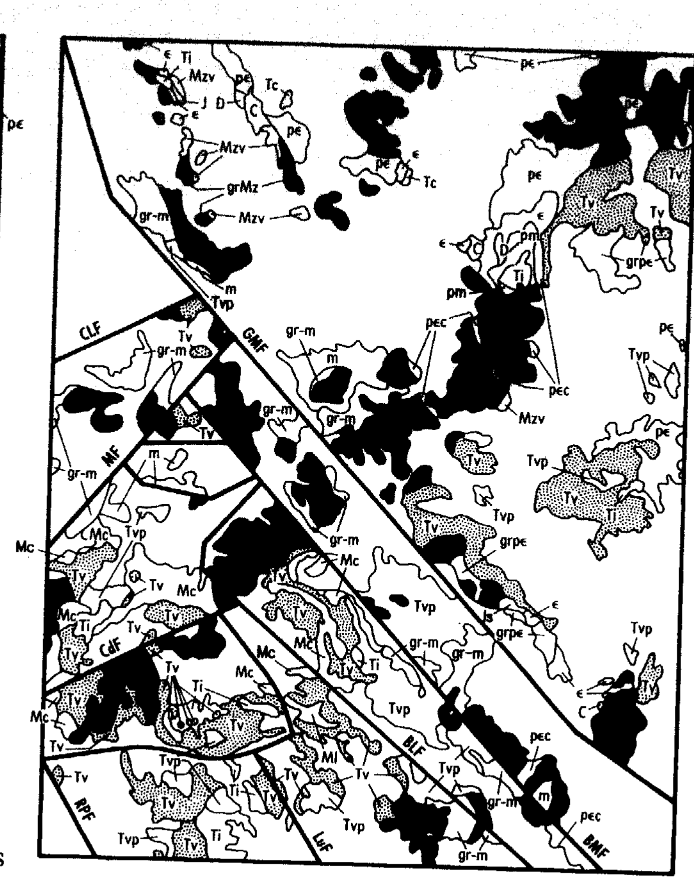




Fig. 16. (a) Present-day geology of the Bristol Mountains-Granite Mountains-Cady Mountains area (modified from Jennings [1977]). (b) The same area following palinspastic restoration of faults of Domains IV and V according the model presented in this paper. This reconstruction results in alignment of similar pre-Tertiary crystalline rocks (Mesozoic granitoids shown in black) and lower Miocene volcanic rocks (Tv, stippled). See Figure 14 for key to abbreviations.

VI. Oblique extension predicted along the Mesquite Valley disturbed zone resulted in an overall increase in the surface area of Domain VI. According to our model, this new space has now been partially filled by fault blocks translated from the north and west (Figure 17b). Dextral shearing of Domain VI along mainly NW striking faults resulted in an overall strain pattern of ~N-S shortening and ~E-W extension (Figure 14). This aspect of our model is in marked contrast with previous models that emphasize the role of east striking, left slip faults in deformation of this region. We view left slip motions along generally east striking faults such as the Fort Irwin and Bicycle Lake fault zones to be secondary and associated with fault blocks that "escaped" eastward towards the extensional Mesquite Valley disturbed zone (Figure 17b). The model predicts that only those fault blocks in the southeastern portion of the domain should show significant rotation about vertical axes; this includes the areas south of the Fort Irwin fault zone and east of the Goldstone Lake fault (Figure 17). As much as 40° of clockwise rotation can be expected in this area. The models of Garfunkel [1974] and Carter et al. [1987] call for the entire domain to be uniformly rotated 0° and 40° (clockwise), respectively. Finally, our model also predicts that shortening occur in the northeastern portion of the domain near the intersection of the Garlock and southern Death Valley fault zones. This predicted feature of the model is supported by the recognition of thrust faulting and folding in the Avawatz Mountains [Troxel, 1970; Spencer, 1981, 1990; Brady, 1984; Brady and Verosub, 1984].

## REGIONAL IMPLICATIONS

### *Eastern California Shear Zone*

If the above model proves to be substantially correct, the Mojave Desert Block-Death Valley region has been the site of a major, throughgoing zone of right shear during late Cenozoic time. We will refer to this regional fault zone as the *Eastern California shear zone* (Figure 18). As much as 65-80 km of right shear may have occurred along this zone since the middle Miocene and may have, along with the San Andreas fault zone, accommodated much of the Pacific-North American transform motion during this interval [R. K. Dokka and C. J. Travis, Role of the Eastern California Shear Zone in accommodating Pacific-North American plate motion, submitted to *Science*, 1989]. We infer that the Eastern California shear zone accommodated at least 9-14% of the total 635±70 km of post-10.6 Ma right shear motion predicted from plate tectonics studies [Stock and Molnar, 1988]. If regional shear was initiated near 6 Ma, then 18-29% of the total 325±45 km of relative plate motion computed by Stock and Molnar [1988] has occurred along the Eastern California shear zone. The kinematic connection of the normal faults and strike-slip faults of the Death Valley region, with the San Andreas fault system via the faults of the Mojave Desert accords with the deduction of Atwater (1970) that late Cenozoic extension in portions of the Basin and Range province is related to Pacific-North American transform shear.

The concept of a regional, throughgoing, right shear zone cutting across the Mojave Desert is not an idea originating with us. Hamilton and Myers [1966] proposed that the Death Valley fault zone continues south into the Mojave Desert to connect with faults mapped in southeasternmost California. They speculated that ~80 km of right slip had occurred along faults of this zone. Davis [1977] showed through field analysis that the southern extension of the presently active Death Valley fault zone cannot be traced to southeasternmost California, nor could he find evidence supportive of a single, large displacement fault zone cutting through the region along the trend postulated by Hamilton and Myers; his work did not rule out, however, the possibility of significant, pre-Holocene movements along other NW striking faults of the region. Although recent mapping by Brady [1988] has revealed evidence of possible Holocene age faults as far south as Soda Lake that may correlate with the Death Valley fault zone (we include these faults in the Mesquite Valley disturbed zone), no evidence has been produced to refute Davis's basic assertions. We concur with Hamilton and Myers' original concept of a province-wide, right-shear zone through southeastern California but, along with Davis [1977], disagree in terms of its location, geometry, and timing relations.

Our inference of the existence of a regional zone of right shear that includes the Death Valley region and the south central and eastern part of the Mojave Desert Block is based on the observation that both areas display similar amounts of late Cenozoic right slip. Using the combined observed and predicted net slips on NW striking, right-slip faults of Domains II, III, and V, the Mojave Desert Block has been the site of ~65 km of distributed right shear during late Cenozoic time. Additional right shear may also be recorded along the margin of the adjacent Eastern Mojave Desert, judging by the apparent bending of mountain ranges east of the Granite Mountains fault [Jennings, 1977]. To the north along the Furnace Creek fault zone, many geologists [Stewart, 1967; Poole et al., 1967, 1977; Stewart et al., 1968; McKee, 1968; Pelton, 1966; Moore, 1976; Poole and Sandburg, 1977; Miller and Walsh, 1977; Oakes, 1977; Cooper et al., 1982] have estimated on the basis of displaced geologic features that 40-100 km of right lateral displacement has occurred. Stewart [1983] reckoned that displacement occurred during the last 6 Ma.

The broadly distributed character of late Cenozoic shear within the Mojave Desert portion of the Eastern California shear zone is in marked contrast to northern Death Valley where shear has been

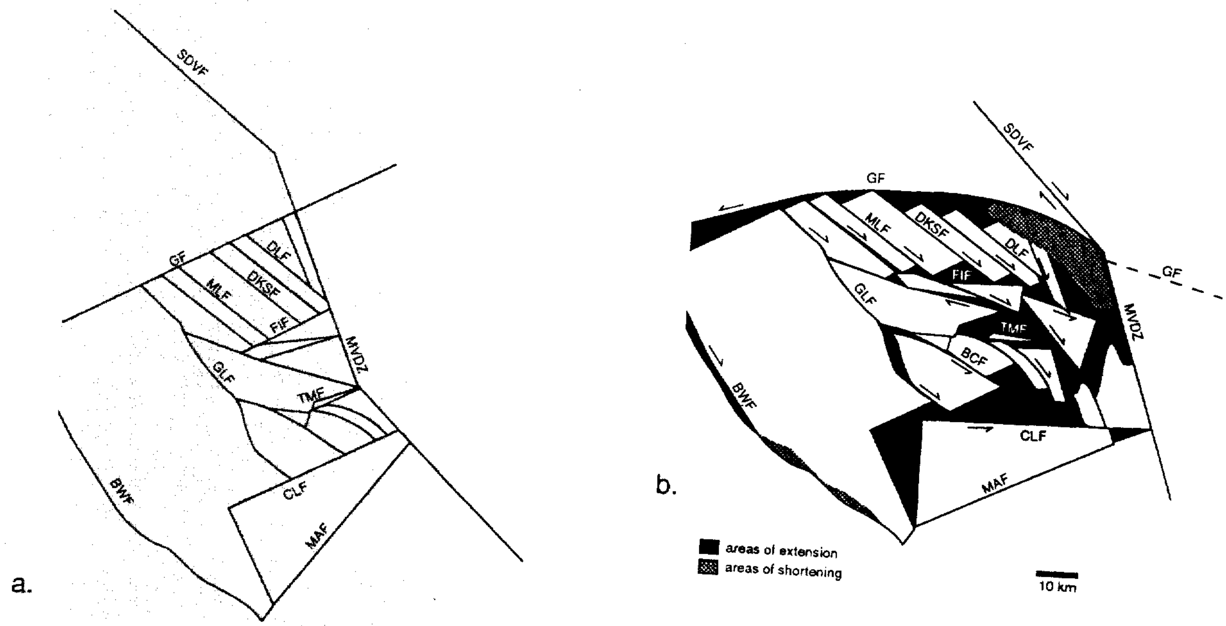



Fig. 17. Speculative restoration of Domain VI. (a) Prefaulting (late Miocene) restoration of structural blocks. (b) Present-day. Geometry of fault blocks of Fort Irwin-Goldstone Deep Space Communication Complex area based on previous mapping [Jennings, 1977], analysis of thematic mapper imagery, and radar scenes and reconnaissance mapping [R. Dokka, J. Ford, R. Blom, and R. Crippen, manuscript in preparation, 1990]. Fragmentation of the domain by strike-slip faults, creation of a belt of shortening in the northeastern portion of the domain, and formation of an extended region in the Mesquite Valley disturbed zone, contributed to the overall N-S shortening and E-W extension of this domain predicted by the model proposed here. Left slip occurs as a consequence of the eastward escape of some blocks. BCF, Bicycle Lake fault; BWF, Blackwater fault; CLF, Coyote Lake fault; DKSF, Desert King Spring fault; DLF, Drinkwater Lake fault; GF, Garlock fault; GLF, Goldstone Lake fault; MLF, McLean Lake fault; MVDZ, Mesquite Valley disturbed zone; NLF, Nelson Lake fault; SDVF, Southern Death Valley fault zone.

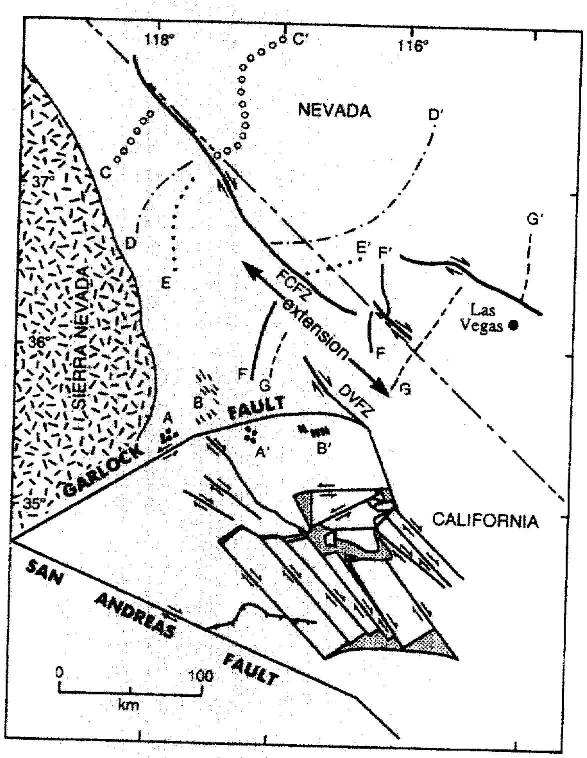



Fig. 18. Location map of faults of the proposed Eastern California shear zone. This zone includes faults of the Mojave Desert Block as well as the southern Death Valley fault zone (DVFZ) and the Furnace Creek fault zone (FCFZ). The Garlock fault is presumed curved due to oroclinal folding within this NW trending zone of right shear. Also shown are offset geologic trends of the Death Valley region that suggest ~80 km of late Cenozoic right shear [from Stewart, 1983]. Offset geologic trends: A-A', Paleozoic metasedimentary rocks [Smith and Ketner, 1970]; B-B', Mesozoic dike swarms [Smith, 1962]; C-C', facies boundary of Lower Cambrian Harkless Formation and Zabriskie Quartzite [Stewart, 1967]; D-D', western limit of Lower Mississippian limestone unit (F. G. Poole, as cited in Stewart et al. [1968]); E-E', 100-m isopach for Upper Ordovician (Caradocian and Ashgillian) rocks [Miller and Walsh, 1977]; F-F', 150-m isopach of Lower Cambrian Zabriskie Quartzite (slightly modified from Stewart [1970]; G-G', 600-m isopach of Proterozoic Z Stirling Quartzite [Stewart et al., 1970].

apparently concentrated at the Furnace Creek fault zone [cf. Stewart, 1983]. This character may explain two controversial aspects of the southern Death Valley area, namely, the apparent variation of slip along the Southern Death Valley fault zone and the origin of the curvature of the eastern Garlock fault. For example, only ~35 km of post-Miocene right-slip has been documented on the Southern Death Valley fault zone near the border with Domain VI [Butler et al., 1988]. Farther south along this fault, Wright and Troxel [1967, 1970], based on the apparent continuity of Precambrian stratigraphic trends across the region, could find evidence for only ~8 km of right-slip. Davis and Burchfiel [1973] and Plescia and Henyey [1982] argued that the eastern Garlock fault and its proposed continuation east of the Southern Death Valley fault zone have been offset ~8 km. Still farther south, Brady [1984] postulates that the Halloran Hills have been displaced ~20 km southward relative to the Avawatz Mountains based on stratigraphic studies. We attribute these apparent conflicting observations not to differences of opinion among workers but rather to real variations within a broad heterogeneous zone of shear. In our view, slip along the Southern Death Valley fault zone represents only a portion of the total right shear across the region and additional shear is expressed in the region to the west in the form of oroclinal folding. We also consider this concept of distributed shear to be useful in explaining the origin of the curved trace of the eastern Garlock fault. Our explanation parallels closely the idea presented by Carter et al. [1987], differing only in the attribution of strain north and south of the Garlock fault.

### *Origin of the Curvature of the Garlock Fault*

We view the Garlock fault as a regional strain marker that has been oroclinally folded due to deformation of Domain VI. N-S shortening of Domain VI implies that the eastern segment of the Garlock fault and adjacent Basin and Range Province originally occupied a more northerly position relative to a point in the Mojave Desert Block. Straightening of the curved eastern part of the Garlock fault to parallelism with the western segment requires the restoration of ~57 km of right shear across Domain VI. This value coupled with the 8-km right-lateral offset of the Garlock fault along the Southern Death Valley fault zone totals about 65 km, an amount similar to that observed along the Furnace Creek fault zone and across the southern Mojave Desert Block. Furthermore, if oroclinal folding is directly related to NW regional shear dated as post-6 Ma, the age of the major phase of movement along the Garlock fault (and associated east-west extension in the southwestern Basin and Range province [e.g., Smith, 1962; Davis and Burchfiel, 1973]) must also predate 6 Ma. This accords with studies by Burbank and Whistler [1987] who dated Garlock fault initiation at ~10 Ma.

### *Westward Migration of Right Shear*

Structural and chronologic data from individual domains of the Eastern California shear zone indicate that the locus of faulting and deformation in this broad, regional zone has not been static but, instead, has shifted with time. Although geologic data indicate that much of the regional right shear in the southern part of the Mojave Desert Block has been accommodated by faults of Domain V during late Miocene and early Pleistocene time, the distribution of earthquakes, present-day strain, and ground rupture indicate that fault activity has shifted westward and is now concentrated in Domains II and III and the western portion of Domain IV. Strain of equivalent magnitude is not apparent north, west, and east of these areas nor is right shear transferred elsewhere in any obvious way to the Death Valley area. We propose three hypotheses to account for the present-day tectonic regime. The first considers the Eastern California shear zone to be currently locked in the central and northeastern Mojave (Domains IV and VI and the Mesquite Valley disturbed zone). Infrequent, moderate (and larger?) earthquakes such as the 1947 Manix event may be the primary strain release mechanism in these areas. In the second hypothesis, strain is accommodated north and east of Domain IV by aseismic creep along unknown faults. The third model requires the abandonment of the eastern faults in Quaternary time (between 1.5 and 0.7 Ma), and the formation of an entirely new fault system in the central Mojave. The locus of seismicity at the northern terminus of the currently active faults of Domains II, III, and IV is interpreted to be a manifestation of a northward propagating fault system. Additional regional strain nets covering the north central and east central Mojave, planned Global Positioning Satellite geodetic measurements, as well as field studies currently in progress by the authors may shed light on the validity of these hypotheses. The cause of this apparent shift of the locus of shear deformation from east to west in the Mojave Desert Block is not understood by us. However, because of the important role that the Mojave has played in the strike-slip faulting history of earthquake-prone southern California, further work on establishing more precise timing relations is also warranted.

## CONCLUSIONS

The following conclusions were reached during this study:

1. Map-scale structural relations presented above such as fault location and fault net slip contradict and thus invalidate models that advocate regionally distributed simple shear for the entire Mojave Desert Block during late Cenozoic time.
2. Data suggest that strain is instead regionally inhomogeneous and is partitioned into six domains that are separated by major strike-slip faults and

extensional zones. Sixty-five kilometers of total right slip is predicted by the model to have occurred on NW striking faults of the Mojave Desert Block. Tectonic rotation of many of the domains as well as their internal deformation by strike-slip faulting occurred as the result of broadly distributed regional right shear. Small (<10°), counterclockwise rotations of domains of the southern Mojave Desert Block may be superimposed on the overall right shear regime and may be related to ~N-S shortening associated with formation of the transpressive "Big Bend" region of the San Andreas fault.

3. In addition to the structures of the Mojave Desert Block, this regional zone of right shear includes the Furnace Creek and Southern Death Valley fault zones. Initiation of movement along this system of faults, termed here the Eastern California shear zone, likely occurred between ~10 and 6 Ma and was probably related to Pacific-North American plate interaction. This shear zone can thus account for 9-14% of the total predicted relative motion between the plates since 10.6 Ma. If motion began near 6 Ma, 18-29% of the predicted transform motion has been accommodated along the Eastern California shear zone.

4. The Garlock fault is not kinematically related to the development of the strike-slip faults of the Mojave Desert Block. The curvature of the eastern segment of the Garlock is oroclinal and is likely the result of regional right shear (shear plane oriented NW) that is distributed between the Blackwater fault and the Death Valley fault zone.

5. Although most of the right shear through the Mojave Desert Block has occurred in the eastern portion of the province, strain measurements, seismicity, and surface faulting indicate that the locus of tectonism has shifted westward to the south-central Mojave in recent times. This shift may have occurred as recently as 1.5-0.7 Ma. Although the displacement rate (~7mm $yr^{-1}$) across this presently active zone is similar to the long-term rate (since 10.6 Ma), strain is not apparently accommodated to the north. The cause of this westward shift of activity as well as the implications that this change may have for regional tectonic synthesis and seismic risk assessment are unknown and deserving of greater study.

*Acknowledgements.* We are grateful to W. Hamilton, B. Luyendyk, and G. A. Davis for their careful and constructive reviews. Discussions with R. Blom, R. Brady, R. Crippen, J. Crowell, J. Ford, E. Frost, M. Golombek, C. G. Groat, H. G. Hawkins, G. Humphreys, S. Jones, C. Jones, H. Kanamori, D. H. Kupfer, M. McCurry, C. McCabe, D. Morton, R. Merriam, B. MacFadden, J. Plescia, T. Ross, P. Sadler, J. Spencer, J. Stock, M. Valentine, and R. Weldon were invaluable.

Enhanced Landsat Thematic Mapper imagery and radar data were kindly provided by the Jet Propulsion Laboratory of the California Institute of Technology. Earthquake data were graciously supplied by the Seismological Laboratory of the California Institute of Technology. R. L. Parratt of Santa Fe Mining, Inc. made available copies of unpublished geologic maps of the Mojave Desert. The figures and plates were carefully prepared by M. Eggart, C. Duplechin, J. Adams, and J. Kennedy. Thanks are also due R. Price and K. Burke, Editors-in-chief, and A. Dole and P. Knox of the staff of Tectonics for their kind and clear advice throughout the course of this effort. Finally, our heartfelt thanks is extended to M. O. Woodburne for his friendship, help, and encouragement. His thoughtful and gently pointed reviews, his sharing of critical unpublished data and insights, and his field discussions greatly helped to clarify both our thinking and the presentation given here.

Studies of the late Cenozoic tectonic evolution of the Mojave Desert by RKD and colleagues have been generously supported by grants from the Crustal Structure and Tectonics Program (T. O. Wright, Director) of the National Science Foundation (EAR-8107524, EAR-8407136, and EAR-8721022). The final phase of the work was completed while RKD was Summer Faculty Fellow at the Jet Propulsion Laboratory of the California Institute of Technology.

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(Received January 30, 1989;
revised August 16, 1989;
accepted August 16, 1989.)