Deformation associated with the Neogene Eastern California Shear Zone, southeastern California and southwestern Arizona

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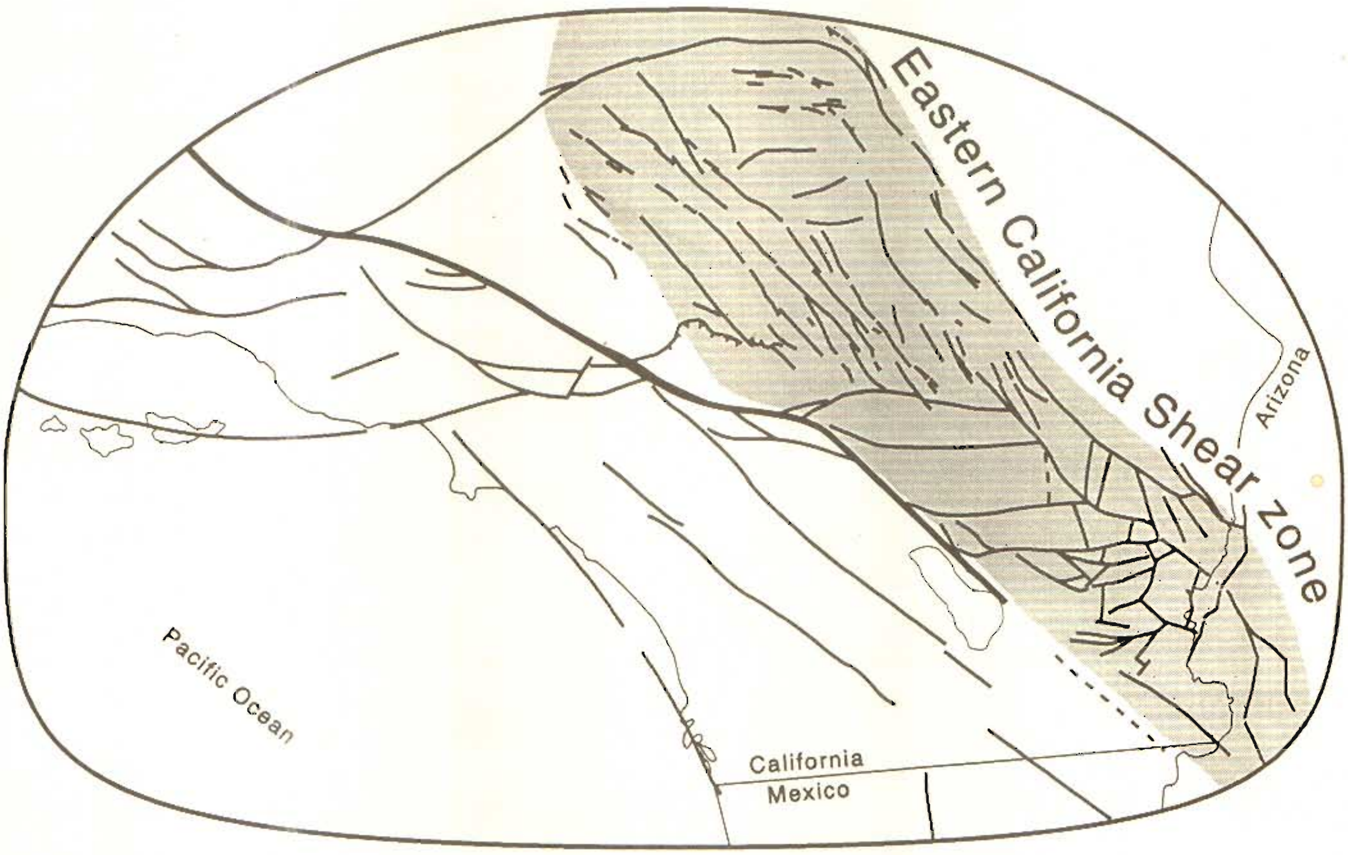

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held at the

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Stephen M. Richard
Editor

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September 4-6, 1991

Roy K. Dokka, Bruce P. Luyendyk and Stephen M. Richard, Conveners

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Introduction

STEPHEN M. RICHARD *Institute for Crustal Studies, University of California, Santa Barbara, CA*
ROY K. DOKKA *Dept. of Geology and Geophysics, Louisiana State University, Baton Rouge, LA.*

This volume is the product of a workshop hosted by the Institute for Crustal Studies at the University of California, Santa Barbara in September, 1991. The purpose of this gathering was to critically examine the geologic and geophysical data available that quantifies the magnitude and timing of Neogene deformation in the Mojave and Sonoran desert regions east of the San Andreas Fault and south of the Garlock Fault. This data set is a necessary pre-requisite for attempts to quantify the distributed deformation of the North American plate margin related its interaction with the Pacific Plate (Carey, 1958; Wise, 1963; Hamilton and Myers, 1966; Atwater, 1970). If extension and strike slip faulting in the southern Basin and Range has accommodated some component of right slip between the Pacific and North American plates, this slip must be transferred southward through the Mojave-Sonoran Desert to link with the strike-slip fault system along the continental margin (Dokka and Travis, 1990b). The name "Eastern California Shear Zone" has been proposed by Dokka and Travis (1990a) to include the broad belt of late Neogene deformation east of the southern Sierra Nevada that provides this kinematic link. In light of the model for late Cenozoic deformation in the region proposed by Dokka and Travis (1990a) and the rapid accumulation of regional geologic and geophysical data, this seemed a particularly appropriate time to bring together interested earth scientists to review and reconsider data, and to identify problems

The papers in this volume focus mainly on presenting available defining the timing, magnitude and sense of shear on faults in the Eastern California Shear zone (ECSZ). Figure 1 provides an index to the faults discussed. No new data were presented pertaining for faults of the western or northern Mojave desert, and the slip estimates summarized in Dokka and Travis (1990a) remain the most up to date. Data are also lacking for southeasternmost California, but an interpretation of late Cenozoic faulting in this region is presented in Richard (submitted). Several papers are included to provide plate tectonic (Atwater) and geologic (Crowell, "Tectonic Mobility...") background. The paper by Luyendyk summarizes paleomagnetic evidence for vertical-axis rotations, which locally have accommodated significant amounts of right shear.

The conference ended with several important questions left unanswered. These included questions pertaining to the regional geology, including: What is the magnitude of slip on the eastern boundary of the ECSZ, known as the Bristol-Granite Mountains fault zone? What is the history of the many faults in the central and eastern Mojave that have separations consistent with either early Miocene normal faulting or Late Miocene and younger strike-slip? Which faults of the ECSZ connect with the San Andreas fault in southeastern California? What areas of the region have undergone rotations to accommodate displacement within the ECSZ?

Finally, questions of interpretation arose, including: How far back in time is Pacific-North America plate interaction manifested in the tectonics of the continent? Is substantial rotation of fault bounded blocks and shallow (<10 km) seismicity within the ECSZ explained by detachment of upper and lower crustal levels? If so, where does this detachment occur? What are the important forces driving the rotations, and where do they originate? (tractions across faults, traction on base of blocks, body forces within continent, coupling with flow in underlying aesthenosphere?) What new implications does the recognition of translated and rotated blocks of the late Neogene ECSZ have for Mesozoic and older tectonics and paleogeography?

Reconstruction of the Cenozoic deformation at the western margin of North America is a goal that has caught the imagination of earth scientists working in the region since the recognition of the San Andreas fault as a major strike-slip fault (Hill and Dibblee, 1953; Crowell, 1962). This volume represents an attempt to bring together data available to define the deformation in one small segment of this deformation zone, providing a database, scrutinized by the participants at the workshop, which can be used as a starting point in the reconstruction process. Future workshops are planned to bring together information on other segments of the plate boundary deformation zone.

Acknowledgements. We would like to thank Joe Cisneros, Brad Laurabee, and Lauren Luyendyk for keeping things running smoothly during the workshop and Joan Dandona, Maureen Evans, Anne Glennister, Tera Ruotsala, and Victoria Wylie for their constant able assistance during all phases of the workshop and preparation of this volume.

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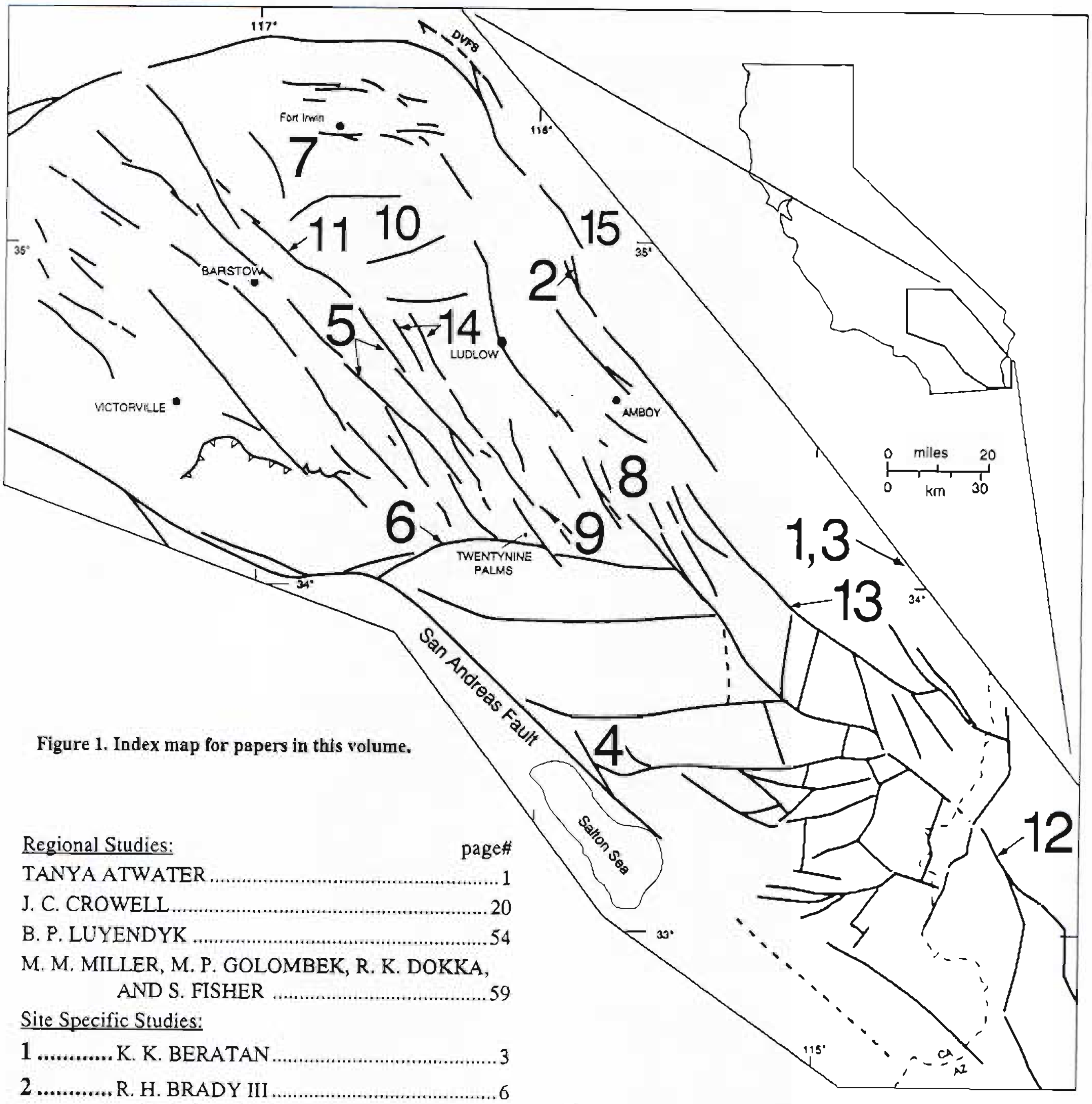

Figure 1. Index map for papers in this volume.

Constraints from plate reconstructions for Cenozoic tectonic regimes of Southern and Eastern California

TANYA ATWATER *Dept. Geological Sciences, University of California at Santa Barbara, Santa Barbara, CA 93106*

The Cenozoic plate history of western North America began with a subduction zone. During the late Cretaceous and early Cenozoic the downgoing slab of this subduction zone is postulated to have flattened (Laramide) and then steepened again (uplift and onset of Basin-Range extension). Since the late Oligocene, segments of the East Pacific Rise have been intersecting the rim of the continent and gradually converting it to the San Andreas plate boundary. Although this basic story has been around since the 1970s, details of timing, location, plate reconstructions and geologic manifestations are steadily being improved and refined (as summarized in Atwater, 1989). These refinements are especially important for eastern California, since this region lies near several of the postulated plate tectonic junctures.

The late Mesozoic and early Cenozoic were characterized by fast, nearly head-on subduction of the Farallon and Vancouver plates beneath North America (Stock and Molnar, 1988). It is commonly postulated that the Laramide orogeny was caused by an episode of flat slab subduction during this time (like that occurring beneath present-day central Argentina and Peru) (Coney, 1976; Cross, 1986; Isacks and Barazangi, 1977, Jordan and Allmendinger, 1986) so that the subducting oceanic plate lay directly beneath the continental plate, dragging and shortening the latter (Bird, 1988). Furthermore, it is often speculated that Basin-Range extension and uplift started as a response to the removal of this flat slab and the re-establishment of more ordinary high-angle subduction. This steepening of the slab appears to have been irregular and transgressive in time and space. As tracked by occurrences of arc magmatism, it was approaching eastern California both from the north and from the east, due to arrive there about 20 Ma (Coney and Reynolds, 1977; Cross, 1986). Another type of slab-removal event, that related to the onset of the San Andreas system, described next, also occurred beneath this region at about this time, so that the geologic manifestations of the two effects may be close in time or intertangled.

Within the ocean basin, the trials and tribulations of the East Pacific rise as it approached North America are clearly recorded in the seafloor magnetic isochrons (Lonsdale 1990, Atwater and Severinghaus, 1989). The demise of the subduction system can be imperfectly inferred from this record, as well (Severinghaus and Atwater, 1990). Refinements in the correlations among the various time scales: geomagnetic, geologic, and radiometric, are also helping to clarify the story. The "chron" dates in the following description refer to events in the geomagnetic time scale. They are also given in millions of years according to Berggren and others (1985), but it should be noted that a new time scale by Cande and Kent (submitted) is nearly completed and it revises some of these dates by as much as two million years.

The transition from the subduction regime began about chron 10 (30 Ma) between the Pioneer and Murray fracture zones with the local breakup of the large subducting plates. The resulting small plates (Monterey and Arguello plates) continued subducting very slowly, gradually arriving at the continental rim between chrons 8 and 5E (27 to 19 Ma). The Mendocino-Pioneer segment continued fast subduction until its demise, about chron 7 (26 Ma), when the Mendocino triple junction was established. Thus, in the whole Mendocino-Murray region (about 800 km length of coastline) the cessation of subduction and the establishment of the Pacific-North America plate boundary (San Andreas system) occurred in a piecemeal way between 27 and 19 Ma. [Other scenarios that include significant post-19 Ma subduction of this region are possible, but they are highly unlikely in my opinion.] After 19 Ma, the San Andreas system was gradually lengthened south of the Murray fracture zone until about chron 5A (12 Ma), when the Rivera triple junction was established near its present position.

Within the continent, the predicted location of the early Pacific-North America contact zone (and the early San Andreas fault) depends upon two reconstructions. First, we use global plate reconstructions to place the Pacific plate with respect to stable North America, (Stock and Molnar, 1988). Second, we restore the mid-Cenozoic geometry of western North America, using reasonable estimates of late Cenozoic displacements in California and the Great Basin (see discussion in Severinghaus and Atwater, 1990). Combining these two, we find that southern and eastern California and northernmost Baja California adjacent to the Mendocino-Murray segment in the mid-Cenozoic, so that they should be the first parts of the continent to be affected by the San Andreas system (Severinghaus and Atwater, 1990, Atwater, 1989).

During the period since the establishment of the Pacific-North America plate boundary, there have been changes both in global plate motions and in more local tectonic configurations, and these should be reflected in geological events. Plate motion reconstructions suggest at least two changes in Pacific-North America relative motions. First, the average motion during most of the Miocene was clearly slower than it has been over the last 10 m.y. (Stock and Molnar, 1988), but the amount and timing of the speedup is not well constrained. Second, a change in direction is postulated in the Pliocene to account for the compression of the central California coast ranges and a small change in trend of the Hawaiian chain (Ben Page, submitted; Engebretson and others, 1985). Again the timing is poorly constrained. Both of these events should have left a clear signal in the tectonic deformations of western North America.

Additional changes in the continental geologic record are expected corresponding to changes in local and regional tectonic configuration. The most obvious example is the transfer of Baja California from the North American plate to the Pacific plate, shifting the primary plate boundary into the Gulf of California. Deep Sea Drilling results from the mouth of the Gulf imply that this occurred at about 5.5 Ma, (Curray and Moore, 1984). This event profoundly changed the overall deformation in southern California from a "releasing geometry" to a "constraining geometry" (Crowell, 1974) and, since this event has the effect of moving the plate boundary inland, it might be expected to cause a sudden increase in San Andreas related deformations in eastern

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California. This is a likely candidate for the cause of initiation of the Eastern California Shear Zone.

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Age Constraints on the End of Detachment Faulting, Colorado River Extensional Corridor, Southeastern California-Western Arizona

KATHI K. BERATAN *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109**

Study of Miocene synextension sedimentary and volcanic rocks in the Colorado River extensional corridor (Howard and John, 1987) of southeastern California and western Arizona is providing constraints on the timing of detachment faulting and the transition to the modern tectonic regime. This research is relevent for studies of the East California Shear Zone (ECSZ) in two ways. First, parts of the ECSZ experienced extension and core complex formation prior to shearing; the topography, structure, and stratigraphy affected by shear zone development were inherited from the prior extensional event. Second, the Colorado River extensional corridor can be used to constrain the eastward geographical extent of ECSZ. Work on the late- to post-detachment strata in the Colorado River extensional corridor is still in its early stages, but some general observations are possible.

In past discussions on the timing of extension, the time of the final tilting event in the area being studied was considered to indicate the end of detachment faulting (e.g., Davis and others, 1980; Spencer and others, 1989). However, detailed stratigraphic work has shown that the picture is more complicated than this. Synextensional strata were deposited in a series of half-graben bounded to the southwest by high-angle normal faults, and to the northwest and southeast by transfer faults (Nielson and Beratan, 1990; Beratan, 1991). Each of these basins behaved semi-independantly, tilting at different times. For example, tilting in the eastern and southern Whipple Mountains (Fig. 1) occurred following deposition of the Copper Basin Formation, and prior to deposition of basalt flows dated at 13.5±1.0 Ma (Kuniyoshi and Freeman, 1974). In contrast, tilting in the Aubrey Hills (Fig. 1), southwest of Lake Havasu City, Arizona, occurred significantly later than deposition of a sedimentary unit that is time-equivalent to the post-Peach Springs Tuff Copper Basin Formation (Beratan, 1991) and eruption of an overlying basalt flow dated at 14.1±0.02 Ma (K-Ar, whole rock, J. K. Nakata, written communication, 1989) (Fig. 2). Thus, the timing of tilting events in one basin does not necessarily constrain the timing of regional extension.

Tertiary strata in the Black Peak area northeast of Parker, Arizona (Fig. 1), includes nearly flat-lying basalt flows that overlie tilted strata. These flat-lying units are deformed by a complex array of small-displacement faults, including low-angle normal, listric normal, and antithetic faults (see Buising, this volume). This fault pattern strongly resembles detachment-related deformation within the tilted upper-plate fault blocks of the Whipple Mountains, suggesting that such deformation continued after the final tilting event. If this is true in other parts of the Colorado River extensional corridor, it indicates that detachment faulting ceased gradually rather than abruptly.

A regional transition from dominantly andesitic volcanism to basaltic volcanism has also been interpreted as marking the change from extension to the modern tectonic regime. Instead, stratigraphic and structural relations indicate that this transition occurred during the final stages of detachment faulting, and was most probably related to the extensional event. Ages obtained from basalt flows in the upper parts of Tertiary sections throughout the Colorado River extensional corridor indicate that basalts were being erupted regionally after about 16 Ma, most notably between 16-13 Ma (based on dates quoted in Buising and Beratan, in press; Eberly and Stanley, 1978; Kuniyoshi and Freeman, 1974; Nielson and Beratan, 1990; Shafiqullah and others, 1980; Simpson and others, 1991; Spencer, 1985; Spencer and Reynolds, 1989; and Suneson and Lucchitta, 1979). The Black Peak area (Fig. 1) contains olivine basalt flows as old as 16 Ma; an angular unconformity separates this volcanic pile into two units (Fig. 2) (Buising and Beratan, in press). A 14.1 Ma basalt flow exposed in the Aubrey Hills is interbeedded with tilted Tertiary strata. The evidence thus indicates that basaltic volcanism began at about the same time

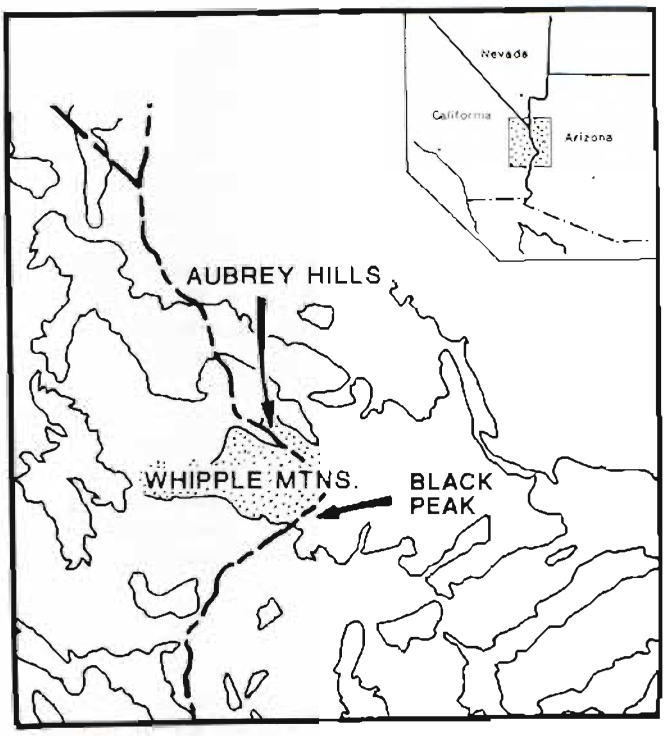

Figure 1: Map showing location of described stratigraphic sections.

* Present Address: Deptartment of Geology and Planetary Science, University of Pittsburgh, 321 Old Engineering Hall, Pittsburgh, PA 15260

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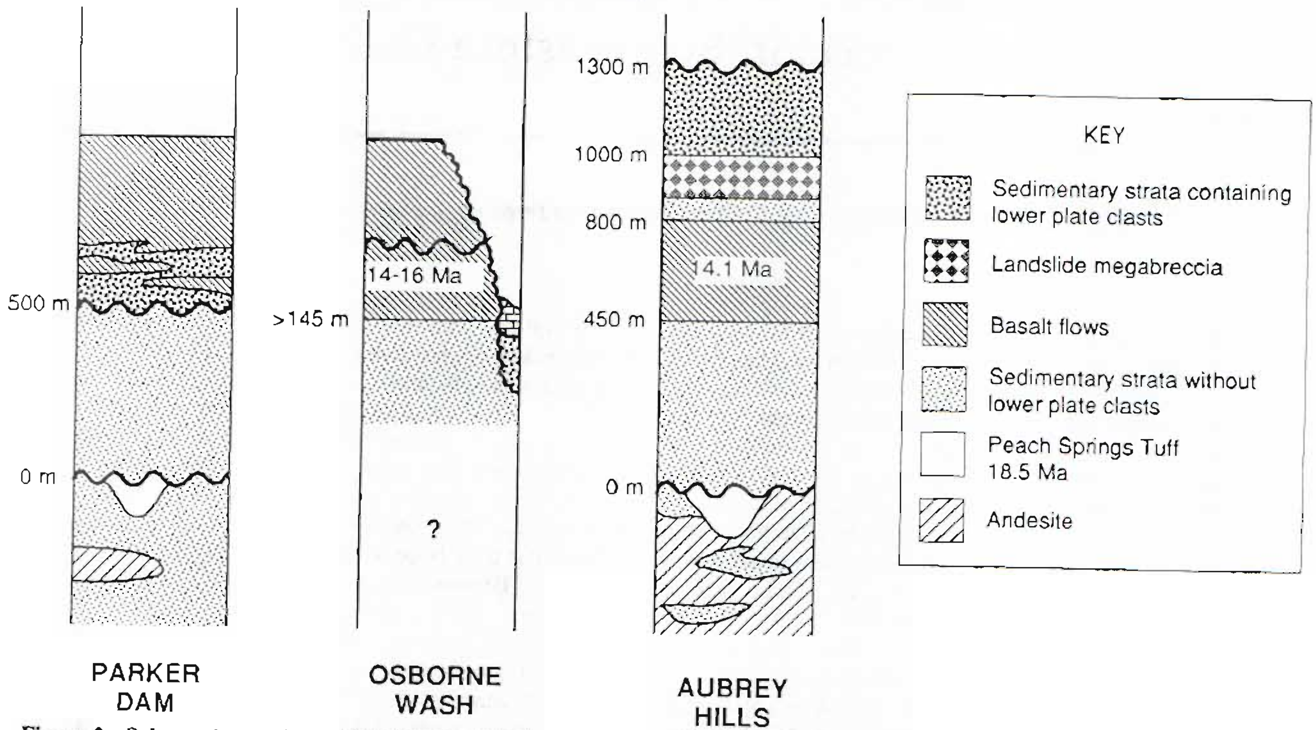

Figure 2: Schematic stratigraphic columns, showing strata deposited after the Peach Springs Tuff. Vertical scale is approximate stratigraphic thickness.

throughout the Colorado River extensional corridor , well before the final detachment-related tilting events.

Based on stratigraphic position and the few available dates, the lower plate of the Whipple Mountains detachment system appears to have been widely exposed to erosion not long after 14.1 Ma. Conglomerates at this stratigraphic position and higher are dominated by clasts of lower-plate mylonitic gneiss; such clasts are largely to wholely absent in older conglomerates (Fig. 2). Mylonite-bearing conglomerates are widely exposed in the alluvial apron flanking the Whipple Mountains. Unroofing of the detachment therefore appears to have occurred over a wide area in a relatively short period of time. This suggests that a tectonic event was responsible. This event appears to have been related to detachment faulting, since the basalt flow dated at 14.1 Ma and overlying mylonite-bearing conglomerate exposed in the Aubrey Hills, Arizona, are tilted about 20° to the southwest and thus experienced significant tilting along a northwest-trending high-angle normal fault. This tectonic event appears to have "stranded" blocks of upper-plate rocks on top of the detachment fault (Beratan and Nielson, 1991), and appears to be the last significant structural event to have affected the Colorado River extensional corridor .

In conclusion, the transition from dominantly andesitic to basaltic volcanism occurred during the final stages of extension prior to the tectonic transition from extension to the modern tectonic regime. The lower plate was structurally unroofed near the end of detachment faulting, after 14.1 Ma. Tilting in different areas occurred at different times; the youngest tilting event appears to be the one affecting the Aubrey Hills, which was younger than 14.1 Ma. Extension therefore continued until significantly less than 14.1 Ma. No evidence of right-lateral shear is found in the Colorado River extensional corridor ; thus the eastern margin of the ECSZ lies to the west of the extensional corridor.

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The Eastern California Shear zone in the northern Bristol Mountains, southeastern California

ROLAND H. BRADY III *Geology Dept., MS #24, California State University, Fresno, CA 93740*

ABSTRACT

The easternmost part of the eastern California shear zone is the Bristol-Granite fault zone, which extends through the northern Bristol Mountains. Faults in Bristol-Granite fault zone are mainly right lateral. Tectonism on these faults was most intense during a period about 26 Ma when it formed syn-tectonic sedimentary basins. Faulting continued at a significantly lesser degree through the Pleistocene. Lateral displacements on these faults appears to be between 6 and 10 km; dip slip is about 250 m.

INTRODUCTION

The purpose of this paper is to describe the Cenozoic structural and stratigraphic framework of the northern Bristol Mountains in relation to the Eastern California shear zone. The northern Bristol Mountains lie at the southeast edge of Soda Lake, approximately 28 km southeast of Baker, California which is located on I-15 between Barstow, California and Las Vegas, Nevada (Fig. 1). The range is 19 km southeast of the southern Soda Mountains, and 11 km southwest of the Old Dad Mountains. The area is accessible with difficulty by four-wheel drive along the power line road parallel to the Union Pacific railroad tracks, and along dry washes.

Although several separate ranges in the eastern Mojave Desert area are referred to as "Bristol Mountains" on published maps, this report includes only the northeastern range immediately south and west of the Union Pacific railroad track. To avoid confusion, a physiographically distinct "Bristol Mountains" lying 7 km to the west, will be referred to herein as "Broadwell Mesa" after its most prominent feature.

Previous Work

The region around the Bristol Mountains has been the topic of considerable study, but detailed work in the range is lacking. Brady (1988) suggested that the southern Death Valley and the Soda-Avawatz fault zones extend through the northeastern Bristol Mountains. Brady and Dokka (1989) proposed that these faults are part of a major shear zone that separates terranes having markedly different tectonic styles. This shear zone forms the easternmost element of a larger, diffuse zone of faults that Dokka and Travis (1990) named the "eastern California shear zone" (ECSZ). Thus, the eastern limit of the eastern California shear zone trends through the northeastern Bristol Mountains.

Brady and others (1989) discussed structural and stratigraphic elements of the Bristol Mountains based on analyses of Thematic Mapper imagery and field mapping, and referred to the prominent northwest-trending shear zone transecting the range as the "Bristol Mountains fault zone", consistent with previous usage by Laird (1959) and Howard and others (1987). Because this structure appears to extend southward into the Granite Mountains, it will herein be referred to as the "Bristol-Granite Mountains fault zone" following the usage of Howard and Miller (this volume). By so doing, it distinguishes this through-going fault from the "south Bristol Mountains fault" of Howard and Miller (this volume), which has also been referred to as the "Bristol Mountains fault" (Miller and others, 1982; Dokka and Travis, 1990). Ford and others (1990) and Dokka and Travis (1990) referred to the westernmost branch of the "Bristol-Granite Mountains fault zone" as the "Granite Mountains fault zone"— a term retained herein (Fig. 2).

Dibblee (1967) mapped the Broadwell Mesa area; although his map does not include the area of this report, it provides, local strati-

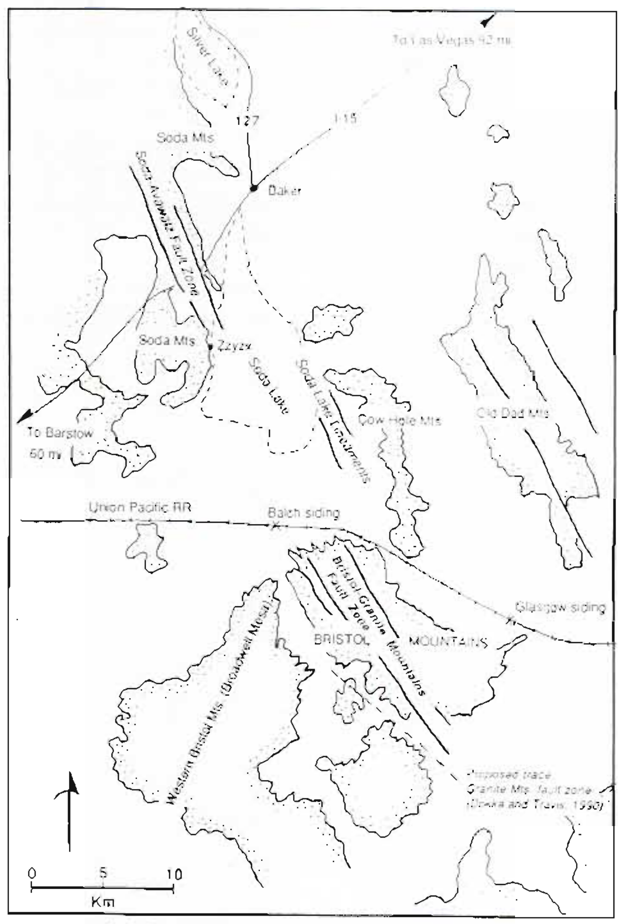

Figure 1. Map showing geographic features and fault zones referred to in this paper. Bristol Mountains Fault Zone is same as Bristol-Granite Mountains fault zone referred to in text.

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 6-10.

graphic and structural background. Kupfer and Bassett (1962) conducted reconnaissance mapping in the northeastern Bristol Mountains, the area of this study, delineating bedrock types and dividing Tertiary sedimentary rocks into "Older" and "Younger" gravels. Brady (in press) discussed Cenozoic sedimentary strata in this part of the range.

Previous Slip Estimate

Dokka and Travis (1990) proposed that the Bristol-Granite Mountains fault zone has a right lateral slip of 21.5 km based on the palinspastic reconstruction of Mesozoic plutonic rocks they interpreted to have been originally contiguous.

GEOLOGIC BACKGROUND

Northwest-striking vertical faults of the Bristol-Granite Mountains fault zone produce a pronounced northwest-trending topographic "grain" in the northern Bristol Mountains. Minor high- and low-angle faults complicate the structural pattern. Bedrock of the range is mainly Mesozoic granite, granodiorite and diorite, with minor amounts of Precambrian(?) gneiss on the western margin (Fig. 2) Sequences of Tertiary sedimentary and volcanic rocks in three fault- and unconformity-bounded basins lie within and flank the range on the west and south sides. These strata contain important information regarding the evolution of the eastern California shear zone, and are described in the next sections.

Balch Wash Sequence

The Balch Wash sequence crops out in the north-central part of the range between major branches of the Bristol-Granite Mountains fault zone. It aggregates a minimum thickness of 255 m, and is interpreted to have been deposited nonconformably on granitic basement rocks. The sequence consists of a lower unit of conglomerate, sandstone, siltstone, basalt lava and lapilli tuff, which contains at least 5 intraformational angular unconformities, and an upper unit which fines upward from conglomerate to siltstone. A north-dipping angular unconformity of 10-20° separates the lower and upper units. Dips of bedding in the upper unit decrease up section from 40° to less than 10° near the top.

Conglomerate clasts are predominantly granitic, with minor Tertiary volcanic rocks; distinctive clasts of Mesozoic silicic metavolcanic rock and red quartzite resembling Aztec sandstone are present in the lower unit. A basalt flow in the lower unit has yielded a K-Ar age of 26.7± 0.6 Ma, and a vitric tuff higher in the section yielded a K-Ar age of 26.0± 0.6 Ma (Brady, in press). A rhyolite clast

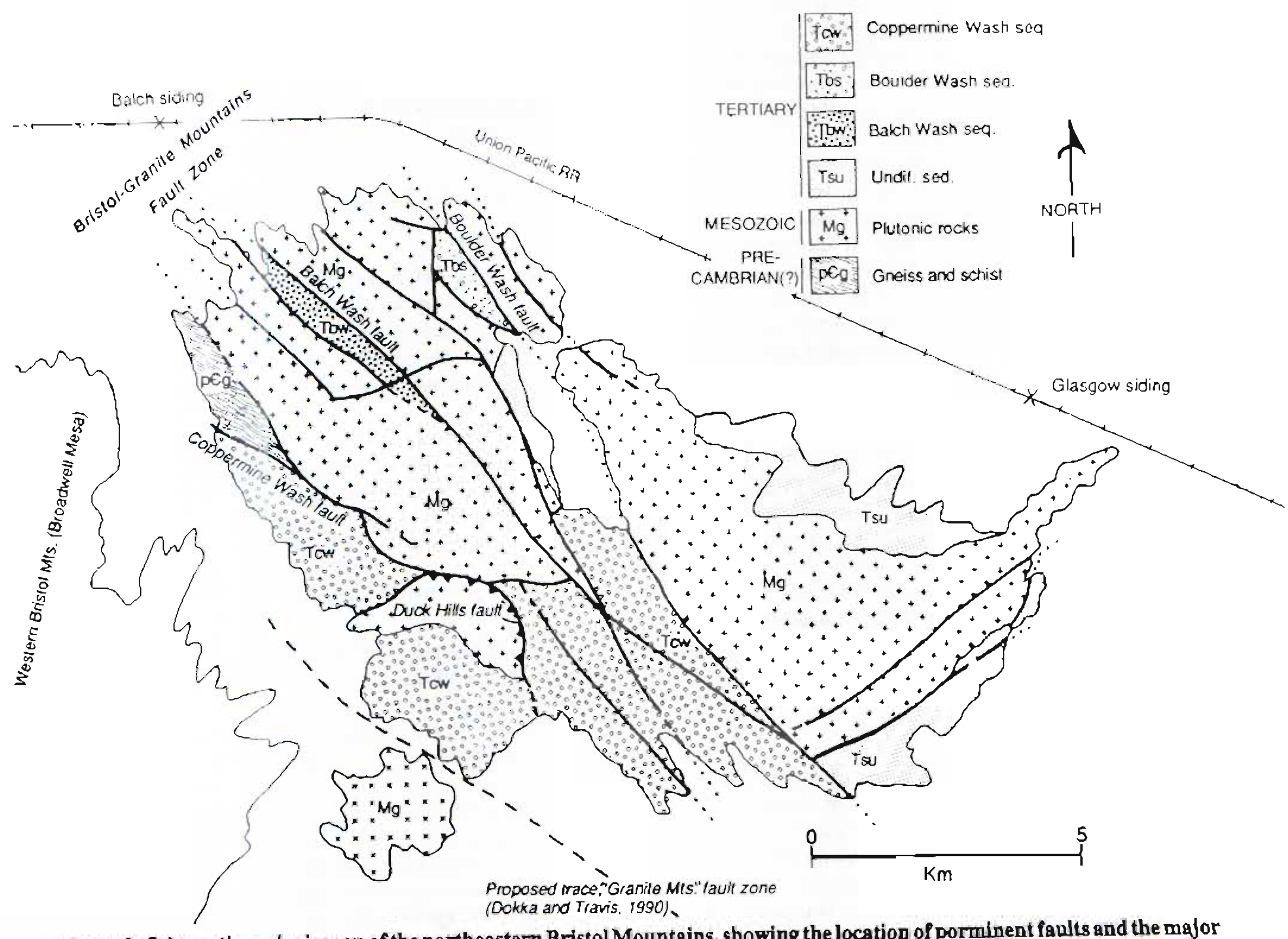

Figure 2. Schematic geologic map of the northeastern Bristol Mountains, showing the location of porminent faults and the major rock units.

near the base of the upper member provides a maximum K-Ar age for the member of 8.99±0.21 Ma. On Broadwell Mesa, sections of volcanic and sedimentary rock stratigraphically very similar to the Balch Wash sequence are also strongly tilted and faulted. They are unconformably overlain by the essentially flat-lying "basalt of Broadwell Mesa" (Dibblee, 1967) which yielded a K-Ar age of 5.28± 0.13 Ma (Brady; unpublished data). These relationships suggest that the structural and stratigraphic evolution of the two ranges is similar.

Unconformably overlying the Balch Wash sequence is a relict, alluvial fan pediment gravel upon which a soil has formed. This gravel and soil is cut in several places by northwest-striking, high-angle faults. On the surface, the bar-and-swale microtopography is reduced mainly to single clasts, the desert varnish is dense, and the clast undersides are deeply rubified; the soil has a well-developed Stage II-III petrocalcic horizon and a moderate cambic B (Bw) horizon. Based on these factors, this surface is strikingly similar to the "Qf1" surface of the Silver Lake area of Wells and others (1984) located 40 km to the north, which is Late Pleistocene in age (36,600-15,500 yr BP).

The Mesozoic metavolcanic and quartzite clasts in the lower part of the Balch Wash sequence have no presently exposed source in the greater Bristol Mountains. Furthermore, the clasts were probably not derived from local sources because the Tertiary strata within and flanking the range consistently overlie crystalline basement rocks. This indicates that if metavolcanic and quartzite had once been present as pendants within the range, these supra-crustal rocks, had already been completely eroded away before the basal (which bears these clasts) conglomerate was deposited, and therefore could not have been the sediment's source. There are two possible origins for the detritus: 1) Fluvial processes carried the sediment southwest from the Old Dad Mountains, which contain the nearest outcrops of Mesozoic supracrustal rocks (Skirvin and Wells, 1990), into a depocenter floored by crystalline rock that later was uplifted differentially between branches of the Bristol-Granite Mountains fault zone. 2) The sediment was derived from an unknown, but more proximal source which now lies buried beneath the intermontane, alluvial valleys. If this hypothesis is true, the conglomerate of Balch Wash was relatively uplifted higher than its source, again perhaps, between branches of the Bristol-Granite Mountains fault zone. Vertical tectonism associated with lateral faults has been well documented by Chinnery (1965) and others.

Boulder Wash Sequence

In the center of the range, 350 m above the adjacent valley floor, is the informally named Boulder Wash sequence (new name) composed of seven, thinning- and fining-upward sequences of cobble conglomerate and pebbly arkose probably representing middle alluvial fan deposits. The detritus is 99% granitic derived and 1% basalt aphanite with a trace of mafic dike rock—all evidently locally derived. This unit is undated, but on the basis of similar degree of induration, clast composition and texture, it is probably correlative with the upper Balch Wash sequence (mid Miocene).

Coppermine Wash Sequence

Prominent exposures of the west-dipping Coppermine Wash sequence (new name) occur all along the west and south flank part of the northern Bristol Mountains. The unit, at least 317 m thick, is a fining- and thinning-upward section of conglomerate, breccia and sandstone with minor basalt and tuff. The base is a dark red, well-bedded heterolithic conglomerate that appears to be deposited on a red-stained, saprolitic weathering surface having considerable relief. About half the conglomerate clasts are granitic-derived, and half are "exotic" metavolcanic, quartzite and carbonate clasts resembling those in the Balch Wash sequence. Although exposures of the contact are poor, the conglomerate appears to be unconformably overlain by massive, gray-to-green, monolithologic breccia composed of clasts of intermediate, plutonic rocks. There appears to be a hiatus between the conglomerate and breccia because the breccia lacks the (pedogenic?) iron cement prominent in the conglomerate and underlying bedrock. The breccia grades upsection into conglomerate, arkose and siltstone having granite and gneiss clasts nearly exclusively.

K-Ar data are not presently available to bracket the age of the Coppermine Wash sequence. The lower boulder conglomerate contains abundant clasts of pale pink rhyolite with chatoyant sanidine that strongly resembles Peach Spring Tuff exposed in the Old Dad Mountains (Skirvin and Wells,1990). If the clasts in the Coppermine Wash sequence are Peach Springs Tuff, the lower conglomerate is younger than 18.5 Ma (Nielson and others, 1990), and may be correlative with the upper member of the Balch Wash sequence.

The clast provenance in the Coppermine Wash sequence changes upsection. Clasts in the red conglomerate were derived from a source not presently existent in the Bristol Mountains; preliminary paleocurrent data indicate that transport was from the southwest, perhaps from Broadwell Mesa. However, beginning with the breccia unit, the composition reflects local bedrock types. This abrupt change in clast composition and increase in grain size is probably due to tectonic over-steepening of the mountain front caused by dip slip (east side up) on the bounding fault (Coppermine Wash fault). The upper fining sequence indicates increasing tectonic stability.

DEFORMATION IN THE NORTHERN BRISTOL MOUNTAINS

Deformation in Tertiary sedimentary rocks

Strata of the Balch Wash sequence are deformed by northeast-trending folds, but overall, they are tilted northeast; dips steepen from 35° in the older beds in the southwest part of the basin, to 70° in youngest beds in the northeast. In the northwesternmost part of the basin where two faults intersect, bedding is vertical to overturned westward.

The Coppermine Wash sequence is highly deformed. In the north, beds are tightly folded along the eastern fault contact. The unit overall dips west to southwest, decreasing from 85° on the east, to 25° on the west. In places it is folded internally, and is cut by numerous, minor, high-angle, mainly dip-slip faults.

The Bristol-Granite Mountains fault zone

The northern Bristol Mountains possess a marked northwest-trending topographic grain produced by sub-parallel, vertical faults, some of which extend for 19 km, the entire length of the range. Two of the most prominent are herein named the "Balch Wash fault" and the "Coppermine Wash fault". The deformation within fault zones appears to have occurred at a fairly shallow level and at a high strain rate. All of the major faults are marked by intense brecciation; in places the rock has been converted to a substance resembling fine-grained sand. Elsewhere, the breccia is more coarse, involving fragments up to 8 m in diameter. Nowhere is there evidence for crystal plastic deformation or mylonite development indicative of ductile faulting at low strain rates or high P/T conditions.

Balch Wash Fault. The Balch Wash fault places the Balch Wash sequence against very highly sheared, pink granitic rock. The fault varies from several discrete splays, to a diffuse shear zone nearly 45 m across containing phacoids of plutonic rock in a matrix of crushed and altered bedrock whose granitic protolith is all but indistinguishable. The trace is quite straight and the fault plane is essentially vertical over at least 10 km of exposure. Within 50 m of the fault zone, Balch Wash strata are complexly cut by minor high- and low-angle faults, and are broadly to tightly folded. In several places, fault-bounded slabs of granitic bedrock are tectonically interleaved with sedimentary strata. At the northern end of the range, the fault juxtaposes pink granitic rock on the east, against highly chloritically altered, green, granitic rock to the west over a distance of approximately 6 km. It is unlikely that the chloritic alteration developed after the faulting because it is confined to the west side of the fault, even though the unaltered rock types are nearly identical on opposite sides of the structure. Statistical analyses of slickenline orientations indicate that the dominant shear direction was lateral.

The youngest movements that can be documented on the Balch Wash occurred on the fault bounding Tertiary outcrops on the south, and on one of the minor internal faults. Along the minor fault within the Tertiary rocks Quaternary alluvial fan deposits are truncated in three places, forming scarps 1-1.5 m high, down to the east. The fault bounding Tertiary rocks on the east is overlain by an undeformed surface that appears to be equal in age (Quaternary) to the deformed surface along the southern margin. The fault bounding Tertiary rocks on the west may cut surfaces of similar age. Thus, some deformation continued into Quaternary time.

Boulder Wash area. The Boulder Wash basin is wedge-shaped, and bounded on all sides by near-vertical faults; two other high-angle faults are within the basin (Fig. 2). The fault on the east side is a northwest-striking, major through-going branch of the Bristol Mountains fault zone. A short fault on the north side strikes nearly due east, and the fault on the southwest strikes northwest; both intersect the eastern bounding fault. A fault on the northwest side of the basin connects the northern fault with another major branch of the Bristol-Granite Mountains fault zone. This geometry is suggests that the Boulder Wash basin was formed in a dilational domain between major northwest-striking faults probably having right lateral slip.

Coppermine Wash Fault. The fault along the western margin of the Bristol Mountains which separates the Coppermine Wash sequence from the crystalline bedrock to the east appears to have a dip-slip component, down to the west. The Balch Wash and Boulder Wash sequences, which lie at elevations of approximately 100 m and 225 m respectively, are topographically above the Coppermine Wash sequence. All of these units contain similar lithofacies representing deposition in similar environments. If these formations are stratigraphically related, they were probably originally deposited at similar topographic elevations. The differences in their present elevations constrains Neogene dip slip along the Coppermine Wash fault to be less than 225 m.

Reverse Faults. Numerous reverse faults are present in the southwest part of the northern Bristol Mountains. The most prominent of these is referred to here as the "Duck Hills thrust". The Duck Hills thrust is well exposed over a distance of at least 1.5 km, and emplaces crystalline bedrock northeast over the middle part of the Coppermine Wash sequence. Smaller reverse faults occur over an area of several square kilometers southwest of the Duck Hills thrust. The origin of these reverse faults is uncertain, but they may be due to transpression in a left (west) restraining bend in a branch (or branches) of the Bristol-Granite Mountains fault zone which bounds the crystalline rock on the southern end of the range (Loriz and Brady, this volume).

Kinematics and Separation, Bristol-Granite Mountains Fault Zone. Sense and slip on Bristol-Granite Mountains fault zone has not been determined with certainty due to a lack of lines or piercing points, but constituent faults are probably mainly strike slip because: 1) fault traces are straight for the entire length of their exposure; 2) fault planes are unvaryingly vertical; 3) the modal rake of slickenlines is horizontal; 4) the structural levels are similar on both sides of the faults; 5) the Tertiary basins tend to be fairly shallow, and where exposed, they are floored by rocks similar to those on their margins. If there was significant dip-slip (normal) faulting during the early Miocene such is so common regionally, it was probably constrained to the now alluviated basins between Broadwell Mesa and the Bristol Mountains, and did not occur within the range itself. Geometric evidence suggests that the faults are probably right lateral if the Balch Wash and Boulder Wash basins formed in "releasing" steps between the faults. The juxtaposition of chloritically altered granitic rock with essentially unaltered granitoid suggests a minimum of 6 km of strike separation on the Balch Wash fault.

Dokka and Travis (1990) suggested that right slip along the "Granite Mountains fault" is approximately 21.5 km based on the separation of Mesozoic plutonic rocks interpreted to have once been contiguous. However, relationships in the Bristol Mountains do not support this contention: 1) similar-appearing granitic rocks are widespread in the area, and no one outcrop is sufficiently unique to be considered as a "piercing point" from which slip can be determined; 2) outcrops of these rocks in the southwestern Bristol Mountains along the proposed trace of this fault (Fig. 2) do not show any evidence of shear or offset; and 3) locally-derived clasts in all three Tertiary sequences, and the similar (correlative?) stratigraphic sections of Broadwell Mesa and the Balch Wash sequence indicates that large (tens of km) lateral offset on faults within the range or between Broadwell Mesa and the northern Bristol Mountains is unlikely.

The northward projection of the Bristol-Granite Mountains fault zone extends along the west side of Soda Lake, but does not re-emerge in the southern Soda Mountains. The southward projection of the right-lateral, Soda-Avawatz fault zone (Grose, 1959; Cregan, in prep.) aligns with the Soda Lake lineaments (Brady, and others, 1989) on the east side of Soda Lake, but passes east of the Bristol Mountains. Soda Lake basin between these fault zones contains a minimum sediment thickness of 750 m, based on gravity measurements; seismic refraction suggests that the shallow strata are faulted on the east, but are otherwise undeformed (Brady and Negrini, unpublished data). The presence of a deep basin between right-stepping, lateral fault zones suggests that the basin of Soda Lake is also a pull-apart structure formed between the Soda-Avawatz and Bristol Mountain fault zones, and further indicates that the Bristol Mountain fault zone is right lateral.

Timing

The age of faulting is constrained by the deformation of sedimentary rocks in the Tertiary basins. The multiple unconformities in the lower member of the Balch Wash sequence, and "growth" structure (upward decrease in dip) in the upper member, indicate that tectonism was synchronous with deposition; it was most intense during the period about 26 million years ago (Latest Oligocene) and less so after about 6 million years (Late Miocene). Movement along eastern branches of the Bristol-Granite Mountains fault zone the basin probably formed the basin into which the Late Miocene(?) Boulder Wash sequence was deposited (Fig. 2). These strata were later deformed by lateral faulting that occurred largely before the Pleistocene(?) alluvial surfaces formed. A major unresolved problem is the relative importance of strike-slip and dip slip during the late Oligocene and early Miocene deposition events.

Faulting of a lesser intensity continued at least through the Late Pleistocene (as indicated by the offset soil). Unlike the earlier Tertiary events, these later movements do not appear to have triggered significant pulses of sedimentation, probably because they had a lesser dip-slip component.

CONCLUSION

The Bristol-Granite Mountains fault zone is a belt of semi-equally spaced, northwest-striking, right lateral faults that represents the easternmost expression of the Eastern California Shear zone, a region of distributed right shear nearly 25 km across. This zone forms a structural boundary between an eastern domain that underwent late Miocene to Pliocene extension and contains active normal faults, and a deeper-level terrane to the west which underwent early Miocene extension and is now dominated by Quaternary lateral faults (Brady and Dokka, 1989).

The Bristol-Granite Mountains fault zone appears to have developed during latest Oligocene time, forming several intermontane and marginal pull-apart basins which filled with volcanic rocks and coarse clastic sediment. Tectonic activity was highest through the middle Miocene, but has continued at a minor level into the Quaternary. The largest lateral displacement on faults within the northern Bristol Mountains is approximately 6 km, and vertical displacement is about 250 m. Lateral displacement on faults bounding the range is probably less than 10 km.

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Small-scale late Cenozoic faulting in the Colorado River Extensional Corridor, western Arizona and southeastern California

ANNA V. BUISING   *Department of Geological Sciences, California State University, Hayward, California 94542*

ABSTRACT

Minor faults with separations on the order of 1 m deform the Osborne Wash Formation (<~14 Ma) and Bouse Formation (<~5.5-8 Ma) in the lower Colorado River region of SE California and western Arizona. These include NW-striking reverse faults of syn- or post-Osborne Wash age, NE- and NW-striking reverse faults of syn-Bouse age, NW- to NE-striking near-vertical (strike-slip?) faults of syn-Bouse age, and NW- and N-striking oblique(?)-slip faults of post-Bouse age. Much of this deformation may reflect extension and settling in the sediment pile during basin subsidence, but some deformation may be related to regional extension and/or strike-slip faulting. The absence of recognized major faults cutting Bouse Formation or younger sediments suggests that the Colorado River trough between Parker and Cibola forms an effective eastern boundary of the Eastern California Shear zone during and after deposition of the Bouse Formation.

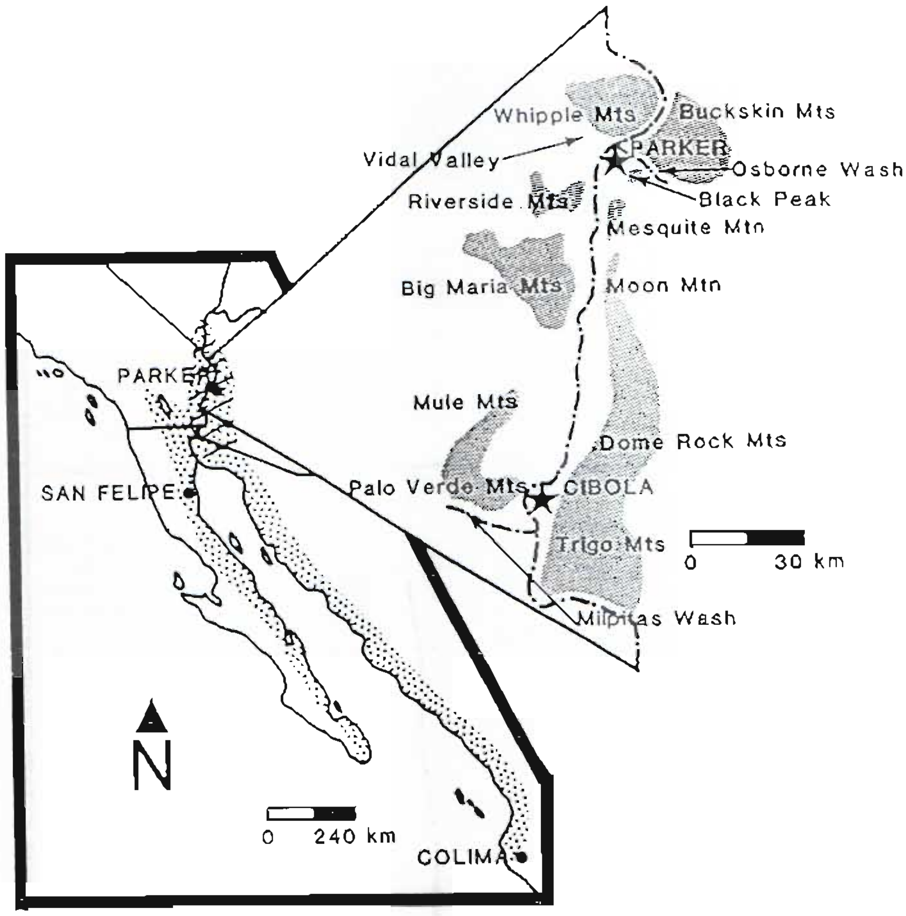


Figure 1. Regional location map. Stippled pattern shows present-day (non-palinspastic) extent of discontinuous outcrop belt of proto-Gulf of California sedimentary units and related structural trends. Hachures represent outcrop-subcrop belt of Bouse Formation. Inset shows geography of lower Colorado River region. From Buising (1990).

INTRODUCTION

This paper addresses small-scale faults affecting the Upper Cenozoic sedimentary units of the Colorado River Extensional Corridor (CREC; Howard and John, 1987) from roughly the latitude of Parker to Cibola, AZ (Fig. 1). Data presented here are drawn from a variety of sources, including work by Buising (1988, 1990; unpublished mapping 1985-1987) and by Buising and Beratan (in press; also unpublished mapping, 1989-1990). Previous studies documenting young faulting in this region include work by Carr and Dickey (1980), Carr and others(1980), Dickey and others (1980), and Sherrod (1988).

Figure 2 shows the Upper Cenozoic stratigraphy of the Parker-Cibola segment of the CREC. These units are flat-lying to gently tilted; they are exposed in more or less discontinuous erosional remnants. They range from friable to moderately indurated; fault plane exposures are extremely rare, and kinematic indicators have not been observed. In most cases, separation is less than a few meters; estimates of separation for individual structures are based on offset of beds in a single outcrop unless otherwise noted.

DESCRIPTION OF STRUCTURES

I distinguish three groups of post-14 Ma faults in the Parker-Cibola segment of the CREC, based on their ages as inferred from the units they offset: (1) syn- or post-Osborne Wash, (2) syn-Bouse (post-Osborne Wash, pre-Quaternary), and (3) post-Bouse (Quaternary).

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 11-15.

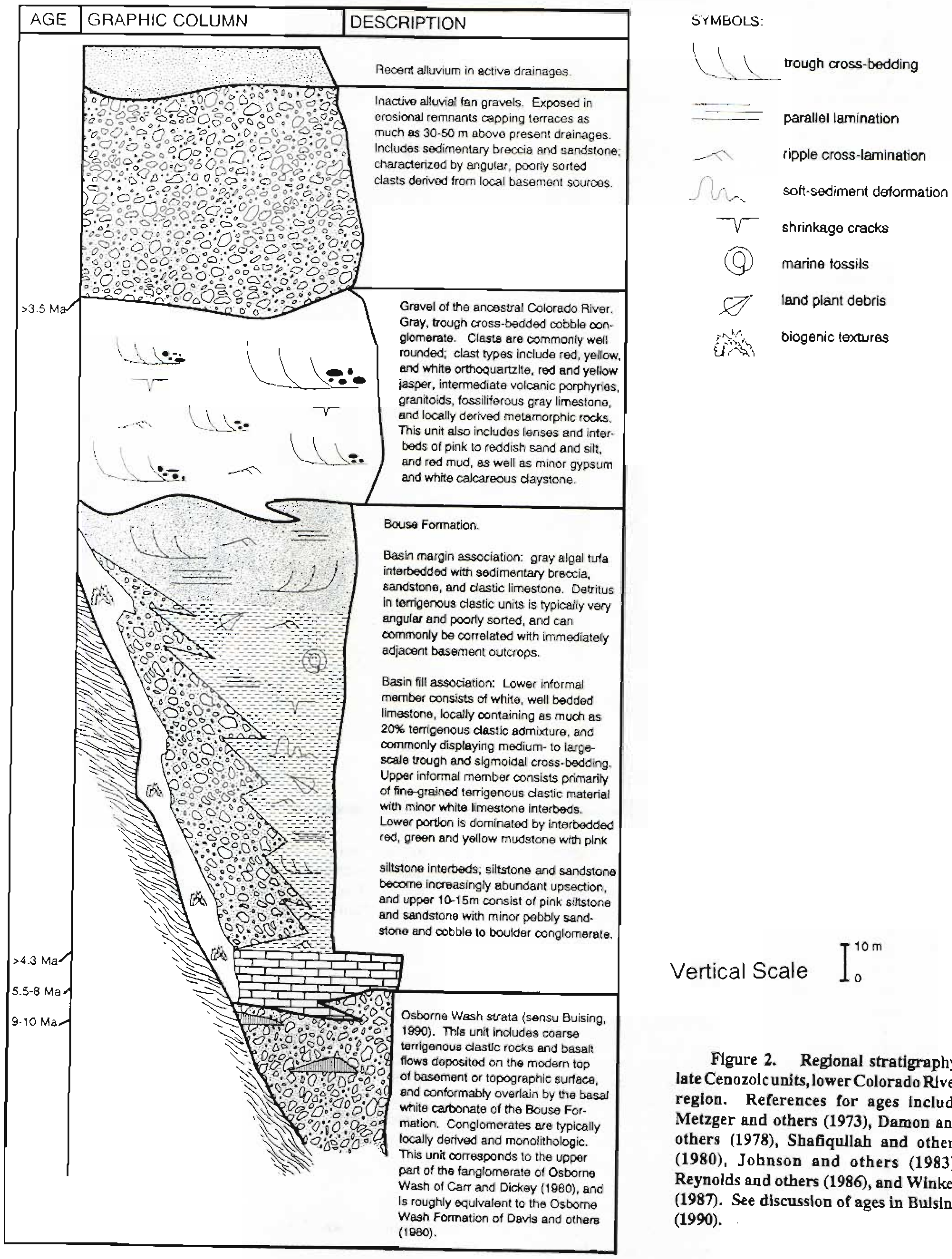


Figure 2. Regional stratigraphy, late Cenozoic units, lower Colorado River region. References for ages include Metzger and others (1973), Damon and others (1978), Shafiqullah and others (1980), Johnson and others (1983), Reynolds and others (1986), and Winker (1987). See discussion of ages in Buising (1990).

Syn- or post-Osborne Wash Faults:

These faults offset beds belonging to the Osborne Wash strata (sensu Buising, 1990; see Figure 2); they are overlapped by erosionally based Quaternary alluvium which immediately overlies the Osborne Wash strata at the relevant outcrops. Since the critical outcrops lack Bouse-Formation strata, it is not clear whether these faults represent pre-Bouse, syn-Osborne Wash deformation, or syn- or post-Bouse structures which also cut Osborne Wash beds. The syn- or post-Osborne Wash faults include high-angle northwesterly striking reverse faults and faults of unknown separation (Fig. 3). No kinematic indicators are exposed. Where offset can be established it is <1 m.

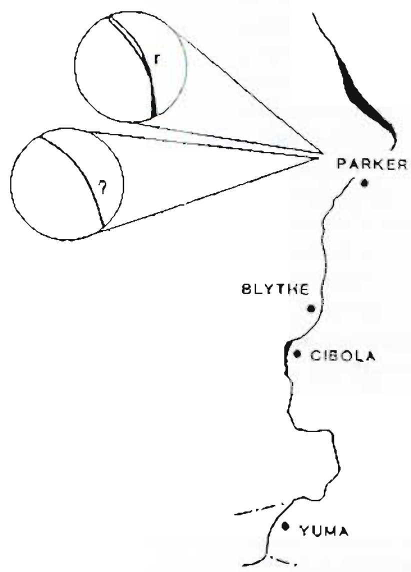


Figure 3. Regional patterns in syn- or post-Osborne Wash faulting. See discussion in text. Exact locations given in Buising (1988). Scale applies for Figures 4 and 5.

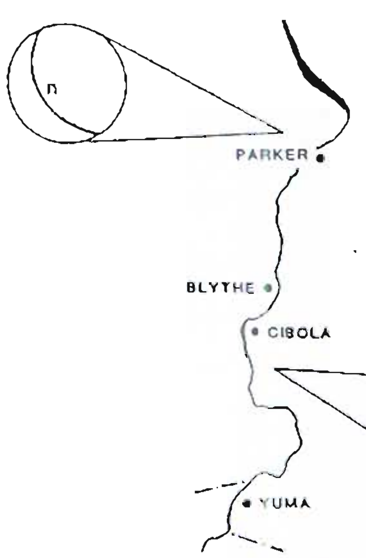
Syn-Bouse (post-Osborne Wash, pre-Quaternary) Faults:

The syn-Bouse faults affect stratigraphically lower portions of the Bouse Formation but are overlapped by undisturbed strata higher in the Bouse section. Structures which involve the Bouse Formation but are overlapped by undeformed, erosionally based alluvium are also included in this category. Syn-Bouse structures include normal- and reverse-separation faults (hereafter referred to as normal or reverse faults) and structures interpreted as minor strike-slip faults. All known faults of syn-Bouse age lack kinematic indicators.

Syn-Bouse normal faults include both northwest- and northeast-striking structures. Dips are generally between 50° and 70° (Fig. 4), but range from 16° in one instance (a minor parasitic fault) to 85°. Fault surfaces show both flat and curviplanar geometries; in one instance (northern Riverside Mountains), the fault surface is kinked or convolute. Separations are generally <1 m; Bouse Formation stratigraphy suggests that in five instances, including the fault with a kinked geometry, normal separation exceeds 1.5 m.

There are fewer reverse faults of syn-Bouse age. Examples include: (1) a minor northeast-striking, southeast-dipping thrust fault entirely within strata of the lower carbonate "member", of the basin fill association, in the Lopez Wash area near Cibola, AZ; (2) a minor high-angle structure associated with soft-sediment deformation of terrigenous-clastic basin fill strata, also near Cibola; and (3) a minor low-angle curviplanar fault associated with extreme soft-sediment deformation in deltaic clastic sediments on the northwest flank of Mesquite Mountain.

Near-vertical faults occur throughout the Bouse outcrop belt (Fig. 4), in both lower carbonate and upper terrigenous-clastic "members" of the basin fill association. These structures show very small separa-



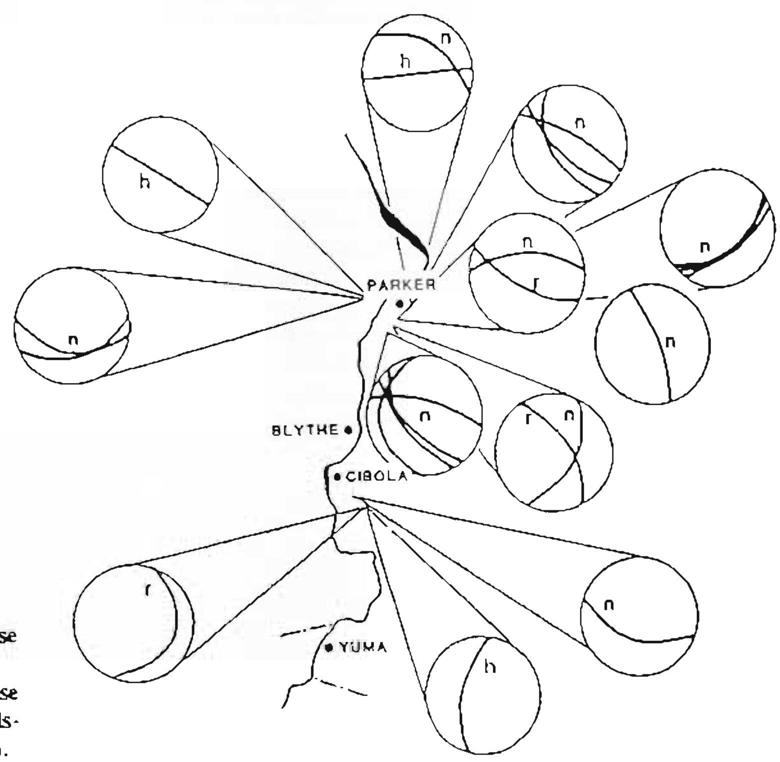


Figure 5. (above) Regional patterns in post-Bouse faulting. Exact locations given in Buising (1988).

Figure 4. (right) Regional patterns in syn-Bouse (post-Osborne Wash, pre-Quaternary) faulting. See discussion in text. Exact locations given in Buising (1988).

tion (probably <<1 m) and extremely limited extent both along strike and down dip. Strikes vary from west-northwesterly to east-northeasterly. Fault surfaces are commonly curviplanar, and commonly shallow and/or splay updip. Separation commonly differs between near-vertical and shallowing portions of the fault plane. Strata adjacent to the fault show drag along fault planes. The overall geometry of these high-angle, shallowing- and fanning-updip structures resembles "flower" or "palm tree" structures described from large-scale strike-slip systems such as the San Andreas fault zone (e.g., Sylvester and Smith, 1976). Based on this resemblance, I have tentatively interpreted these structures as minor wrench faults active during Bouse deposition.

Post-Bouse Faults:

I have documented two faults which cut Quaternary alluvium in the study area (Buising, 1988, 1990) (Fig. 5). One, in the eastern Vidal Valley, strikes 330° and dips 41°SW, juxtaposing fine-grained Bouse clastic material with overlying alluvium in normal separation. The fault surface steepens with depth; this geometry is unusual for a fault of pure normal slip and may suggest a strike-slip component of motion. Another Quaternary fault is exposed in the Lopez Wash area, near Cibola. This is a northerly-striking, east-dipping feature with a pronounced listric geometry. It shows both reverse and normal separation in the same outcrop, suggesting a component of oblique or rotational slip; the outcrop separation could also be explained by a multistage slip history, although this seems unnecessarily complex for such a minor feature. Neither of these faults shows kinematic indicators.

DISCUSSION

No major faults have been recognized cutting the Bouse Formation or younger sediments in the Colorado River trough between Parker and Cibola, suggesting that this part of the Colorado River trough forms an effective eastern boundary of the Eastern California Shear zone after sometime between 5.5 and 8 Ma (lower age bracket for Bouse Formation; see Buising, 1990). The regional significance of the observed minor faults described above is uncertain. Several points are clear: (1) NW-striking reverse faults of syn- or post-Osborne Wash age suggest at least localized NE-SW compression during or after Osborne Wash time; (2) NE-striking reverse faults of syn-Bouse age suggest NW-SE compression during Bouse time; (3) NE-striking normal faults of syn-Bouse age suggest at least localized NW-SE extension during Bouse time; and (4) NW-striking normal faults of syn-Bouse age (perhaps roughly contemporaneous with the NE-striking syn-Bouse normal faults) suggest at least localized NE-SW extension during Bouse time. Best-estimate ages for the stratigraphic units involved imply that, with the possible exception of the syn- or post-Osborne Wash faults, all of these fault sets were active within a very short period of time. Yet, if displacement on these faults was pure normal or reverse slip, they cannot represent contemporaneous regionally extensive systems. There are several possible explanations for this apparent contradiction:

1. These fault sets are not entirely contemporaneous. The faults of syn- or post-Osborne Wash age may represent a separate, early generation of deformation. The thrust fault bracketed by strata of the Bouse-basin-fill carbonate may be as old as 6-8 Ma and thus separated by as much as 2-4 m.y. in age from the normal faults within the >4.3-Ma old deltaic clastic section. However, the remainder of the syn-Bouse faults are bracketed by deltaic strata representing at most 1-2 m.y. of deposition and must be considered as essentially contemporaneous.

2. Some or all of these faults accommodated a component of strike slip, such that they represent conjugate oblique slip shear sets. In the absence of kinematic indicators, this suggestion is untestable. However, strike slip seems feasible; possible small-scale wrench faults are locally present, and strike slip has been documented in adjacent areas (e.g. Bill Williams River fault zone; Sherrod, 1988).

3. These faults sets are not regionally extensive, and represent highly variable and localized responses to regional events.

4. Some or all of the faults may be the result of soft-sediment deformation. If so, they reflect slumping of coherent, semi-brittle strata as a result of local oversteepening, perhaps triggered by tectonism. Slumping is the most likely explanation for faults such as the strongly listric, locally convoluted normal structures in the Riverside Mountains, and for the listric reverse faults associated with local extreme soft sediment deformation in the Mesquite Mountain area. It is also a possible, but perhaps less tempting, explanation for faults such as the minor thrust of the Cibola area, which are simple planar breaks with no associated soft-sediment deformation.

If (1) the high-angle reverse faults of syn-Bouse age are discounted as localized results of soft-sediment deformation; and (2) some age separation between the minor syn-basal carbonate thrust fault and the later syn-deltaic normal faulting is assumed, then the pattern of syn-Bouse deformation is reduced to normal faulting recording two roughly perpendicular directions of maximum extension. This may reflect extension and settling in the sediment pile as the basin continued to subside.

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Cenozoic Faulting in the Little San Bernardino - Orocopia Mountains Region, Southern California

JOHN C. CROWELL *Institute for Crustal Studies and Department of Geological Sciences, University of California, Santa Barbara, CA 93106-1100.*

Within mountain ranges bordering the northeastern margin of the Salton Trough and Coachella Valley, southern California, gneisses and granitic rocks of Precambrian and Mesozoic age are mainly exposed. Relatively small tracts of marine Middle Eocene and nonmarine Lower Miocene also occur in the eastern Orocopia Mountains. Elsewhere late Cenozoic rocks are found only as small slices within fault zones or lie buried beneath the few alluviated valleys. As yet the fault slices of unconsolidated conglomerate and sandstone are undated but are probably late Cenozoic in age (Fig. 1).

A few of the faults, such as the Blue Cut, break modern alluvial deposits and form fault scarps and are therefore considered as active. Other faults in this geographic sector are inferred to have been active in late Cenozoic time because they have similar trends with those known to cut young beds and contain soft clayey gouge probably formed at shallow depths.

Faults in this geographic region are here grouped into six categories: 1) Old faults of pre-early Cenozoic age, such as those intruded by dated Mesozoic plutons, including the Red Cloud Thrust (Powell, 1981, 1982). These are not discussed here further. 2) Inferred faults of Eocene age, such as those deemed responsible for steep topography along cliffs at Middle Eocene shorelines bordering outcrops of the Maniobra Formation (Crowell and Susuki, 1959; Advocate and others, 1988). 3) Inferred faults of latest Oligocene and Early Miocene age viewed as required for steep topography during the deposition of coarse conglomerates of the Diligencia Formation, including sedimentary breccias of probable landslide origin (Crowell, 1975; Spittler and Arthur, 1982; Squires and Advocate, 1982). This formation was laid down in intermontane basins, and coarse deposits grade laterally into playa deposits, including evaporites. Tectonically controlled irregular topography is implied, but the location of probable faults responsible is still undocumented. 4) Straight faults of roughly east-west trend, such as the major Pinto Mountain, Blue Cut system, Chiriaco, and Salton Creek - Aztec Mines Wash system, and the relatively minor Porcupine Wash, Smoke Tree Wash, Substation, Victory Pass, Corn Springs Wash, and Ship Creek faults (Fig. 1). These faults at places cut Pleistocene (?) alluvium and terrace deposits. Locally, however, the youngest alluvial deposits are not truncated, showing that these parts of the faults are not now active. 5) Faults with orientations and inferred histories relating them to the San Andreas Fault, the major fault bordering this geographic sector on the southwest. These faults include the Hidden Springs, Painted Canyon, and other faults in the Mecca Hills and the foothills of the Little San Bernardino Mountains. 6) Problematic fault zones, discussed next below, such as the Clemens Well Fault, the Dillon Fault or Dillon Shear Zone, and the Orocopia fault system.

The Clemens Well Fault, named by Crowell (1960), trends northwesterly through the Orocopia Mountains and truncates the Diligencia Basin on the southwest (Crowell, 1962, 1975). It trends subparallel to the nearby San Andreas Fault but so far as now known does not intersect it (Fig. 1). If extended on northwestward from where it is last exposed within the Orocopia Mountains, it meets a region of disturbed Quaternary alluvium with minor fault scarps that are also on trend from the Hidden Springs Fault (a branch of the San Andreas Fault) and the east-west striking Chiriaco Fault. It is not yet known which fault is responsible for this disturbed topography. On the southeast, the Clemens Well Fault is probably truncated by the Salton Creek - Aztec Mines Wash Fault, a member of the east-west set (Powell, 1981). It is therefore likely that it is older than this set and may be a mid-Cenozoic strand of the San Andreas system, as advocated by Smith (1977) and other geologists. If so, the disturbed modern topography along its northwestward extension is probably the result of activity on the presumed younger faults: the Hidden Springs and the Chiriaco. The Clemens Well Fault displays a vertical zone of crushed rock and gouge up to 10 m wide in several canyons within the Orocopia Mountains, and slices of volcanic rocks similar to those well to the southeast within the walls of the fault suggest a minimum right slip of several kilometers. Basement rocks across it are so different, however, that its total slip is probably many times greater. Investigations recently undertaken suggest that the complex fault zone, especially where it dips steeply to the northeast and is enmeshed with strands of the Orocopia Thrust (?) system, is in fact an oblique-slip normal fault as shown by some kinematic indicators, with displacement primarily down to the northeast (Goodmacher and others, 1989). If so, it may be a member of the flattening down-dip normal faults associated with mid-Tertiary extension (e.g., *papers in* Frost and Martin, 1982).

The Orocopia Fault, first named the Orocopia Thrust (Crowell, 1960), is well exposed on the northern and eastern flanks of the Orocopia Moutains. This complex fault zone has emplaced highly fractured granitic, gneissic, and anorthositic-syenitic rocks above Orocopia Schist (correlative broadly with Pelona Schist) (Crowell, 1962, 1975). Over the years, however, the nature, timing, and depth of displacements along the many fault strands, have been controversial, and many regional studies bear on the interpretation of its history (e. g., Dillon and others, 1990). Mylonite along the fault is interpreted as formed along deep thrusts or burial faults, on the one hand, or by deep exhumation faults with normal-slip along them, on the other. These exhumation or unroofing faults are viewed as related to the up-arching and erosion of the Orocopia Antiform which is thus considered a metamorphic core complex. The Orocopia fault system is also folded as are also the schists immediately below it, and broken and comminuted basement rocks above. These structures are associated with clay gouge and brittle fracturing, and were probably formed during Oligocene and Miocene detachment faulting or perhaps younger events (Robinson and Frost, 1989). Modern landsliding downslope to the northeast has affected these incompent rocks as well.

The Dillon Fault or Dillon Shear Zone (Rogers, 1965) is a major broad belt of crushed and broken basement rock with slices of Ceno-

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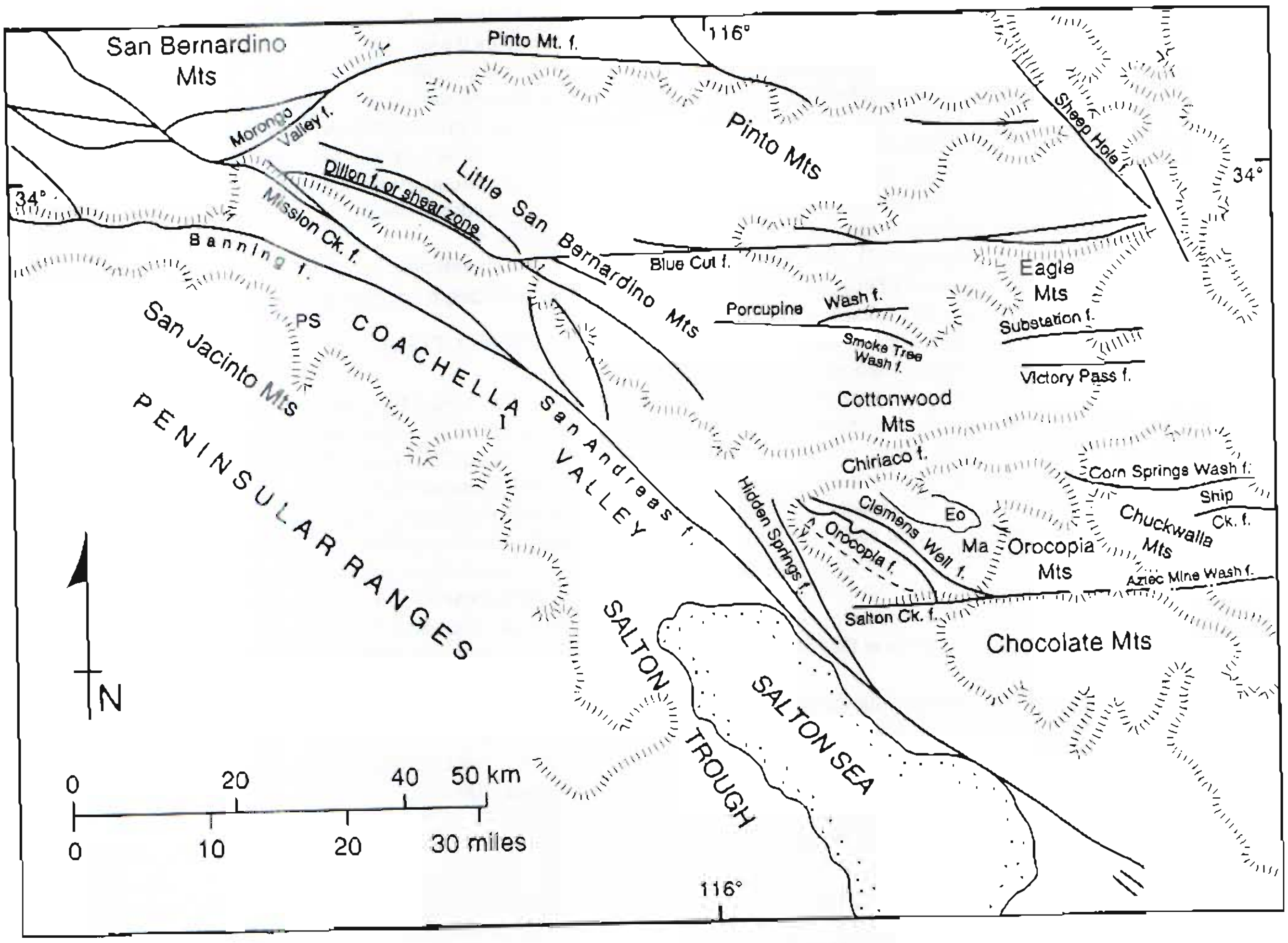

Figure 1. Map showing location of geographic and geologic features mention in text. *f.* = *fault*. Em = Eocene Maniobra Formation; Md = Oligo-Lower Miocene Diligencia Formation. PS = Palm Springs; I = Indio. The Orocopia Antiform is shown as a dashed line with arrows. Base modified from Jennings (1977).

zoic conglomerate and sandstone locally caught along discrete faults within the belt. The shear zone, at places several kilometers wide, trends through the foothills of the Little San Bernardino Mountains and joins splays of the San Andreas Fault on the south and the Mission Creek Fault on the northwest. The Blue Cut Fault curves from a roughly east-west to northwest trend upon joining the Dillon Shear Zone, where the basement rocks are especially broken and brecciated. Southeast of this juncture, the Dillon Shear Zone is less marked, and continues toward the western Orocopia Mountains where its relationship to the Clemens Well and Hidden Springs faults is still unclear. Skylab photographs of the region suggest that panels of terrane between the regional east-west trending faults are slightly rotated clockwise where they extend into the Dillon Shear Zone. The belt of broken rock along the slopes of the Little San Bernardino Mountains has not yet been mapped and investigated at a scale large enough to elucidate its tectonic history. The total displacement and tectonic significance of the Dillon Shear Zone are still unknown.

The conspicuous set of east-west trending faults in this region includes four major members from north to south: the Pinto Mountain Fault with a maximum known left slip of about 16 km shown by the offset of a distinctive porphyritic intrusive rock (Dibblee, 1975), the Blue Cut and its several subparallel strands with a maximum known left slip of about 6 km deduced from offset of correlated near-vertical contacts within the basement terrane (Hope, 1969; Powell, 1981), the Chiriaco Fault with about 11 km of left offset demonstrated by offset dikes and contacts (Powell, 1975, 1981), and the Salton Creek - Aztec Mines Wash fault system. Rocks on either side of the Salton Creek sector show few common characteristics, but if a suspected antiform in the Chocolate Mountains to the south matches with that in the Orocopia Moutains that brings Orocopia Schist to the surface, the left offset of the antiformal crest is about 10 km. Powell (1981) joins the Salton Creek Fault with the Aztec Mines Wash Fault to the east across a wide spread of alluvium, and reports a left slip of basement contacts of about 8 km. The several minor east-west trending faults (Fig. 1) do not offset north-striking belts in the basement gneisses more than a few kilometers each. Several on trend apparently do not connect at the surface, such as the Porcupine Wash - Substation faults (Hope, 1969; Powell, 1981), and the Smoke Tree Wash - Victory Pass faults. The accumulative left slip across all of these faults between the Pinto Mountain and the Salton Creek - Aztec Mines Wash Fault is about 55 km. The system probably originated in late Pliocene or Pleistocene time, judging from the small recognized offsets, brittle shattering of the rocks, and the presumed age of sparse slices of alluvium caught along some of them, and a few of the faults are still active. Members of the fault system probably are present within the Chocolate Mountains to the southeast of the Orocopia Mountains, and include the faults of the Mammoth Wash system (Dillon, 1975).

Tectonic blocks of the Little San Bernardino - Orocopia Mountains sector have been rotated clockwise as deduced from paleomagnetic measurements from volcanic rocks at eleven discrete localities within this region, and extended to include the Pinto, Eagle, and Chocolate Mountains (Carter and others, 1987). Rotations at these sites appear to average about 40°, except in the Diligencia Basin within the eastern Orocopia Mountains, where they are measured as high as 170°. Younger unrotated volcanic rocks crop out at the northeastern edge of the Eagle Mountains. Under the assumption that the rotations are all related in time, the youngest volcanic sequences have an age between 6.4 and 4.5 Ma and the tectonic rotations are Pliocene and Quaternary in age (Luyendyk, this publication). The large clockwise rotations in the Diligencia Formation may be due to accumulated simple shear near the San Andreas Fault. Inasmuch as simple shear is still underway along the San Andreas belt, the rotations are probably ongoing as well. It is unlikely that there is much internal tectonic rotation in the Little San Bernardino - Orocopia region before the laying down of the volcanic rocks because gneissic units show very little deflection or bending from north to south as they are mapped by Powell (1981).

The pattern of young folds and faults along the margins of the Salton Trough suggest a basic control by simple shear associated with the transform displacements of the San Andreas Fault (Crowell, 1985). Southwest of the Little San Bernardino - Orocopia region, the San Andreas Fault itself is viewed as a through-going shear, and the Hidden Springs and other faults with similar trend and characteristics, as synthethic faults (R shears) (Wilcox and others, 1973). The east-west trending set of left-slip faults constitute the antithetic set (R' shears). The orientation of folds oriented obliquely to the San Andreas where young deposits predominate, with horsts and grabens roughly normal to their axes, fits the scheme as well (e.g., in the Indio Hills, Keller and others, 1982). It is therefore likely that the sector extending for an unknown distance to the east of the San Andreas Fault is undergoing simple shear even though reference surfaces and other reference features within the basement terranes to document it are lacking. Nonetheless, these granitic and gneiss blocks are probably being folded. Most of the region also displays a marked conjugate joint system, with elements of the system trending both northwest and northeast (Powell, 1981). Such a joint pattern also suggests partial control by simple shear.

In summary, the Cenozoic tectonic history of the region includes several different and overlapping events. Burial thrusting probably prevailed into the Paleogene Period from the Cretaceous Period when plate convergence predominated, as shown by mylonites and metamorphic facies within the Orocopia Schist and along the Orocopia Thrust. Unroofing or exhumation followed, first at depth, and then more shallowly as the Orocopia Core Complex evolved, along with its attendant antiform and detachment features. Perhaps the first stages of this extensional regime resulted in mid-Eocene faulting, and the deposition of the Maniobra Formation at the surface. Somewhat later, in the Late Oligocene and Early Miocene, extension culminated, resulting in deposition of the Diligencia Formation. Listric normal faults or arrays of down-to-basin planar faults prevailed. Next came displacement along the Clemens Well Fault, perhaps in mid-Miocene time, a fault that may be a mid-Miocene strand of the San Andreas system. In the Pliocene, marked clockwise rotation of blocks and panels was underway, followed and accompanied by simple-shear imprinting across the terrane. Simple shear, associated with faulting and rotations, is probably still ongoing. Much still remains to be discovered through seismic profiling in order to learn more about the depth and shape of presumed discontinuities upon which rotations and deformation of surface panels takes place. Much can also still be learned through careful mapping and investigations of exposed rocks in the field, including additional paleomagnetic, petrographic, and geochemical work.

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Tectonic Mobility of the San Andreas Fault Belt Bordering the Mojave and Colorado Deserts, Southern California

JOHN C. CROWELL *Institute for Crustal Studies and Department of Geological Sciences, University of California, Santa Barbara, CA 93106-1100.*

Faults and related structures of the San Andreas fault system extend across the southwestern United States from the deep Pacific Ocean to within Arizona and Nevada. Particularly active and conspicuous strands, including the San Andreas Fault itself, border the Mojave and Colorado Desert regions on the southwest, and constitute the boundary of the region primarily under consideration in this workshop (Fig. 1). Since its inception in mid-Cenozoic time, this fault system has broadened and right-slip displacements have accumulated. Parts of the Mojave - Colorado Desert terrane have been truncated by the present San Andreas fault belt, and some have been displaced so that they are now located up to several hundred kilometers relatively northwestward. Discrete episodes in this history of movements along the bordering San Andreas belt are recognizable within the rock record accompanied by changes in structural style and rates of displacement. These match well with plate-tectonic events deduced from the pattern of magnetic anomalies on the Pacific floor to the west of California (Atwater, 1989). The time stages of displacement history are described here briefly, working back from the present into the geologic past.

The southwestern United States is now undergoing deformation related to the San Andreas transform boundary as shown by earthquake activity, geodetic measurements, and geomorphic interpretations. Active faults with northwesterly trend, subparallel to the San Andreas Fault itself, are conspicuous in the Mojave Desert (Dokka and Travis, 1990). Deformation is particularly marked along the San Andreas belt extending from the Coast Ranges southeastward through the Transverse Ranges, and into the opening head of the Gulf of California in the Salton Trough. Some rotation of small tectonic blocks between the San Andreas and San Jacinto faults is suggested by the interpretation of earthquake first-motions in the San Gorgonio Pass region (Nicholson and others, 1986), and clockwise rotation of blocks in the western Transverse Ranges is still underway (Jackson and Molnar, 1990).

Plio-Pleistocene tectonic activity along the San Andreas belt, extending back to about 5 Ma, is especially noteworthy, and is associated with the progressive opening of the Gulf of California. In the Big Bend Region of the central Transverse Ranges, west of the triangular Mojave Desert block, older faults of the San Andreas system, such as the San Gabriel fault, were abandoned at about 5 Ma (Crowell, 1982). After this abandonment, the main strand of the system broke across this region and through Cajon Pass and San Gorgonio Pass into the Salton Trough (Crowell, 1982). In late Pliocene or early Pleistocene time, transpression across this new course of the San Andreas, including both the Big Bend and the evolving Little Bend in the San Gorgonio - Cajon Pass region (Meisling and Weldon, 1989), is associated with the sharp rise of the Transverse Ranges themselves (Sadler, 1982a, b). From northwest to southeast, the high mountains such as the Mount Pinos - Frazier Mountain massif, the Tehachapi - San Emigdio Mountains, the Liebre - Sawtooth massif, and the San Gabriel, San Bernardino, and San Jacinto Mountains were elevated, as shown by summit surfaces, some of which are capped with Pleistocene gravels. At places, nonmarine sediments of Plio-Pleistocene age with provenances preceeding uplift are caught as slices within fault zones associated with the uplift (Sadler, 1982a,b). These high mountains did not exist previously. The timing of the uplifts is closely associated with an increase in the component of transpression (an increase in the convergence angle) across the plate boundary (Atwater, 1989; Harbert, 1991), and fits the history of contraction across the central Coast Ranges (Page and Engebretson, 1984; Namson and Davis, 1988; Medwedeff, 1989).

From 5.5 Ma to the present, the geology along the San Andreas belt in southern California is dominated by the breaking through of the main fault from the head of the Gulf to joining with its counterpart in the Coast Ranges. These events follow upon the opening of the Gulf of California, as documented at its mouth by magnetic anomalies on the sea floor (Londsdale, 1989). The breakthrough and associated transpression were accompanied by fault slicing, uplift of nearby ranges, and by drainage changes carrying sediments to new depositional sites. Total offsets along the main San Andreas Fault during this interval are about 250 km, or at a rate of about 5 cm/yr. Along the northeastern flank of the Salton Trough paleomagnetic data suggest increasing clockwise block rotation in approaching the San Andreas Fault from the northeast (Terres, 1984; Carter and others, 1987; Luyendyk, *this volume*). In the Big Bend region, uplifted and exhumed portions of the northwestern San Gabriel Fault, now exposed along the eastern flanks of the Frazier Mountain thrust system, are interpreted as rotated clockwise by about 30 degrees by movements associated with the nearby modern San Andreas Fault (Crowell, 1950). The pattern of Plio-Pleistocene faults and some folds, especially along the Salton Trough borders, imply that simple-shear partially controlled their arrangement inasmuch as Riedel shears (R and R') (antithetic and synthetic faults) are recognizable (Wilcox and others, 1973). To the southwest in the northern Peninsular Ranges, faults of the San Andreas system, such as the San Jacinto and Elsinore, and several within the Mojave Desert to the northeast, are regarded as having originated and evolved during Pliocene to Holocene time. At about the same time, the deep Ventura, Los Angeles, and southern San Joaquin basins were strongly compressed (Crowell, 1987).

The next oldest tectonic episode recognized along the San Andreas belt bordering the Mojave - Colorado Desert block spans the time between about 12 Ma and 5.5 Ma. In the Big Bend region on the northwest, the San Gabriel Fault was active beginning about 12 Ma as shown by the age of the Violin Breccia (Ensley and Verosub, 1982; Crowell, 1982). The breccia is well dated by both paleontology and magnetostratigraphy, with the oldest beds documenting a rising fault scarp on the southwest at about 12 Ma. Deposition of the Violin Breccia and the ending of major right slip on the fault ended at about 5 Ma (Crowell, 1982). The fault was continuously active during this

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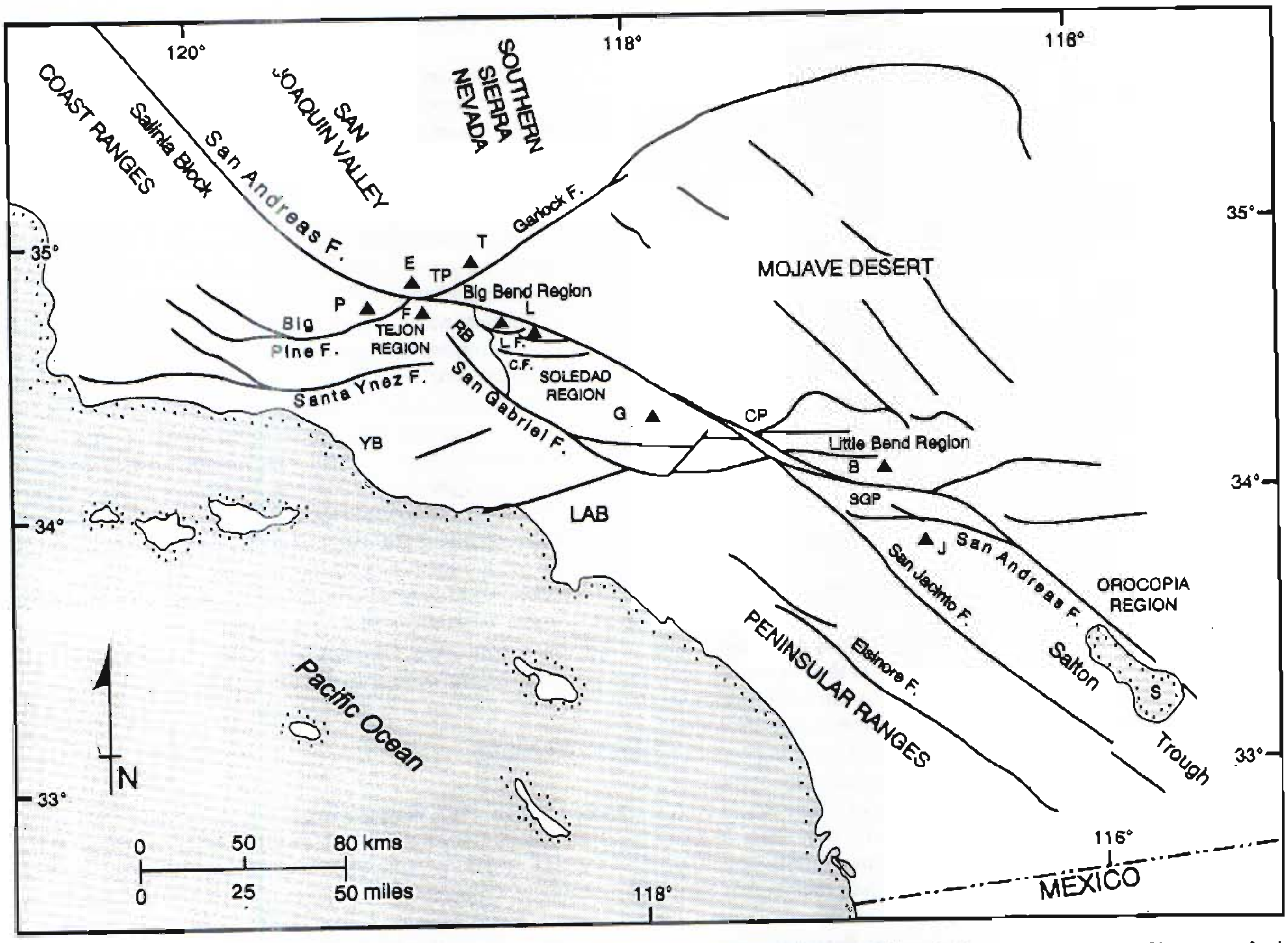

Figure 1. Map showing location of geographic and geologic features mentioned in text. Abbreviations: *f.* = *fault*, *C* = *Clearwater fault*, *L* = *Liebre fault*, B = San Bernardino Mountains, E = San Emigdio Mountains, F = Frazier Mountain, G = San Gabriel Mountains, L = Liebre - Sawtooth Mountains, J = San Jacinto Mountains, P = Mount Pinos, S = Salton Sea, T = Tehachapi Mountains, CP = Cajon Pass, SGP = San Gorgonio Pass, TP = Tejon Pass, LAB = Los Angeles Basin, RB = Ridge Basin, VB = Ventura Basin.

interval and offset older rocks from those correlated with them in the Soledad region by a total of about 60 km. Although the San Gabriel Fault is dismembered and offset in the eastern San Gabriel Mountains, strands of the fault made their way through the San Gorgonio Pass region into the Salton Trough region during the late Miocene. This is shown by similarities of several basement types and sequences of Eocene and mid-Tertiary sedimentary and volcanic rocks n the Orocopia region, which are so similar to those in both the Soledad and Tejon regions as to preclude their repetitions independently (Crowell, 1960, 1962). During the three decades since this correlation was first proposed, additional work by many investigators has reenforced its acceptability and the conclusion that the two major strands of the San Andreas system in southern California (the San Andreas and the San Gabriel) have offset these terranes about 60 km on the San Gabriel, and about 240 km on the San Andreas proper (e. g., Bohannon, 1975; Ehlig and others, 1975; Powell, 1981, 1982). This makes a total of 300 (perhaps as much as 320 km) on the combined strands since about 12 Ma, a displacement history which fits well with that identified in the central Coast Ranges (e. g., Stanley, 1987). Again, it is noteworthy that plate-tectonic reconstructions dovetail with this interval of tectonic activity on land. They show a marked change in style at about 12.5 Ma when the tectonic pattern offshore of southern California shifted from one primarily of crustal fragmentation and oblique extension. The Rivera Triple Junction "jumped" far to the south to an oceanic region offshore from the future mouth of the Gulf of California (Atwater, 1989).

In southern California, if the three terranes (Tejon, Soledad, and Orocopia, Fig. 1) are brought back together in a reconstruction, difficulties with the fit in detail are conspicuous. For example, the Orocopia antiform, which brings Orocopia Schist to the surface, lies to the south of the Oligo-Miocene Diligencia Basin, whereas its counterpart in the Soledad region, the Sierra Pelona antiform, lies to the north of the Vasquez Basin, a basin correlated with the Diligencia. In addition, marine Middle Eocene beds of the Maniobra Formation lie unconformably on distinctive granite in the Orocopia Region, and fossiliferous marine Eocene beds of quite similar lithology and age lie unconformably on similar granite in the Tejon Region along the southern flank of Mt. Pinos (Crowell, 1962; Carman, 1964). The similarities in these and other associations suggest that they were close to each other before displacement, but reconstructions so far attempted fail to bring them back together so that they are satisfactorily near each other (Bohannon, 1975; Tennyson, 1989; Powell, 1981). In short, considerable deformation, including block rotation, uplift, disappearance of slices through erosion or burial, and perhaps extension or thrusting, seem to have accompanied the displacement of the three terranes. Tectonic rotations of blocks west of the San Andreas belt, which started in Early Miocene time, continued into the mid- and late Miocene, and are still weakly underway (Luyendyk and others, 1985; Jackson and Molnar, 1990). Moreover, some of the displacement along faults of the San Andreas system may well have preceeded the 12 to 5.5 Ma stage.

Late Miocene reconstructions favored at present (e. g., Crowell, 1962; Powell, 1981) involve melding the San Gabriel and San Andreas faults in the Cajon - San Gorgonio regions, but the details of their joining have not yet been satisfactorily worked out. Such a scheme, however, brings the terrane underlying Ridge Basin on its east (Liebre Mountain region) against the Orocopia region far to the southeast on the other side of the San Andreas belt. The San Gabriel Fault was probably the active strand of the San Andreas system during this 12 to 5.5 Ma interval, so that Ridge Basin, which lies to the east of the San Gabriel Fault, was part of the Colorodao Desert block. As the basin filled, the terrane bounding the basin on its west moved relatively northwestward, strewing coarse deposits of the Violin Breccia into the basin as it moved alongside. Several faults underlying Ridge Basin on the east were active during this interval, such as the Clearwater and Liebre (Crowell, 1982). This is documented by unconformities and overlaps along the eastern margin of Ridge Basin which show that these two faults ceased movement at about 8 and 6 Ma respectively. They therefore contributed to the right-slip displacement during this late Miocene interval, but similarities in rocks on either side of both faults suggest that their combined displacement is only about 20 km. Both the Liebre and Clearwater fault systems appear to be truncated by the present San Andreas Fault on the east, but their counterparts have not yet been identified in the Colorado Desert block.

In addition, younger beds of Ridge Basin, or those laid down between about 8 and 5 Ma are of the same age as the Imperial and Bouse Formations of the Salton Trough region (Winker, 1987; Buising, 1990). These three Upper Miocene formations were all deposited in a low swale (often referred to as the proto-Gulf of California) before the true opening of the Gulf. As yet, however, there is no satisfactory reconstruction of the paleogeography at that time showing how these units were geographically related.

Before about 12 Ma, evidence for displacements along the San Andreas belt bordering the Mojave - Colorado Desert block has not been identified. Old faults with mylonitic rocks presumably formed at mid-crustal depths abound, but these probably formed during pre-San Andreas extension, thrusting, and other events. It is not known whether any of these older movements were related to the onset of the San Andreas transform. Plate-tectonic reconstructions, however, indicate that the edge of the North American continent was affected by the impingement of the Pacific Plate as far back in time as 30 Ma (Atwater, 1989). Before 30 Ma, subduction predominated back into Mesozoic times. Many geologic events are documented in coastal California and its borderland during the 30-12 Ma interval, but how far transform related displacements reached inland is unknown as yet. Continuing research on the history of emplacement of the Salinia Block, now west of the San Andreas in central California, may show that slices of it came from between the Sierra Nevada and the Peninsular Ranges, or in part from the region now occupied by the Salton Trough. If so, mid-Cenozoic or even older strike-slip strands, and other structures, will be required in the San Gorgonio Pass and adjacent regions.

In summary, blocks have been sliced from the Mojave - Colorado Desert region during late Cenozoic time, and have been moved northwestward in stages during the past 12 million years or so, and perhaps before. During these displacements, older blocks within the San Andreas belt and now sited to the west have been overprinted in different styles as the deformation has continued. These have been subjected to more rotation (Luyendyk and others, 1985; Hornafius and others, 1985), and greater contraction than those to the east (Yeats, 1983). Rocks constituting the desert blocks have been affected in somewhat different ways and many of the noted fragmentations and rotations in both regions are older than 12 Ma. Blocks to the southwest of the San Andreas belt will now display evidences of these events before offset, rotation, and overprinting of a different style. In fact, in working out the sequence and style of older tectonic events in the Mojave - Colorado Desert regions, documentation may be better preserved in the region west of the San Andreas belt, because here more datable strata and volcanic rocks are preserved. To understand the tectonic mobility of the region therefore requires awareness of these types of movements through time, and the conceptual and graphical removal of rotations, strike-slip, fragmentation, and other overprinting styles in stages back into the geologic past.

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Neogene Movements on Calico and Camp Rock Faults, Mojave Desert, California

THOMAS W. DIBBLEE, JR. *University of California, Santa Barbara, CA 93106*

OVERVIEW

The Calico and Camp Rock faults are northwest-trending high angle faults from 6 to 9 mi. (9 to 14 km) apart in the central Mojave Desert, along which movements have been primarily right slip. Each is a zone of one or more faults about 130 mi. (200 km) long and die out just north of the east-trending Pinto Mountain fault (Fig. 1). Each is aligned with a fault zone for another 40 mi (64 km) to the northwest that dies out just south of the east-trending Garlock fault (Fig. 1). These two major fault alignments between the left slip Pinto Mountain and Garlock fault are in large part the easternmost of a group of major northwest-trending right slip high angle faults in the western and central Mojave Desert. The geology along the faults mentioned is shown in Dibblee (1960, 1964a and b, 1966, 1967a, b, c, and d, 1968, 1970, 1990, and Dibblee and Bassett, 1966).

CALICO FAULT ZONE

The Calico fault extends along the SW margin of the Calico Mountains diagonally SE through the Mojave Valley, thence along or near the NE margin of the Newberry-Rodman Mountains SE to Hidalgo Mountain where it bifucates and extends into the alluviated valley of Mesquite Lake (Fig. 1). NW from the Calico Mountains, the Calico fault is aligned with a group of NW trending faults in the Mud Hills, and farther NW with the Blackwater fault, which dies out in the Lava Bed Mountains just south of the Garlock fault (Fig. 1). The faults in the Mud Hills displace the synclinally folded Barstow and underlying formations (Miocene) with small amounts of right slip (Dibblee, 1968). The Blackwater fault deforms granitic basement as well as unconformably overlying Miocene formations. The Pleistocene Black Mountain is buckled into anticlinal folds by transpression associated with right slip movement on the Blackwater fault (Dibblee, 1968, 1980).

In the Calico Mountains Miocene volcanic and sedimentary formations are squeezed up somewhat anticlinally and along the SW margin of this range are thrust SW along the Calico fault against Miocene and Pleistocene formations. In the southern part of these mountains near Yermo, Miocene volcanic rocks and underlying Mesozoic metavolcanic rocks are elevated on the S side of this fault (Dibblee, 1970).

The Calico Mountains are squeezed up adjacent to and north of where the Calico fault veers eastward from its otherwise N40°W trend and near where this fault is intersected by the westward extension of the Manix fault (Fig. 2) along which a small amount of left slip is probable. The eastward bend of the Calico fault and uplift of the Calico Mountains mostly N of the Manix fault is attributed to impediment of right slip movement on this segment

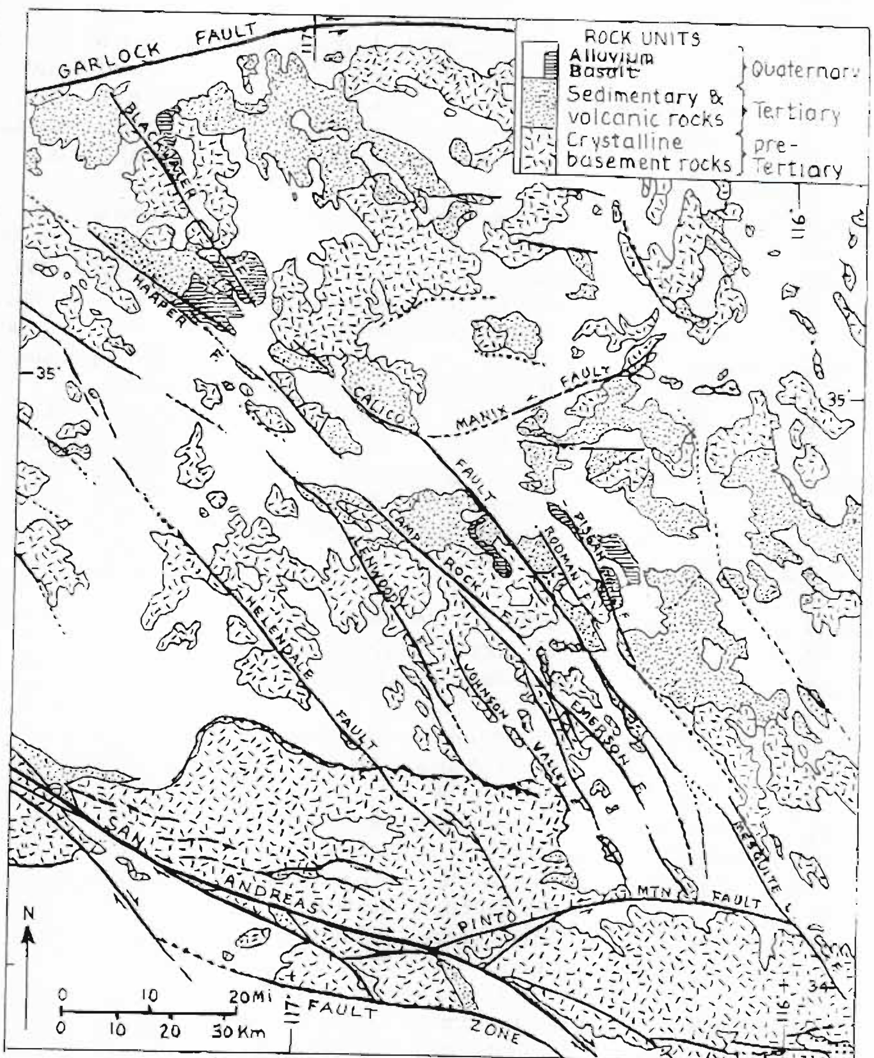

Figure 1. Simplified geologic map of the central Mojave Desert showing major Quaternary faults. Note the proximity of Quaternary basalt lavas to the Blackwater-Calico fault trend.

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by the intersection with the Manix fault of probable left slip. This condition apparently caused right slip on this segment of the Calico fault to be converted to compressive uplift of the Calico Mountains (Dibblee, 1980).

Across Mojave Valley SE of the Calico-Manix fault intersection, the Calico fault appears prominently on aerial photographs where it strikes about S42°E. It must form a barrier to ground water moving E down this valley in the alluvium to cause ground water to back up and reach the surface along the SW side of the fault. The resulting wet alluvium has apparently anchored wind-blown sand grains to accumulate as low sand dunes. Lack of a scarp on this segment of the fault (Fig. 2) suggests that recent movements are entirely strike-slip. In the Newberry - Rodman Mountains, units in the thick SW-dipping series of Oligocene-early Miocene volcanic and sedimentary rocks show an estimated 6 mi. (9 km) of right separation across the Calico fault (Fig. 2; Dibblee, 1980, 1991).

Southeastward from the Newberry Mountains, the Calico fault extends, partly as two strands, to Hidalgo Mountain, where it splays into two somewhat diverging branches (Figs. 1 and 3; Rogers, 1967; Jennings, 1977). Throughout this area this fault system transverses an area of Mesozoic granitic basement eroded to low relief, overlain by Quaternary granitic alluvial fill in the valley areas. This segment is paralleled on the east by the Rodman, Pisgah and other SE-trending faults (Fig. 3). Hidalgo Mountain is unusual because it is an uplift of granitic basement between diverging strands of the Calico fault which form prominent escarpments on each side of this mountain. This uplift has a generally smooth, even crest that is much higher than adjacent hills of granitic basement and its flanks are deeply dissected (Dibblee, 1967). Several small adjacent canyons that drain its south slope are deflected northwestward as they cross the south strand of the Calico fault near its south base by active right slip movement. The lower but jagged hills of granitic basement west of Hidalgo Mountain (Fig. 3, Dibblee, 1967) appear to be the crestal part of an old mountain range that is in large part buried by alluvium. This range remained static and was eroded to low relief while Hidalgo Mountain has been actively elevated between strands of the Calico fault.

Southeastward from Hidalgo Mountain, the north strand of the Calico fault forms low scarps in Pleistocene alluvium, then becomes buried under Holocene alluvium W. of Deadman Dry Lake (Fig. 3). Between this fault and a parallel fault 3 mi. (4 km) east Pleistocene alluvium is slightly compressed into folds with axes trending WNW (Dibblee, 1967a, 1967b) apparently the effect of right lateral drag or shear movement between the two faults. Farther SE of where the north strand of the Calico fault is buried by Holocene alluvium it may reappear as the Mesquite Lake fault (Fig. 3). This fault transects Mesquite Lake where it appears on aerial photographs. East of Twenty-nine Palms, this fault forms a prominent SW-facing scarp in Pleistocene alluvium that is tilted NE from the fault (Dibblee, 1968). This fault intersects the Pinto Mountain fault of which inferred relations are discussed in Dibblee (this volume). Southeastward from Hidalgo Mountain, the south strand of the Calico fault forms a topographic break in east-sloping Pleistocene alluvium, with apparent uplift on the NE side (Fig. 3).

CAMP ROCK FAULT

The Camp Rock fault extends from the low hills about 4 mi. (6 km) south of Daggett straight SE along and near the SW border of the Newberry and Rodman Mountains for about 25 mi. (32 km), then dies out SE under alluvium south of Iron Ridge. About a mile SW a splay of this fault appears as the Emerson fault (Fig. 3) along a NE-facing low scarp of granitic basement. This fault in turn splays into four strands in low mountains to the SE, two of which extend nearly to the Pinto Mountain fault. At its northwestern tip the Camp Rock fault dies out, or is buried under Quaternary alluvium SW of Daggett. Aligned to the

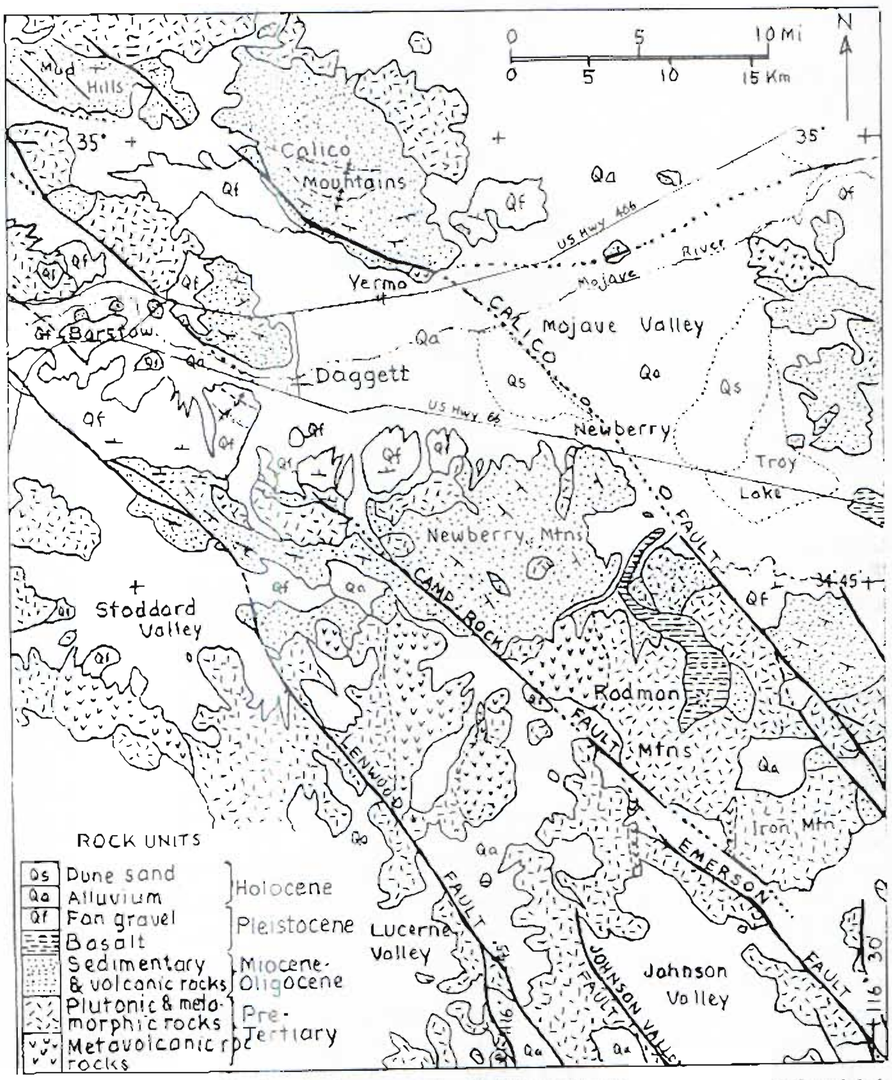

Figure 2. Simplified geologic map of the Calico and Camp Rock faults in the vicinity of the Calico, Neberry and Rodman Mountains. Note the right lateral offset of Tertiary rocks and of metavolcanic rocks.

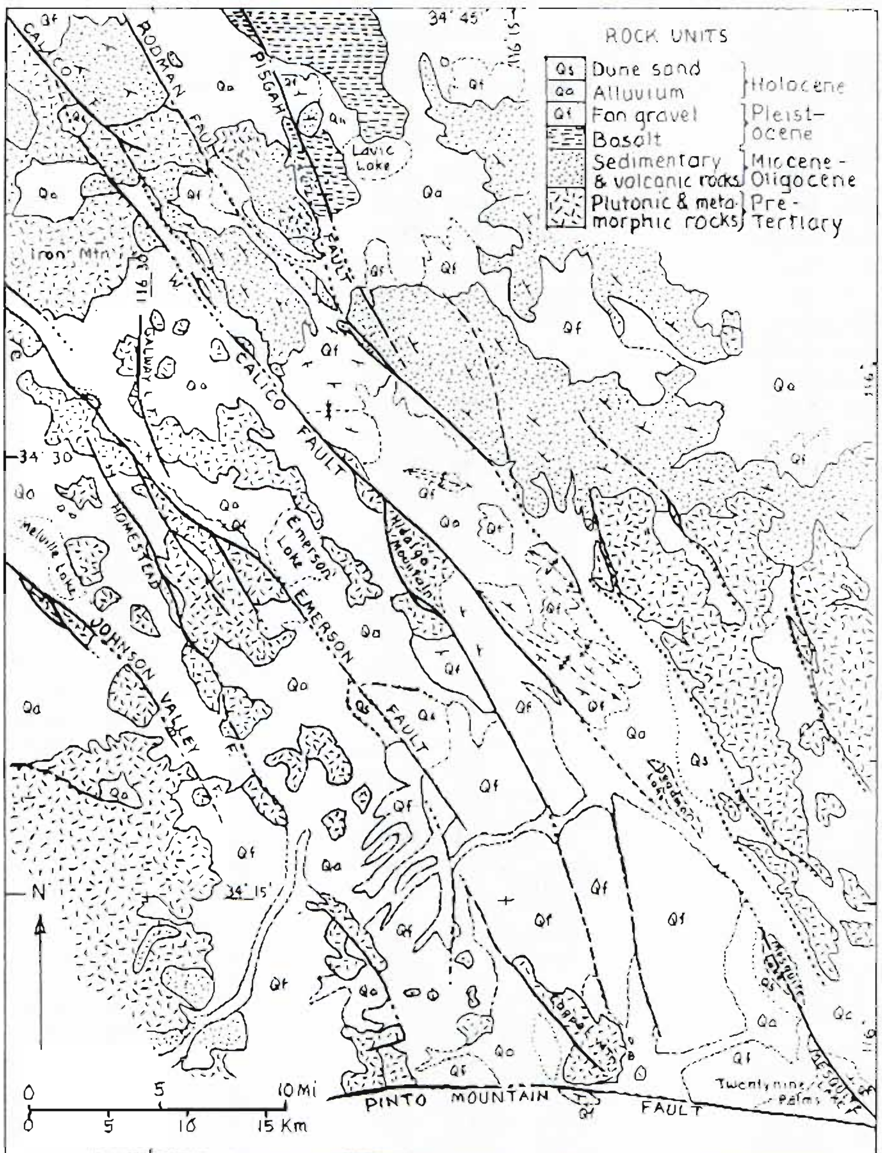

Figure 3. Simplified geologic map of the Calico, Emerson, and associated faults between the Iron Mountains and Twentynine Palms. Note the folding of Pleistocene fan gravels east of the Calico fault, probably due to right-lateral shearing.

NW across the Mojave River is the Waterman fault along the straight SW base of the Waterman Hills NW of Barstow. Aligned NW of this fault is a group of faults of the Harper-Gravel Hills fault zone along the NE margin of Harper Valley (Fig. 1). These faults and their right lateral drag effects on Miocene formations and the Pleistocene Black Mountain basalt flow are described in detail by Dibblee (1986b).

Along the Camp Rock fault north-trending metavolcanic rocks and associated granitic rocks in the Rodman and Ord Mountains appear to have been displaced by about 4 mi. (6 km) of right slip movement. The overlying Oligocene-early Miocene volcanic and sedimentary series in the Newberry Mountains and Daggett Ridge area have been displaced by lesser amounts of right slip (Fig. 2, Dibblee, 1990).

The Emerson fault and its southward splays are within a terrane of low relief in Mesozoic granitic rocks and alluviated valleys. The northwestern segment forms a low scarp in granitic basement facing NE toward the SW-facing scarp of the Camp Rock fault of the southern Rodman Mountains. South of Iron Ridge the Emerson fault and its main or NE strand form a prominent NE-facing escarpment along the NE border of low mountains of granitic basement west of Emerson Dry Lake (Fig. 3). In these mountains other faults splay and diverge to the south. Small amounts of right separation on these faults are observed in plutonic rock units. SE of these mountains the main strand disappears under the large alluviated valley of Emerson Dry Lake, but is interpreted to reappear to the SE as several faults in Pleistocene alluvium, and as the Copper Mountain fault, which may extend to the Pinto Mountain fault.

The most westerly strand in the mountains west of Emerson Dry Lake strikes about S30°E for about 17 mi (27 km) and forms a low NE-facing scarp on a low ridge of granitic basement. This fault is referred to as the Homestead fault which caused a magnitude 4.9 earthquake on March 15, 1979, and aftershocks (McJunken, 1980). During that event left-stepping ground ruptures in the soil formed along the south segment of this fault as a result of right-slip movement.

NW of Emerson Dry Lake the Galway fault splays northward from the main strand of the Camp Rock fault for about 6 mi. (9 km) along the eastern base of a line of low hills of granitic basement. Movement on this fault generted a magnitude 5.2 earthquake on May 31, 1975 that formed left-stepping ruptures in alluvial gravel as the effect of right slip (Beeby and Hill, 1975).

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Geology and Inferred Tectonics of the Pinto Mountain Fault, Eastern Transverse Ranges, California

THOMAS W. DIBBLEE, JR. *University of California, Santa Barbara, CA 93106*

INTRODUCTION

The Pinto Mountain fault was first recognized by Vaughan (1922) and named by Hill (1928). It is traceable for 55 km (47 mi) and is a high angle fault along the southern border of the eastern San Bernardino Mountains in its western sector and near the northern border of the Pinto Mountains along its eastern sector. Direction of movement on this east-trending fault was unknown although physiographic relations mentioned above imply uplift on the north side along its western sector and on the south side along its eastern sector. Hill and Dibblee (1953) suggested possible left-lateral movement on the Pinto Mountain (also then known as the Warren's Well) fault, because of its east-west trends parallel to the Garlock and other similar faults of known left-lateral movement. Even though there is little if any physiographic indication of left lateral movement on the Pinto Mountain fault during late Quaternary time, later geologic mapping (Dibblee, 1967a, 1967b, 1968, 1975, 1980, 1982) revealed evidence of left lateral separation or displacement of pre-Cenozoic rock units of the crystalline basement complex, as much as 16 km (11 mi) near the central part of the fault (Fig. 1).

GEOLOGIC SETTING

The Pinto Mountains fault is one of the major east-trending transverse high angle faults of late Cenozoic left-slip movement associated with the San Andreas fault in southern California. The Pinto Mountain and three other east-trending faults to the south about 17 km (12 mi) apart extend eastward from the San Andreas fault within the crystalline basement complex of the Eastern Transverse Ranges. All are apparently genetically related (Dibblee, 1982). The Pinto Mountain fault is nearly aligned with the west-trending zone of faults that extends westward from the San Andreas fault zone along the southern boundary of the Transverse Ranges (Fig. 1).

The Pinto Mountain fault is located within part of the Mojave block composed of pre-Cenozoic crystalline metamorphic and plutonic rocks exposed in mountain areas, overlain by late Cenozoic terrestrial deposits in low land and valley areas. These rock units are as shown on figure 2.

QUATERNARY MOVEMENTS

The Pinto Mountain fault appears to have been active mostly during Pleistocene time. West of Yucca Valley (Fig. 2) it splays into two strands that veer SW toward their juncture with the San Andreas fault (north branch). Both form prominent escarpments along margins of elevated masses of crystalline basement.

The main or north strand forms a south-facing escarpment along the south margin of the elevated eastern San Bernardino Mountains; westward it forms a trench-like rift through the southern part of those mountains. The south strand or Morongo Valley fault forms a prominent NW-facing escarpment along the NW margin of the Little San Bernar-

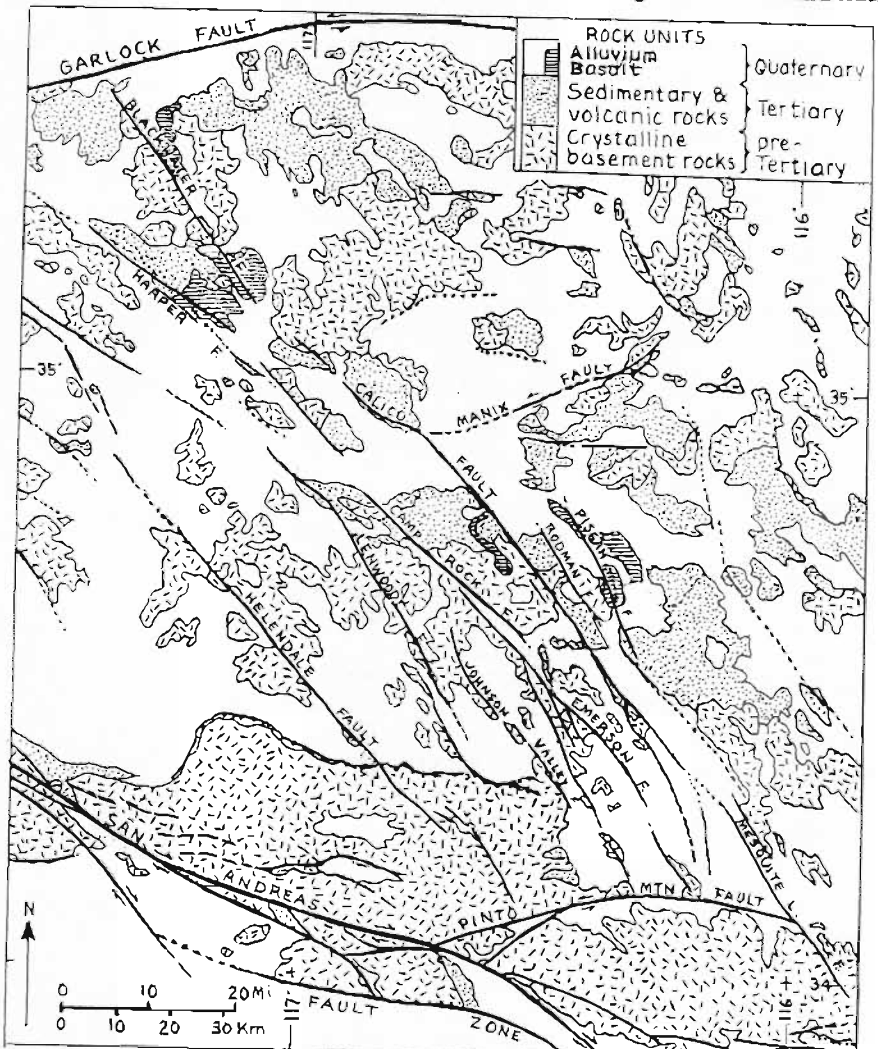

Figure 1. Simplified geologic map of the central Mojave Desert showing the location of the Pinto Mountain Fault in relation to other Quaternary faults in the central Mojave Desert.

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 28-31.

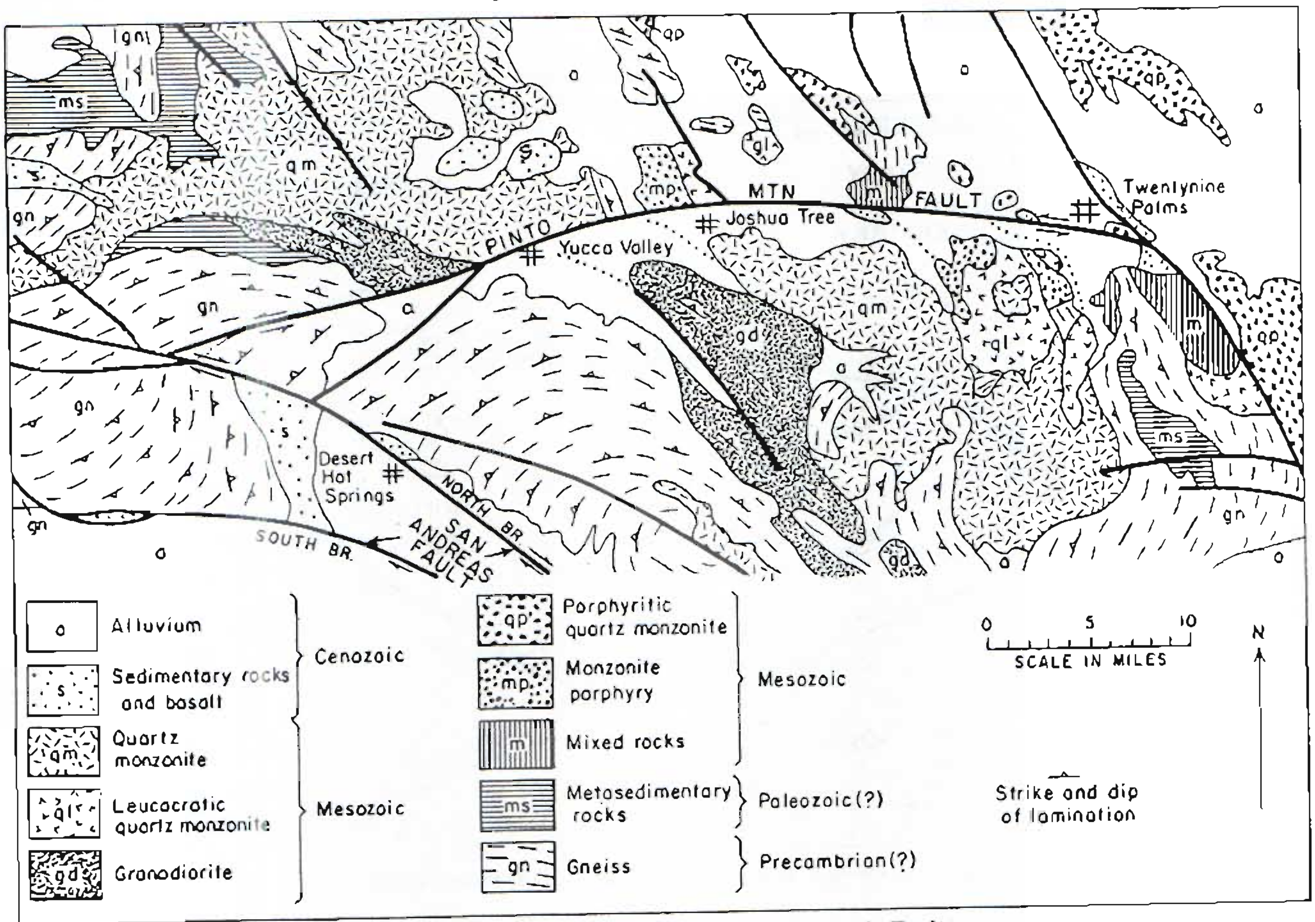

Figure 2. Geology along the Pinto Mountain Fault.

dino Mountains (Fig. 3). The Morongo Valley fault was interpreted by Matti et al (1985) to abruptly curve NW into two minor NW-trending faults I had mapped (Dibblee, 1967a). I do not accept this interpretation.

These two diverging strands of the Pinto Mountain fault bound a depressed or unelevated wedge, including Morongo Valley, that separates the eastern San Bernardino Mountains from the Little San Bernardino Mountains. This wedge appears to be a small pull-apart graben. This depression may be the effect of left-slip movement on these diverging strands and/or right slip movement on the San Andreas fault (north branch) as it veers westward from Coachella Valley.

East of Yucca Valley, the Pinto Mountain fault is a single strand striking nearly east-west for 35 km (28 mi). Between Yucca Valley and the town of Joshua Tree it forms a south-facing escarpment along the south margin of the easternmost San Bernardino Mountains (Fig. 4). Eastward from Joshua Tree this fault transects the alluviated desert plain with little evidence of its existence except for scattered small hills of elevated Pleistocene alluvial gravel along its course, and springs along a mile-long lineament at the Twenty-nine Palms oasis. On the largest of these hills, such as one just west of this oasis (Fig. 5) and another about 8 miles farther west, the gravel dips rather steeply away from the fault. This condition indicates that the alluvial gravel has been tilted locally by movements on the Pinto Mountain fault.

The Pinto Mountain fault intersects the Mesquite Lake fault just east of Twenty-nine Palms. Whether or not it extends eastward beyond this intersection and how far, is a matter of interpretation. Some investigators claim evidence that it extends at least 3 miles east-southeastward (K. A. Howard, oral communication, 1991). However, this needs to be carefully field-checked. The eastern segment of the Pinto Mountain fault veers southward as it intersects the southeast-striking Mesquite fault (Fig. 1). Southeast of this intersection the Mesquite fault veers slightly eastward, then resumes its normal SE strike (Fig. 2, 6). These conditions presumably are the effect of conflict or impediment of lateral movements on these faults SE of their intersection. The resulting impediment has converted strike slip to vertical or compressive movements, mostly along the Mesquite fault, with uplift of the relatively high mountains on the SW side of that fault. Northeast-sloping alluvial fans deposited in the lowland along the NE side of this mountain are broken by several scattered scarps parallel to the Mesquite fault.

From these conditions it is evident that the Pinto Mountain fault definitely terminates eastward against the Mesquite fault and does not extend beyond it. However, the low mountains of basement rocks east of the Mesquite fault appear to be broken into several blocks bounded by north-of-east trending faults nearly parallel to the Pinto Mountain fault, but are not aligned with it and are only local.

CONCLUSIONS

The Pinto Mountain fault is one of the major north of east-trending left-slip transverse faults within the Mojave block. The Pinto Mountain fault evolved during Pleistocene time if not earlier, between the NW-trending right slip San Andreas fault system and the Mesquite fault. Maximum cumulative left-slip on the Pinto Mountain fault amounts to about 17 km (11 mi) on its central part as indicated by displacement of basement rock units (Fig. 1). Left-slip on the Pinto

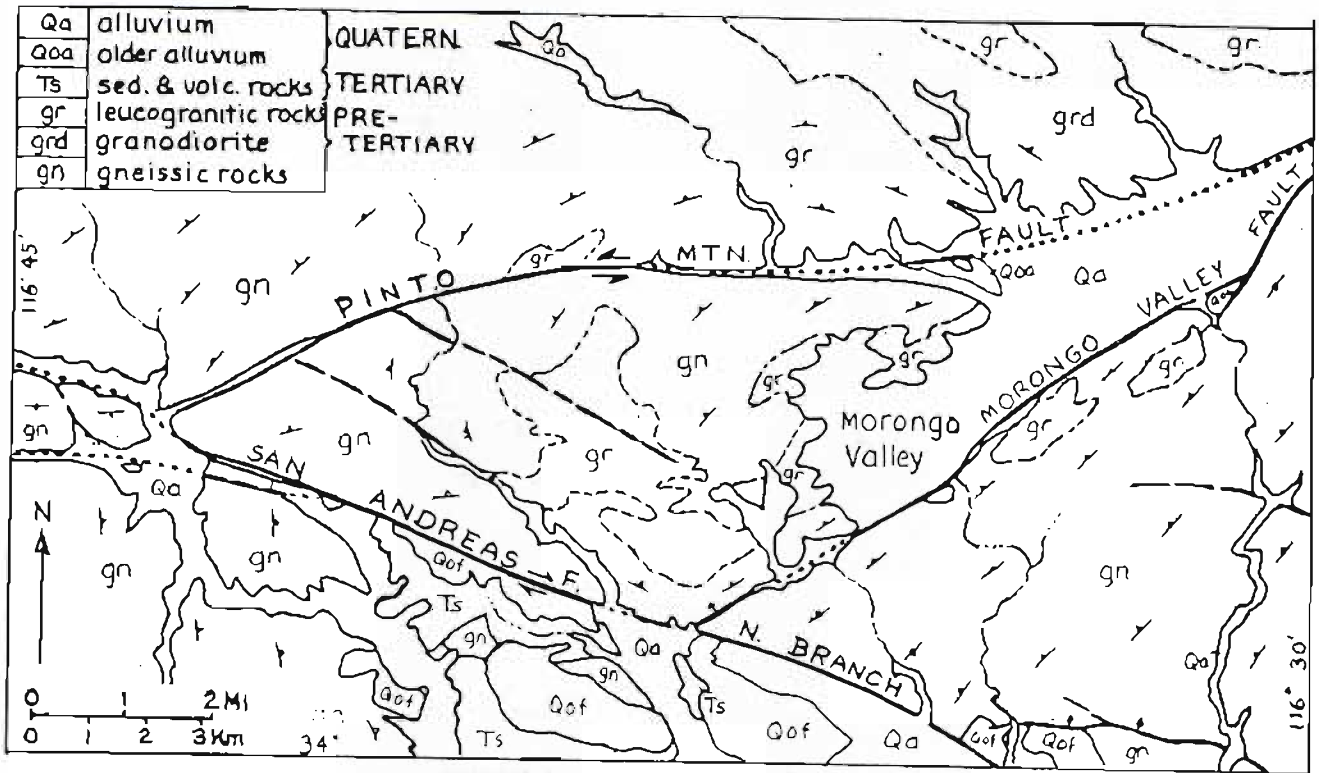

Figure 3. Geology of the western segment of the Pinto Mountain Fault.

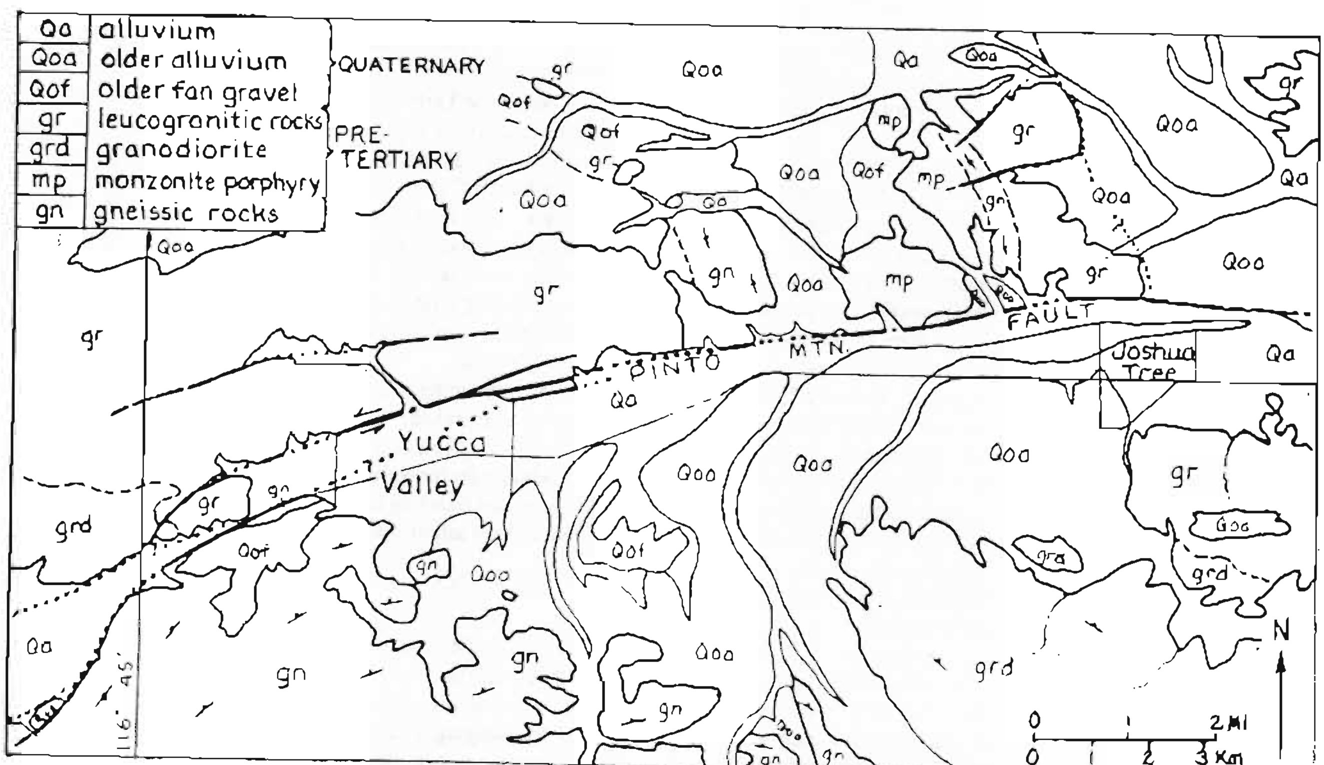

Figure 4. Geology of the central segment of the Pinto Mountain Fault.

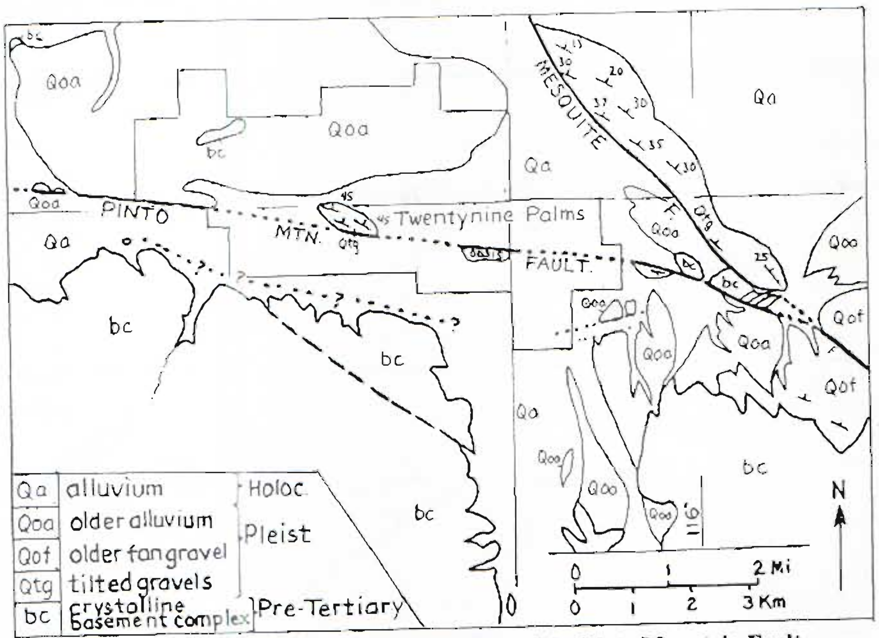

Figure 5. Geology of the eastern segment of the Pinto Mountain Fault.

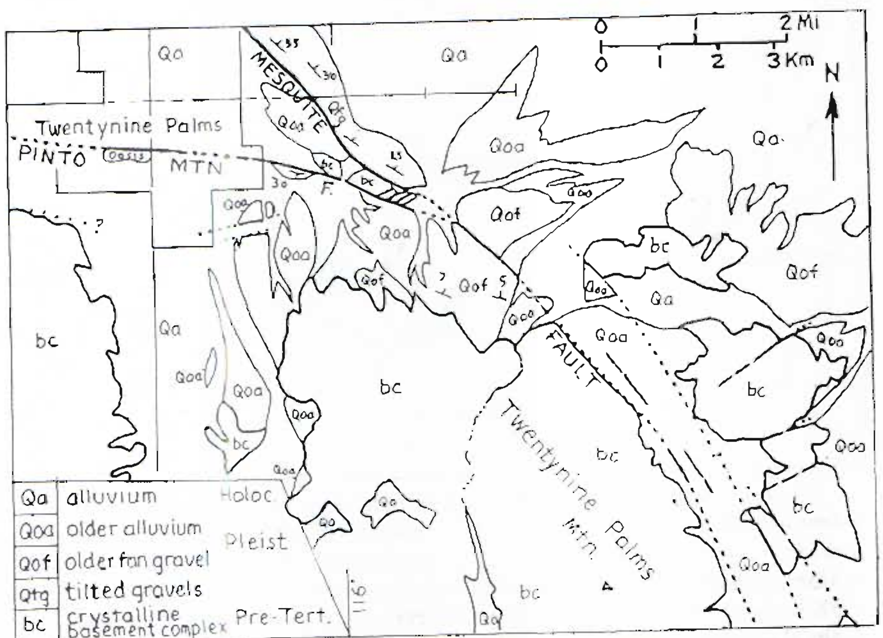

Figure 6. Geologic map of the intersection of the Pinto Mountain and Mesquite faults.

Mountain fault as it evolved in Pleistocene time has apparently impeded right slip on the pre-existing San Andreas fault system at and near the intersection of these faults. These conflicting movements were thereby converted to compressive movements that elevated the part of the Mojave block north of their intersection to form the San Bernardino Mountains. (Dibblee, 1968b, 1975, 1982).

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Neogene faulting in the Goldstone-Fort Irwin area, California: A progress report

JOHN P. FORD — *Jet Propulsion Laboratory, Pasadena, California*
DAVE F. MACCONNELL, ROY K. DOKKA — *Department of Geology, Louisiana State University, Baton Rouge, Louisiana*

Combined use of Landsat thematic mapper (TM), SPOT panchromatic, synthetic-aperture radar (SAR) images, and field mapping have shown that Neogene faulting is more pervasive throughout the Goldstone-Fort Irwin area (northeast Mojave Desert block) than has previously been reported. Color patterns on enhanced TM images denote compositional differences among exposed rocks and sediments. This helps to discriminate surface materials at infrared wavelengths. It has allowed detection of faults where topography is not diagnostic and it helps to constrain the extent and amount of strike-slip on east- and northwest-striking faults. Registration of TM to corresponding SPOT panchromatic data improves spatial resolution in the images. Radar coverage enhances topographic features that are oriented transverse to the illumination. This improves the detection of fault structures that are expressed by aligned topographic features.

Detailed geologic mapping is sparse as the Goldstone-Fort Irwin military reservation area is restricted and mostly not open to the public. Most mapped faults in the area strike approximately parallel to the Garlock fault (east). Our analysis has revealed a number of fault scarps and truncated spurs that strike northwest and form alignments that extend from 10-30 km. The geometry and local structure determined from ground studies of these features suggest that they represent right-slip faults. Our results support the notion that the faults in the northeastern Mojave form part of a complex regional network of right shear in eastern California that connects faults in the southern Death Valley region with the San Andreas fault system.

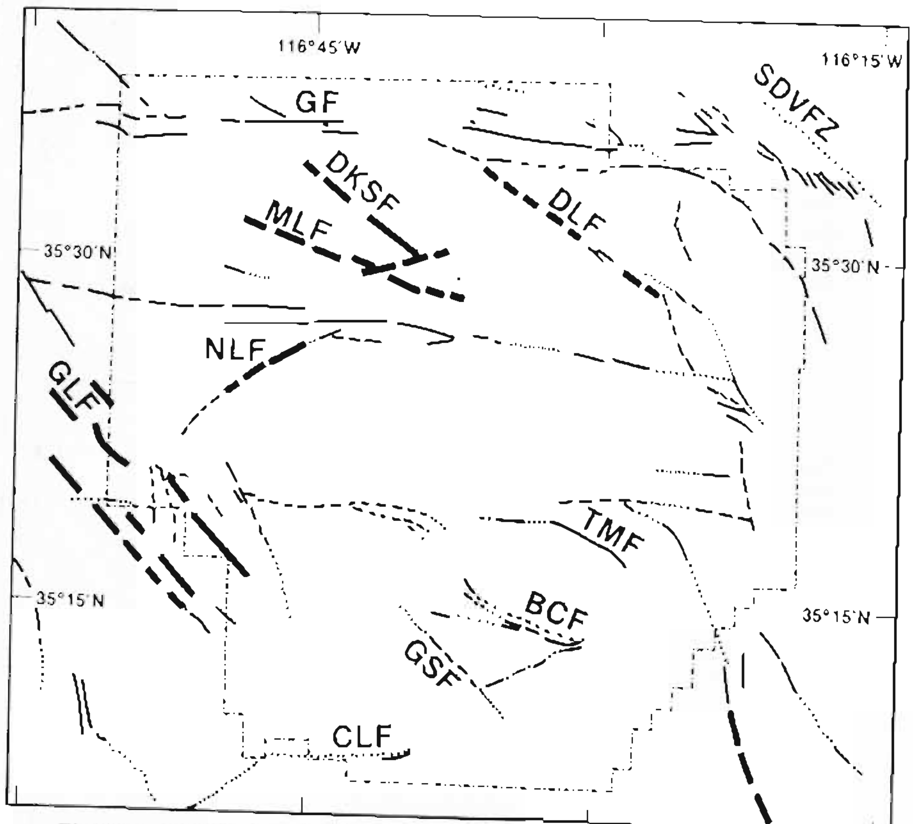

Figure 1. Sketch map showing known faults (thin) and newly observed faults and extensions (thick) in the Ft. Irwin area. Abbreviations are : Known faults--BCF-Bicycle Lake fault; CLF-Coyote Lake fault; GF-Garlock Fault; GSF-Garlic Spring fault; SDVFZ-southern Death Valley Shear zone; TMF-Tiefort Mountain fault. Newly observed faults-- DKSF-Desert King Springs fault; DLF-Drinkwater Lake fault; GLF-Goldstone Lake fault; MLF-MacLean Lake fault; NLF-Nelson Lake fault.

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 32.

Preliminary Application of Satellite Image Analysis to the Eastern California Shear Zone in the Northern Bristol Mountains, southeastern California

CARA FRANCKE-LORZ AND ROLAND H. BRADY III *Department of Geology, California State University, Fresno*

INTRODUCTION

Satellite image analysis and geologic field investigations have provided new information on faults in the northern Bristol Mountains, and on their role in the eastern California shear zone (ECSZ). The northeastern Bristol Mountains of San Bernardino County, California, are situated 28 km (17 miles) south of Baker, California (Fig. 1). The range is remote, but is accessible from Interstate 15 by following intermittent dirt roads, four-wheel drive trails, and dry washes. The mountains consist of a northern and a southern mass each surrounded by alluvial fans and plains.

Previous Work

Geologic maps of the northern Bristol Mountains are scarce. Kupfer and Bassett (1962) included the range in their reconnaissance map of the southeastern Mojave Desert. Dibblee (1967) mapped the northwestern Bristol Mountains area, known as Broadwell Mesa. A fault labeled the "Granite Mountain fault" on a regional map of the eastern Mojave Desert (Dokka and Travis, 1990) separates the northern mass of the range from Broadwell Mesa and the southern mass (Fig. 1); this fault is considered to represent the eastern border of the Mojave Desert crustal block, and a branch of the eastern California shear zone (ECSZ).

In addition to the geologic work described above, several remote sensing studies of the eastern Mojave Desert have included the northern Bristol Mountains area. Brady and others (1989) interpreted Landsat Thematic Mapper (TM) imagery to aid field investigations that identified Tertiary basins bounded by northwest-striking faults. Ford and others (1990) identified faults throughout the Mojave area using enhanced Landsat images.

Geologic Framework

Geologic formations within the northern Bristol Mountains as mapped by Dibblee (1967) and Kupfer and Bassett (1962) can be divided into two major categories: 1) Mesozoic and older plutonic and metamorphic rocks, and 2) Tertiary to Quaternary alluvium and volcanic rocks. The plutonic rocks are primarily granite, with lesser quartz monzonite and diorite. Metamorphic rocks include Precambrian gneiss and minor schist. Tertiary sedimentary and volcanic rocks are exposed mainly in the washes within the range and along its western and southern margins. In the north, some of these rocks have been described by Brady (in press). Tertiary deposits are distinguished from Quaternary alluvium by: 1) presence of interlayered volcanics and volcanic clasts, 2) greater degree of induration, 3) presence of highly weathered granite clasts, and 4) degree of internal deformation or tilted bedding. The most abundant alluvial units are fan deposits; eolian sand ramps are common along the base of west-facing ridges.

Previous Slip Estimates

Based on palinspastic reconstruction of Mesozoic plutonic rocks, Dokka and Travis (1990) suggested that the Granite Mountain fault has accommodated approximately 21.5 km of right slip. Rocks on the southern mass of the range lie on the southwest side of the proposed projection of this fault.

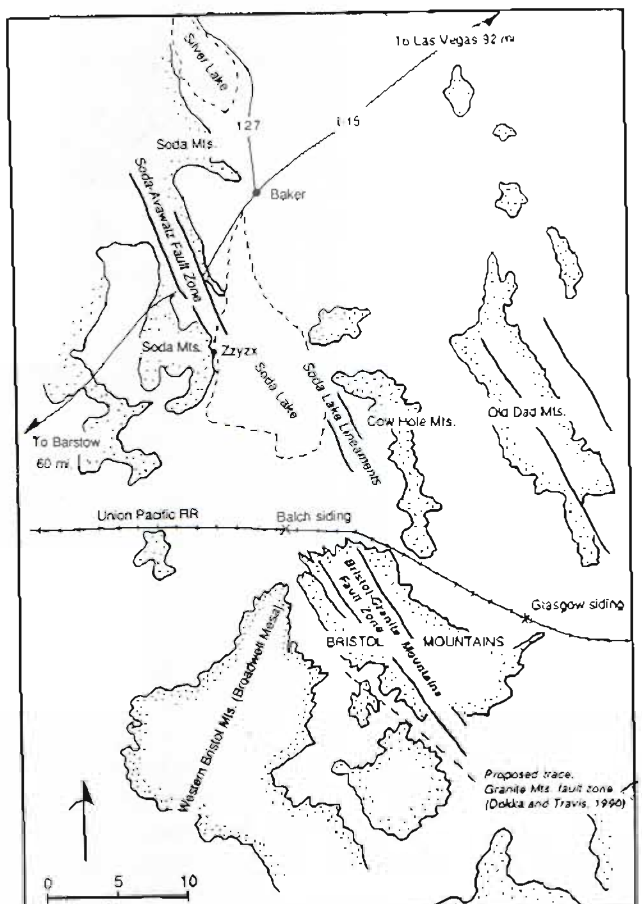

Figure 1. Map showing geographic features and fault zones referred to in this paper. Bristol Mountains Fault Zone is same as Bristol-Granite Mountains fault zone referred to in text.

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 33-36.

SATELLITE IMAGE ANALYSIS

In this study, Landsat TM and SPOT panchromatic images were processed in the GeoIPS Laboratory of Dr. Jack Paris at California State University, Fresno. The image files of TM bands 1-5 and 7 were combined to create color composite images, and were mathematically transformed to emphasize unique spectral classes. Albedo and topographic information recorded by each band of the sensor introduced a great deal of electromagnetic redundancy in the data set. An effort was made to reduce redundant information deemed geologically unimportant by using a principal component (PC) transformation (Ready and Wintz, 1973; Gillespie, 1980), described as follows. When the digital numbers for pixels of the correlated bands are plotted against each other on an x-y plot, highly correlated, and thus statistically redundant, spectral data will form a straight line through the origin. The PC transformation uses this line and its normal as a set of axes for a new coordinate system. Pixel values will vary greatly along at least one of these axes, which encompasses more of the variance in the data set than the other (if the data are perfectly correlated, one axis can fully define the data set). The PC transformation is an iterative process resulting in a series of new images, each comprising a progressively smaller percentage of the total variance in the data. The Principal Component 1 (PC-1) image accounts for most of the data variance, due largely to surface albedo (brightness) and differences in surface illumination related to topography. PC-2, PC-3, and PC-4 contain only a small fraction of the total variance of the image, but this small variance represents much of the unique spectral data related to lithologically determined reflectance. A color composite image with PC-2 as red, PC-3 as green, and PC-4 as blue yielded the greatest displayed spectral variation and hence, was used to distinguish lithologic units and areas of high color contrast (interpreted as possible fault contacts).

CORRELATION BETWEEN IMAGERY AND FIELD DATA

Geomorphic features were identified more easily in black-and-white, SPOT images which have high spatial resolution. Lineations and changes in surficial "grain" such as an abrupt break between rough and smoother appearing surfaces were considered as indicators of possible faults. The interpreted TM and SPOT satellite imagery was combined with existing geologic data to generate the preliminary geologic map (Fig. 2). This map and photographs of the computer-generated satellite images were used to identify areas for field investigation.

Reconnaissance mapping was performed in order to field check the image interpretation. Field work focused on faulting of the Cenozoic alluvial deposits along the southwestern flank of the northern mountain mass. The northwest-trending structural grain of the range was evident in both the TM and SPOT images. It is most apparent within the bedrock and between bedrock and alluvial units where it occurs as well-defined, northwest-striking, high-angle faults. It shows to a lesser degree in the imagery along the western flank of the range in an area where Kupfer and Bassett (1962) identified "Quaternary/Tertiary Tilted Gravels" (labeled as "conglomerate" in Figure 2). In the field, the rocks consist of southwest-dipping sandstone and conglomerate of the middle Miocene (?) Coppermine Wash sequence (new name; Brady, this volume) covered by a veneer of Quaternary alluvium. The alluvium is sufficiently thin that bedding in the underlying Coppermine Wash sequence, which strikes sub-parallel to the faults, can be distinguished on the satellite imagery.

Areas in the PC image which displayed unique color or sharp, linear contacts were also targeted for field investigation as possible faults. An area having a spectral signature similar to that of the granitic outcrops but of greater intensity, was identified on the imagery in an area west of the conglomerates described above. (The area is too small to show on Figure 2). In the field, this spectral signature proved to represent outcrops of granite intruded by dioritic dikes faulted against alluvium-covered Tertiary conglomerates along a west-northwest trending, discrete shear zone (approximately 1-2 m wide).

One small, isolated area in the south, labeled with a "?" on Figure 2, displayed an anomalous gray color in the PC image, and was considered as a unique lithologic unit. In the field, it is an isolated, lavender-colored, volcanogenic conglomerate with clasts of basalt and welded tuff coated by an opaline precipitate. The rock does not occur anywhere else in the area. The unit is located adjacent to granitic and alaskite outcrops, and may be separated from them by a fault. No tectonic disturbance of the Quaternary alluvium between these outcrops is apparent in the SPOT image or on the ground.

Color contrasts in the bedrock, linear washes, and low mountain front sinuosity are observed on processed satellite imagery along the proposed trace of the Granite Mountains fault of Dokka and Travis (1990), but the outcrops through which the fault is projected, although highly jointed, lack the distinctive cataclasis typical of major, lateral faults in the range (Fig. 2).

Structural Features not Identified in the Imagery

In the course of field investigations five, small, reverse-separation faults were recognized in the western parts of the distal fans where they are exposed in steep washes eroded through the Quaternary pediment. Their orientations vary, but generally, the fault planes dip 20° to 35° north and east. The structures are 2.5 to 5 m long and contain fault zones approximately 3 to 11 cm thick consisting of clay, carbonate, and siliceous gouge. Two of the faults place pink Tertiary fanglomerate, containing deeply weathered granitic clasts similar to those in the Coppermine Wash sequence, over a younger Tertiary or Quaternary gray fanglomerate containing angular granite and diorite clasts. Splays of another reverse-separation fault in the gray fanglomerate offset a horizontal, Stage III pedogenic caliche layer by approximately 45 centimeters. Throughout the eastern Mojave area, similar horizons of this type have been dated as Pleistocene in age (Wells and others, 1984). Although the fault offsets the caliche, the ground surface does not appear to be disturbed.

MOVEMENT AND TIMING

The small reverse faults in the distal fans are located approximately 1 km northwest of the location of the Granite Mountains fault proposed by Dokka and Travis (1990). The theoretical, greatest principal compressive stress direction (sigma 1) associated with right-lateral shear along the Granite Mountain fault (as mapped by Dokka and Travis, 1990) is perpendicular to the general strike of the reverse faults. This pattern is consistent with the Andersonian model for principal stresses and shears, and indicates that the reverse faults and the Granite Mountain fault could be kinematically related. The scattered minor faults may indicate that the strain field is more dispersed than would be represented by simple shear along a single, through-going lateral fault. The reverse faults are younger than the Coppermine Wash sequence (mid-Miocene?) which they offset. The age of the faulted younger, gray conglomerate is uncertain, but the offset caliche is probably Pleistocene in age.

The trace of the Granite Mountain fault of Dokka and Travis (1990) southeast through the northern Bristol Mountains (Fig. 2) shows characteristics on the TM and SPOT imagery generally associated with faults, but there is no structural evidence for shear, and no direct support for the 21.5 km of dextral slip postulated by Dokka and Travis (1990).

CONCLUSION

Satellite image interpretation proved to be a useful tool in designing and implementing a fault investigation of the northern Bristol Mountains. Both structural and lithologic features were represented in the images, and lead to the discovery of deformed sedimentary rock, shear zones, and unusual (possibly fault-bound) outcrops. The PC image was superior for identifying lithologic contrasts, while the SPOT image more clearly represented geomorphic features. The satellite images were of limited use in the distal fan area where there was little surficial or lithologic contrast. Field investigations were necessary to identify the faults that although small, may be tectonically significant.

The Bristol-Granite Mountains fault zone does not appear to extend westward between the Bristol Mountains and Broadwell Mesa. The southern Bristol Mountains fault zone of Howard and Miller (this volume) appears to represent the southeastern limit of the eastern California shear zone in the southern Bristol Mountains, but further north the Bristol-Granite Mountains fault and then the Vulcan Wash fault zone in the eastern Old Dad Mountains (Skirven and Wells, this volume) form the eastern boundary.

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Late Cenozoic Faulting at the Boundary between the Mojave and Sonoaran Blocks: Bristol Lake Area, California

KEITH A. HOWARD AND DAVID M. MILLER *U.S. Geological Survey Menlo Park, CA 94025*

ABSTRACT

Parallel northwest-striking faults show evidence of Quaternary motion in a 50-km-wide area in the eastern part of the neotectonically active Mojave block. Eastern faults in this area adjacent to the stable Sonoran block last moved probably in the early Pleistocene or perhaps the Pliocene, whereas western ones cut Holocene deposits. Right-lateral slip measured in kilometers can be documented for some of the faults; others seem best explained as reverse and normal faults. The south Bristol Mountains fault accounts for an estimated 6.5 km of dextral slip. Constraints on slip for most of the faults remain incomplete, but cumulative slip is likely less than the several tens of kilometers proposed in a recent model.

INTRODUCTION

Late Neogene and Quaternary right-lateral faults slice the seismically active central Mojave Desert along northwest trends (Dibblee, 1961; Dokka and Travis, 1990a). This fault domain has been termed the Mojave block (Hewett, 1955), western Mojave region (Howard and others, 1978), or eastern California shear zone (Dokka and Travis, 1990a). The adjacent Sonoran block on the east is seismically quiet and lacks many Quaternary faults (Howard and others, 1978; Goter, 1988; Carr, 1991). This report describes faulting at the boundary between these two neotectonic domains in the western half of the Needles 1°x 2° sheet (fig. 1). The area lies northeast of the eastern Transverse Ranges where east-striking left-slip faults dominate (Dibblee, 1967a, 1975; Hope, 1969).

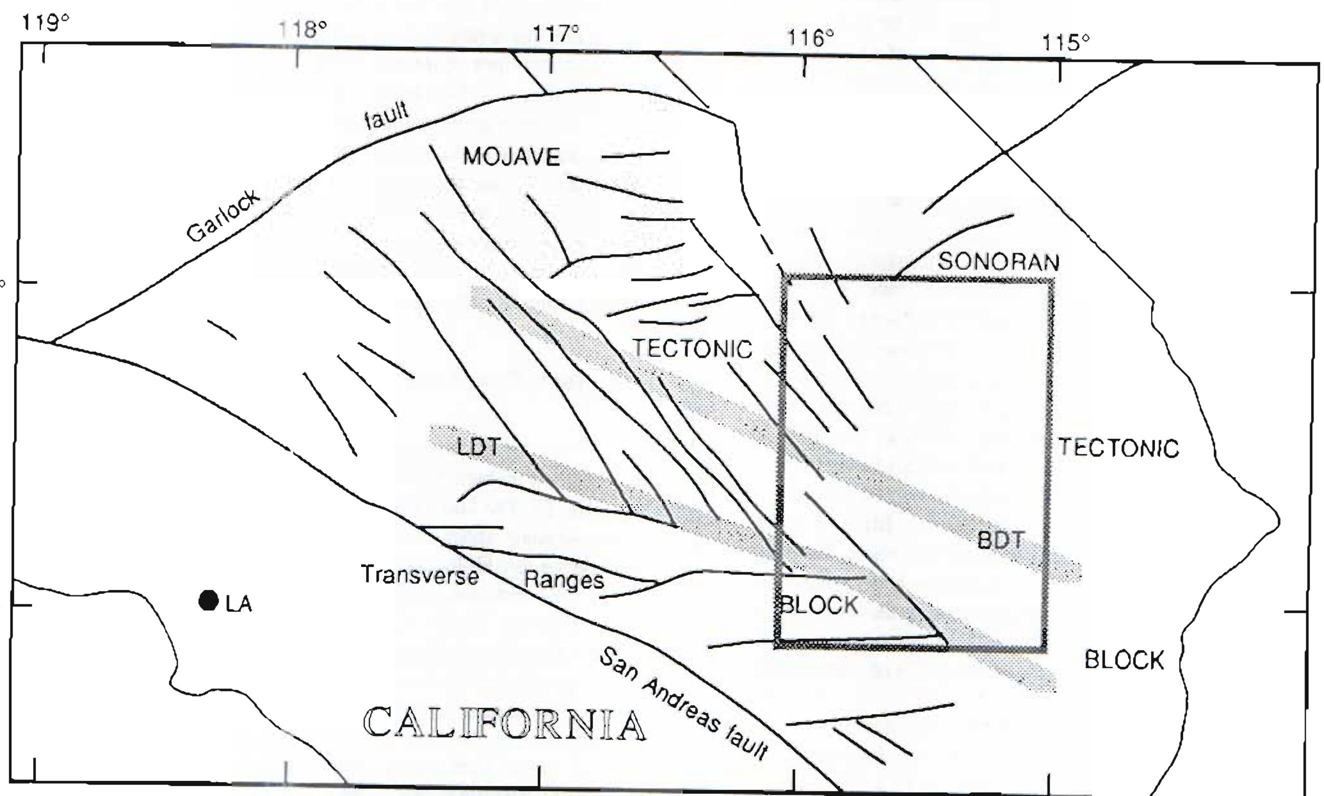

Figure 1. Sketch map of young faults in southeastern California. Mojave tectonic block lies between Garlock and San Andreas faults and is made up of many fault blocks. Sonoran tectonic block lies to east. Box indicates the study area on the margin between the Mojave and Sonoran blocks (fig. 2). Patterned zones are Bristol-Danby trough (BDT) and Lucerne-Dale trough (LDT). LA=Los Angeles.

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STRATIGRAPHIC FRAMEWORK

Youngest faults in the study area (fig. 2) strike northwest parallel to mountain ranges. Elongate Mesozoic plutons and early Miocene extensional faulting and tilting produced northwest structural trends prior to the young faulting. Consequently the present structure and landforms result from a combination of older and younger intrusive and tectonic events. The ranges expose mostly Jurassic and Cretaceous plutonic rocks (Miller and others, 1982). Surficial deposits in the valleys consist of Quaternary alluvium, windblown sand, basalt, and playa deposits.

Establishing the youngest age of faulting depends foremost on subdivision and age assignment of alluvial units. We use the terms alluvial and alluvium here to apply to poorly sorted piedmont deposits occupying present-day lowlands which served as the sites of their deposition; the deposits are semiconsolidated to loose and consist of poorly sorted sandy conglomerate, composed largely of subangular, locally derived clasts. The deposits represent alluvial fans deposited by intermittent streams and debris flows. Although such processes probably have acted more or less continuously since inception of mountainous landforms in the Miocene, we contend that most deposits for which sedimentation can be related directly to the present landforms are little or no older than Quaternary. We subdivide these deposits into four broad units, while recognizing that correlations between the units from area to area can be uncertain and that multiple generations of fan deposits and surfaces can be recognized locally within units. Successively older generations of alluvium tend to be marked by increasingly darker surfaces on aerial photographs.

The four units of alluvium numbered for this report are distinguished in the basis of geomorphic expression, degree of preservation of depositional surfaces, and degree of soil development (after Bull, 1974). The youngest unit (unit 4) floors active washes and is assigned to the Holocene, as is also the next oldest unit (unit 3), which forms alluvial fans exhibiting bar-and-swale topography. Dark-patinaed smooth desert pavements characterize the surface of the next oldest, unit 2, which is assigned to the upper Pleistocene but we can not exclude the possibility that some lower Pleistocene material is included. Unit 2 deposits typically have slight pedogenic calcite and reddish soil developed at their surface. Unit 2 near the Ludlow fault contains clasts of basalt dated at about 0.36 Ma. We correlate unit 2 with geomorphologically stable, paved surfaces in the Cima volcanic field that are 300 to 700 ka in age (Dohrenwend and others, 1984). The oldest alluvium, unit 1, consists of moderately lithified deposits with extensive pedogenic calcite and reddish soil where the depositional surface is preserved; it forms dissected ridge-and-ravine topography. Unit 1 is assigned to the lower Pleistocene in the Twentynine Palms area where it contains an ash bed thought to be correlative with the 0.7-Ma Bishop Tuff (Bachellor, 1978). A sequence of possibly correlative beds near Twentynine Palms contains a late Pleistocene Rancholabrean fauna in its upper part (Bachellor, 1978). Similar deposits in the Cima volcanic field are 0.6 to 1.0 Ma in age (Dohrenwend and others, 1984). Sandstone and breccia locally interfinger with unit 1.

Regional correlations of the alluvial units are at best imprecise, especially where the units are structurally disrupted, so we emphasize that parts of unit 1 could be as young as late Pleistocene or as old as late Pliocene. Unfaulted alluvium surfaced by desert pavement, which we assign to unit 2, in several instances directly overlies faulted alluvium that we assign to unit 1. Both units occupy depositional sites in still-existing valleys between bedrock mountains. This similarity in depositional setting relative to modern highlands, as well as similarities in sedimentary textures and the lack of intervening section between units 1 and 2, suggests to us that the hiatus between them was less than 1 m.y. We exclude from unit 1 similar conglomeratic units, which we suspect may be as old as middle or late Miocene, that do not relate depositionally to the modern topography.

We focus on faults that cut deposits of probable Quaternary age (fig. 2; table 1). Other northwest-striking pre-Quaternary faults and faults with less-well-constrained age of last movement may relate to the same tectonic regime that governed the Quaternary faulting. East-striking Quaternary sinistral faults occur in the Pinto Mountains area in the southwest corner of the area of Figure 2 but are beyond the scope of this paper. Faults are described here from southwest to northeast.

DESCRIPTION OF FAULTS

Valley Mountain faults

Two northwest-striking faults 2 km apart cross an alluvial plain southeast of Valley Mountain. They were shown as part of the Bullion fault by Kupfer and Bassett (1962). Short northeast-striking faults that truncate against the east Valley Mountain fault on its southwest side were described as grabens (Woodward-McNeil and Associates, 1974a, p. 93), and may represent pull-aparts related to strike-slip motion on the east Valley Mountain fault. The Valley Mountain faults represent the youngest faults described in this report. They form groundwater barriers (Moyle, 1961; Bachellor, 1978), lineaments seen on aerial photos, and linear raised tracts as high as 6 m in the alluvial plain. The deformed alluvium contains a component of windblown sand and is assigned to unit 3 (Holocene) because its bland depositonal surface lacks desert pavement and is underlain mostly by brown soil, but the local presence of reddish soil suggests the possibility that it may be as old as unit 2 (late Pleistocene). A third vague northwest-striking lineament on Landsat thematic-mapper imagery provided by R. Blom lies 4 km northeast of the east Valley Mountain fault and may represent a fault strand but is not known to form a groundwater barrier. Offsets on the Valley Mountain faults are not known.

Cleghorn Pass fault

This zone of faults strikes northwest through Cleghorn Pass between two masses of Jurassic granitoid rocks in the Bullion Mountains (fig. 2). The fault zone cuts unit 1 alluvium in Cleghorn Pass and to the southeast, and is covered by units 2, 3, and 4 assigned to the upper Pleistocene and Holocene.

On the north side of Cleghorn Pass the fault zone is 1 km wide and includes several breaks. Chloritic and actinolitic alteration and brecciation affect the granitoid rocks along the western part of the zone. Ridges parallel to the fault zone are formed on alluvium assigned to unit 1, which dips 25° east into a fault strand that dips 75° west, marked by gouge several feet thick separating the alluvium from a footwall of sheared quartz monzonite. This fault shows a separation >50 m measured vertically between the alluvium in the hanging wall and the bedrock footwall. Cobbles in the faulted unit 1 are equigranular quartz monzonite like the juxtaposed rocks east of the fault, and unlike porphyritic quartz monzonite that the alluvium nonconformably overlies. This relation suggests recurrent faulting, whereby the two basement rock types were juxtaposed prior to deposition of unit 1, and later the alluvium was faulted and tilted but not isolated from its source. Two kilometers southeast of Cleghorn Pass the faulted unit 1 coarsens upward from sandstone to boulder conglomerate and finally boulder

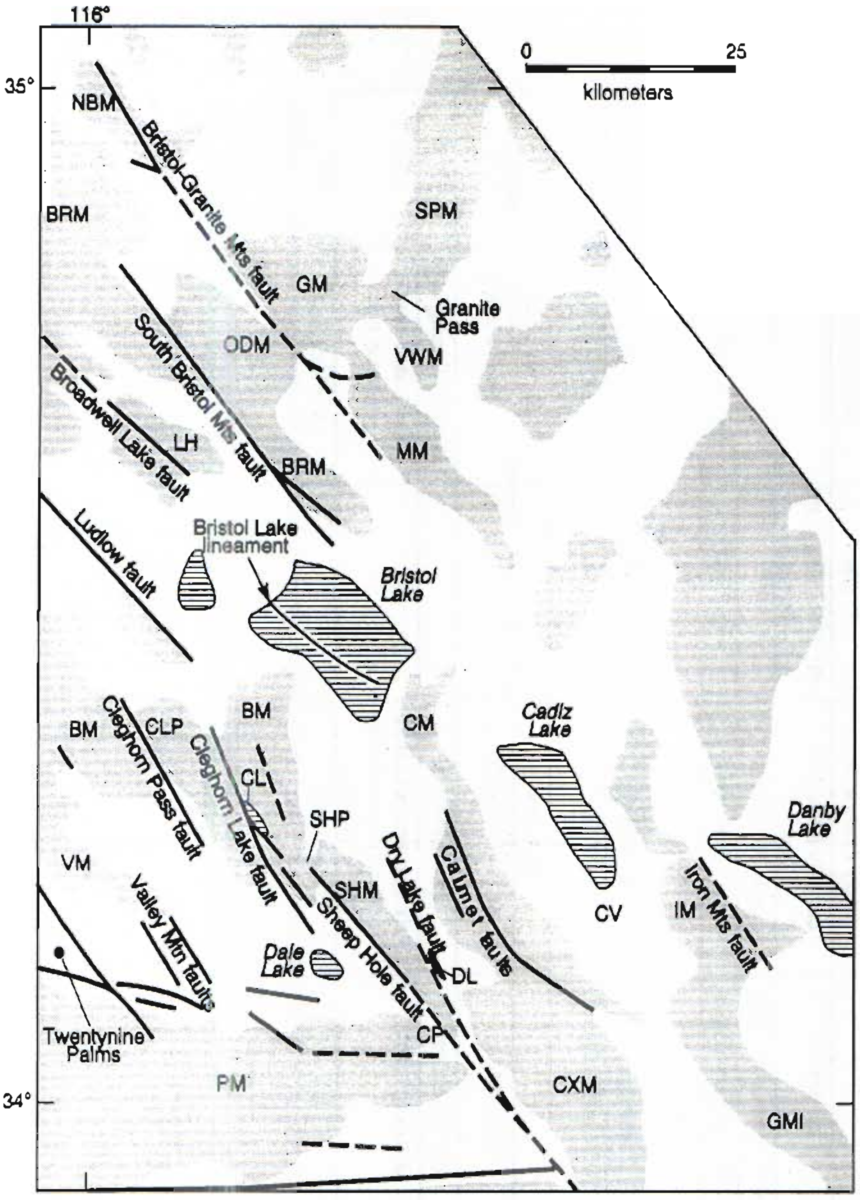

Figure 2. Sketch map of the Bristol Lake area showing faults that cut probable Quaternary deposits (solid lines), and related older faults (dashed lines). Mountain ranges are shaded and playas are shown by line pattern. Abbreviations: BM=Bullion Mountains, BRM=Bristol Mountains, CL=Cleghorn Lakes, CLP=Cleghorn Pass, CM=Calumet Mountains, CP=Clarks Pass, CV=Cadiz Valley, CXM=Coxcomb Mountains, DL=Dry Lakes, GM=Granite Mountains near Bristol Mountains, GMI=Granite Mountains near Iron Mountains, IM=Iron Mountains, LH=Lava Hills, LM=Lead Mountain, MM=Marble Mountains, NBM=northern Bristol Mountains, ODM, Old Dad Mountains, PM=Pinto Mountains, SHM=Sheep Hole Mountains, SHP, Sheep Hole Pass, SPM=south Providence Mountains, VM=Valley Mountain.

breccia derived from the east. Mylonite locally exposed in the faulted granitoids is 3-5 m thick and dips 60° west, and lineation plunges down the dip. The presence of chloritic breccia and even mylonite in the Cleghorn Pass fault zone suggests that early faulting was at depth, and that the fault zone may have a long history of repeated faulting and topographic evolution.

Jagiello and Blom (1990) and Jagiello and others (this volume) proposed that the fault offsets by 16 km in a dextral sense a post-Jurassic fault and a bleached granitoid they term the Cleghorn Pass pluton. Restoration of this proposed offset has one potential misfit in that it would juxtapose volcanic and hypabyssal rocks that occur 1-3 km south of the eastern bleached rock against granitoids west of the Cleghorn Pass fault, where volcanic counterparts are unknown.

Cleghorn Lakes fault

A northwest-striking fault zone separates two major ridges of the eastern Bullion Mountains and passes under the dry Cleghorn Lakes playas. The fault projects northwest toward the southern end of the more westerly-striking Ludlow fault (as mapped by Kupfer and Bassett, 1962, and Bishop, 1964), and may represent its southern continuation (fig. 1). The Cleghorn Lakes fault cuts along and near the intrusive border of the Cretaceous Cadiz Valley batholith on the east against Jurassic granitoids on the west.

Nine kilometers north of the Cleghorn Lakes, the fault places the western intrusive border of muscovite granite of the Cadiz Valley batholith against Jurassic granitoids. A low area of granite exposures 0.5 km wide contains at least 5 breaks occupied by breccia or gouge. The easternmost dips northeastward 46°. Juxtaposed Jurassic granitoids 150 m farther east indicate the presence of an unexposed strand concealed by young alluvium. Clasts of dacite and muscovite granite in unit 1 in the area show provenance from the ridge on the east.

Two kilometers north of the Cleghorn Lakes the fault zone juxtaposes unit 1, dipping 45°, against Cretaceous granite on the east. In a bedrock pass south of Cleghorn Lakes the fault zone is 0.4 km wide and comprises several strands exposing broad zones of gouge and (locally hematite-stained) breccia. Dips of the faults vary, averaging near vertical. Faulted unit 1 on the south side of the pass dips 12°-44°. Upper Pleistocene unit 2 covers the fault, except 5 km farther southwest along its projected trace where two aligned small patches of unit 2 crop out surrounded by unbroken Holocene alluvium.

Separation on the fault can be estimated based on two lines of evidence. In the north the fault causes an apparent right-lateral separation of at least 2.8 km of a poorly exposed north- to northeast-striking contact between Jurassic and Cretaceous granites mapped by reconnaissance. In the pass south of Cleghorn Lakes, both sides of the fault expose Jurassic quartz monzonite that is hornfelsed and locally foliated by original proximity to the Cretaceous batholith, which lies to the east. Both walls of the fault zone also expose rare

FAULT	PROBABLE SLIP	PERMISSIBLE TRANSLATION, KM	YOUNGEST MATERIAL CUT (PROBABLE AGE)	FAULT DIP (°)	CHARACTER	WIDTH OF FAULT ZONE
West Valley Mountain						
East Valley Mountain			Holocene			
Cleghorn Pass		12 km dextral	early Pleistocene	75 to 90° SW	gouge, breccia, chloritic breccia	1000 m
Cleghorn Lakes	2-3 km dextral	>2.7 km dextral	early Pleistocene, locally late Pleistocene	avr. 90	breccia and gouge zones	500 m
Ludlow		>6 km dextral	late Pleistocene			
Sheep Hole	0 to >1.2 km dextral		early Pleistocene	75 SW	quartz breccia	2 m
Dry Lakes		11 km dextral	early Pleistocene or Pliocene?	80° SW (older parts dip east)		
West Calumet	normal	1-2 km unknown sense	early Pleistocene	90°		
Calumet	normal	1-2 km unknown sense	early Pleistocene	45-55 NE	breccia and gouge	
Cadiz Lake		25 km dextral	early Pleistocene	60°	slickensides, dipping beds	
Iron Mountains	right-oblique normal	5.5km dextral	Pliocene(?)	75°-90° SW	breccia and gouge	
Bristol Lake	dip slip	0.1 km dip-slip	2.1 Ma (Rosen, 1989)		dipping beds, sedimentation surge	
Bristol Lake lineament			Holocene		radar lineament	
Broadwell Lake	0-6 km dextral and normal	6 km dextral	early Pleistocene		breccia and gouge	10 m
South Bristol	6.5 km dextral	6.5 km dextral	late Pleistocene		breccia, dipping beds	10 m
Bristol-Granite	reverse?	0-10 km dextral	early Miocene in Granite Mts area, Pleistocene in N. Bristol Mts	NE	brecciated quartz, calcite,gouge	<5 m
Granite Pass	normal	1 km	Cretaceous		chloritic rocks	150 m

Table 1. Dataon faults in the Bristol Lakearea.

north- to northeast-striking contact between Jurassic and Cretaceous granites mapped by reconnaissance. In the pass south of Cleghorn Lakes, both sides of the fault expose Jurassic quartz monzonite that is hornfelsed and locally foliated by original proximity to the Cretaceous batholith, which lies to the east. Both walls of the fault zone also expose rare aplite dikes associated with the Jurassic granitoids, as well as both porphyritic and equigranular facies of Jurassic quartz monzonite. The similarities across the fault suggest to us that fault separation in this area is no more than 2 km. We propose right-lateral separation between 2 and 3 km for the Cleghorn Lakes fault.

One of several northwest-striking undated faults midway between the Cleghorn Lakes fault and the Sheep Hole fault to the east separates bedrock features 30 m in a right-lateral sense (Howard and John, 1984). These faults may accommodate motion between the southern part of the Cleghorn Lakes fault and the Sheep Hole fault.

Ludlow fault

The Ludlow fault has been postulated to extend over 60 km northwest from Lead Mountain (Kupfer and Bassett, 1962; Bassett and Kupfer, 1964; Dibblee, 1967b).

Northwest of Lead Mountain 4 km, a linear chain of low hills composed of buckled lower Pleistocene alluvium (unit 2 or 1) lies along the southwest side of a rounded scarp. The scarp is aligned with the Ludlow fault farther to the northwest. Unit 3 deposits do not appear to be cut by the fault, limiting its most recent movement to the Pleistocene. The remnant scarp contrasts with completely beveled faults in the Bristol Mountains that cut basal deposits of unit 2, suggesting a younger age; we consider that this part of the Ludlow fault last moved in the late Pleistocene.

A zone of highly altered Jurassic quartz monzonite and vertically dipping, northwest-striking lower Miocene volcanic and sedimentary rocks 2 km north of Lead Mountain peak may relate to deformation along the Ludlow fault. Alternatively they may relate to early Miocene tilting and extensional faulting.

The southeastern third of Lead Mountain exposes an undated, probably Neogene sequence of conglomerate and alluvial sandstone dipping south 15-30° (Howard, submitted). Hilly exposures of this sequence end abruptly northeastward, where they are buried by alluvial fans (units 2 and 3) at the projected trace of the concealed Ludlow fault. An upper age to movement on the Ludlow fault here is established by the presence in undeformed unit 2 of clasts of the basalt of Lead Mountain, which has been dated by the potassium-argon method (whole-rock) at 0.36+0.04 Ma (J.K. Nakata, written commun., 1985). Clasts in the dipping conglomerate unit include rocks derived from Jurassic granitoids, Miocene dacite, and (deeper in the section) wollastonite marble and muscovite granite (as big as 0.6 m across) for which the nearest source is in the Bullion Mountains east of the Cleghorn Lakes fault. The dipping sedimentary sequence shows no depositional relation to current landforms in its present position but could be restored adjacent to that source if at least 6 km of right-lateral slip were assumed along the Ludlow-Cleghorn Lakes fault system. Bedrock markers on the Ludlow fault are lacking in the study area, but current directions could be measured in the sedimentary sequence to test whether depositional patterns are more consistent with a formerly adjacent or a distant source..

Sheep Hole fault

The Sheep Hole fault places plutonic rocks in the Sheep Hole Mountains against lower Pleistocene alluvium on the southwest flank of the range (Hope, 1969; Woodward-McNeil and Associates, 1974b; Howard and John, 1984). Brecciated vein quartz 2 m thick is exposed in the fault, which dips 75° southwest. Jagiello and others (this volume) found that clasts in the alluvium have been offset 1.2 km in a right-lateral sense from their source.

At its north end in Sheep Hole Pass the fault splays into several northeast-dipping faults small-displacement having small displacement within the Cretaceous granite of Sheep Hole Pass (Howard and John, 1984). Along the northwestern projection of these faults a possibly related fault in the Bullion Mountains cuts a swarm of early Miocene dacite dikes. Should this fault connect to the Sheep Hole fault, right slip on the combined fault system could explain the provenance of flat-lying lower Pleistocene alluvium that crops out 1-2 km north-northeast of Cleghorn Lakes. This alluvium contains clasts of the granodiorite of Green Scorpion mine, a rock type for which the nearest outcrops now are topographically lower and to the east and south. The alluvium is separated in a dextral sense about 2.5 km northwest from the nearest outcrops of the granodiorite of Green Scorpion mine. No current direction measurements have been made to test whether this provenance tie is best explained by alluvial or by fault transport.

Dextral displacement on the fault evidently decreases southward. An aeromagnetic high anomaly crosses the southwestern front of the Sheep Hole Mountains south of Dale Lake, strongly suggesting little or no translation across the Sheep Hole fault there (Simpson and others, 1984). The magnetic high correlates with metamorphosed quartz diorite where exposed in the range

Southwest of the Sheep Hole Mountains, several left-slip faults in the eastern Transverse ranges truncate eastward against the Sheep Hole fault (Hope, 1969). Despite this truncation, evidence in the Clarks Pass area at the south end of the Sheep Hole Mountains argues against large strike-slip offset on the Sheep Hole fault there. The metamorphosed quartz monzodiorite to quartz diorite mentioned above appears on both sides of the fault. On the east side in the southern Sheep Hole Mountains, this rock type occurs as inclusions or pendants and wall rocks to the Late Cretaceous Cadiz Valley batholith. On the west side in the Pinto Mountains, the metamorphic texture of the apparently equivalent rock type, and a 68-Ma K-Ar cooling age on biotite (Calzia and Morton, 1980), suggest original proximity to an intrusive contact of the Cadiz Valley batholith, which underlies the ranges to the east (Howard and Allen, 1988). The relative rarity of the quartz monzodiorite to quartz diorite unit suggests correlation and little separation across the Sheep Hole fault at Clarks Pass.

Dry Lakes fault

The Dry Lakes, small playas in a valley on the northeast side of the Sheep Hole Mountains, overlie a gravity low that indicates a local basin fill about 370 to 490 m thick (Simpson and others, 1984). The basin flanks a northwest-striking linear scarplike front of the southern Sheep Hole Mountains.

Seven kilometers northwest of Dry Lakes, the valley becomes a pediment in which alluvium less than a few meters thick veneers granitic bedrock cut by at least 10 steeply east-dipping faults in granite and granodiorite. A fault dipping 80° southwest cuts a locally exposed pebbly arkosic sandstone of unknown age that overlies the granitic rocks in the pediment and underlies unbroken alluvium. Similar sandstones (but lacking pebbles) are interbedded with unit 1 alluvium in the Twentynine Palms area and in the southern Bullion Mountains. The pebbles are well-rounded, in contrast to their matrix of subangular granitic sand, suggesting that the pebbles are not first-cycle debris but have been cannibalized from older conglomerate. Pebble compositions suggest ultimate provenance from the Pinto and southern Calumet Mountains. The fault that cuts the sandstone steps right from the mountain-front scarp that overlooks Dry Lakes. Unbroken unit 2 alluvium laps against this scarp and suggests that faulting had ceased by the late Pleistocene if not earlier.

Ranges on either side of the Bristol-Dry Lakes valley expose light-colored granitic rocks of the Cadiz Valley batholith, within which no unequivocal offset markers have been identified (Miller and others, 1982; Howard and John, 1984). The granodiorite of Clarks Pass, exposed in the southeastern Sheep Hole Mountains, has its closest mapped counterpart 40 km to the north in the northern Calumet Mountains. The steep northeast-striking exposed margin of the oval-shaped Cadiz Valley batholith steps to the right about 11 km from the northeastern Bullion Mountains to the northern Calumet Mountains, and could be restored to a linear contact if 11 km of right slip were assumed across the valley. However the wide alluviated valley conceals too much bedrock to confirm the projection of the irregular plutonic contact. Outcrops of the granodiorite of Green Scorpion mine in the northern Sheep Hole Mountains lie due west of lithologically similar rocks across the valley in the southern Calumet Mountains. The geologic map (Howard and John, 1984) thus allows a range of permissible restorations across Bristol-Dry Lakes valley, including no translation.

The presence of the linear valley and local thick basin fill suggested local basin opening associated with faulting along the valley (Simpson and others,1984). This is consistent with the right-stepping of faults in the valley if they are dextral.

Calumet faults

The Calumet fault (Howard and John, 1984) shows as a notable trace on Landsat images and aerial photographs of the southern Calumet Mountains. The fault curves across the range from the Bristol Lake-Dry Lakes valley in the northwest to Cadiz Valley in the southeast. The fault dips 45-55° northeast where it cuts Cretaceous granitoids. Unit 1 alluvium is localized in and apparently deposited in a narrow valley along the trace of the fault and dips as steeply as 25°. The parallel west Calumet fault 1.5 km to the west juxtaposes unit 1, also in a narrow fault valley, against bedrock.

Rare inclusions or pendants of wollastonite marble crop out within Cretaceous granitoids on opposing sides of the west Calumet fault, strongly suggesting that any lateral separation is less than 1 km. Separation on the Calumet fault is harder to constrain and is of unknown sense, but is likely to be less than 2 km based on the distribution of mapped pendants of metamorphosed Paleozoic strata. A parallel fault in bedrock 1.5 km east of the Calumet fault shows a 20-m sinistral separation (Howard and John, 1984). Dip slip on the Calumet faults might explain better than strike slip the distribution of pendants around the Calumet faults. Further, the Calumet fault projects northwestward toward faulted and steeply southwest-dipping lower Miocene rocks, the tilting of which implies rotation on normal faults. These observations suggest the possibility that the Calumet faults record Quaternary reactivation of normal faults that formed during early Miocene extension.

Cadiz Valley

Cadiz Valley parallels the northwest-striking young faults described in this report, suggesting control by similar faults. On a broader scale, the valley coalesces with basins occupied by Bristol Lake, Danby Lake, and several other playas to form the Bristol-Danby trough, which strikes obliquely west-northwestward across much of the Mojave Desert, interrupting the northwest grain of faults and ranges (Bassett and Kupfer, 1964). Quaternary faults are rare and small in California east of Cadiz Valley (Purcell and Miller, 1980; Carr, 1991).

Slickensides dipping 60° were drilled in sediments beneath Cadiz Lake at 80 m depth; the fault surface bounds horizontal beds above from dipping beds below (Bassett and others, 1959). Sedimentation rates in Cadiz Lake are unknown, but if rates are comparable to those constrained beneath Bristol Lake by Rosen (1989), the buried fault cuts lower Quaternary sediments.

Evidence is equivocal whether Cadiz Valley conceals lateral separation between the bounding ranges. Restoration of 8 km of right slip across the valley could align the north margin of the Cadiz Valley batholith. Restoration of 25 km right slip would place near each other two roof pendants that contain distinctive dark granodiorite gneiss characterized by highly flattened mafic enclaves. The pendants are in different plutons of the Cadiz Valley batholith, one in the southeastern Calumet Mountains and the other in the central Granite Mountains. On the other hand, restoration of any right slip would increase the distance between outcrops of porphyritic Proterozoic granite (containing distinctive large allanite grains) that we currently correlate from the northeastern Calumet Mountains to the southern Marble Mountains. Further, restoration of any right slip would separate outcrops of mylonitized batholith rocks in the southern Iron Mountains from nearby ones in the southeastern Calumet and northeastern Coxcomb Mountains. Mylonitic foliation in the Iron Mountains dips west whereas in the southeastern Calumet Mountains it dips east, a difference that could be explained by dip-slip tilting of the Iron Mountains rather than by lateral displacements along Cadiz Valley.

Iron Mountains fault

The Iron Mountains fault dips vertically to steeply northeast or southwest, exposing gouge and breccia in granitoid rocks. Rare striae plunge 20° to the southeast. A youthful, Pliocene or, perhaps, early Pleistocene age is suggested by a linear scarplike mountain front over 450 m high in granitoid rocks above Danby Lake valley, and by landslide boulder breccia along and locally cut by the fault. The faulted breccia was included in a unit assigned to the Pliocene(?) and Pleistocene by Miller and Howard (1985), but which is undated. The presence nearby of undrained Danby lake playa suggests a youthful tectonic basin.

Rock units match across the fault if 5.5 km dextral slip is assumed or if 1 km of dip slip, east-side down is assumed (Miller and Howard, 1985). Right-oblique slip would fall between these values.

Faults at Bristol Lake

Bristol Lake basin and Cadiz Valley contain thick upper Neogene and Quaternary deposits extending below sea level (Bassett and others, 1959; Rosen, 1989), indicating basin formation by youthful tectonism.

Radar imaged a lineament striking northwest across the surface of Bristol Lake playa (Sugiera and Sabins, 1980) The lineament, subtly expressed on aerial photographs and earlier mapped as a zone of faults by Kupfer and Basset (1962), may be a groundwater barrier across Holocene playa deposits (Sugiera and Sabins, 1980). The radar lineament does not trace into the basalt of Amboy crater (Ford and others, 1989), which is of late Pleistocene (Glazner and others, 1991) or early Holocene age (Parker, 1963; Miller, 1989). The origin of the lineament and its structural significance remain obscure.

Drill cores dated by tephrochronology revealed dipping beds and strong evidence for a local surge in sedimentation rate at about 2 Ma in deposits beneath Bristol Lake, compared to a thinner section with a near-constant sedimentation rate under the west margin of the basin; the dipping beds and sedimentation surge were attributed to deepening of the basin interior by faulting (Rosen, 1989). Rosen (1989) found that 270 m of cored sediments at the margin of Bristol Lake underlie an ash bed at 200 m depth correlated with a 3.7-Ma tephra. Extrapolated sedimentation rates below the ash bed suggested to Rosen (1989) that the deepest cored sediments may exceed 6-10 Ma in age and deeper undrilled sediments require an even older age for initiation of the basin. Persistent playa environments and lack of long-lived lakes since at least 3.7 Ma (Rosen, 1989), and incision and modern capture of streams in the Bristol Mountains (Miller, submitted), suggest that subsidence of the basin began by the Pliocene and continues in the present-day.

Broad well Lake fault

Ford and others (1990a,b) described a dextral-slip fault in the Lava Hills that they named the Broadwell Lake fault. To the northwest, the fault follows a prominent range front, where it dips northeast and is marked by down-dip striae, suggesting normal separation (Ford and others, 1990a), but in the Lava Hills it is close to vertical and locally has horizontal striae. Parallel faults appear to be related to the Broadwell Lake fault, since all faults are joined by east-striking conjugate faults.

Faults in the Lava Hills are marked by breccia and gouge where they cut volcanic rocks and by wide crush zones in granite. Unit 1 alluvium at one locality is cut by the Broadwell Lake fault, but unit 2 lies across faulted bedrock. The faults cut southwest-dipping Miocene volcanic rocks and underlying Mesozoic granitoids, all of which were faulted and tilted during Miocene extension (Miller, submitted). Offset on the system of faults is poorly constrained because moderately-dipping features such as volcanic strata and their basal nonconformity are the only available markers, so dip-slip movement would induce significant errors in apparent offset. In addition, the faults may be reactivated from earlier Miocene normal faults. Offset strata are separated dextrally about 1 km on the Broadwell Lake fault and another 4 to 5 km on nearby parallel faults. Thus, faults in the Lava Hills may record as much as 6 km of right slip. However, a component of normal slip, down to the northeast, is likely to account for a small Pliocene(?) basin of conglomerate north of the Lava Hills that does not correlate with present-day physiography. Normal slip decreases the dextral component by an unknown amount, as does the unknown component of Miocene faulting.

South Bristol Mountains fault

A northwest-striking fault system bounds the southwest side of the southern Bristol Mountains. Faults within the system in several places form rhombohedral patterns consistent with right-stepping dextral separation. Breccia zones as wide as 10 m mark individual faults in bedrock, and moderately lithified alluvium of unit 1 dips as steeply as 60° near the faults. The faults cut unit 1 but generally do not cut unit 2 deposits. In one place the lower part of unit 2 is cut by a fault but the upper part of that unit is not.

Restoration of the south Bristol Mountains fault using offset Mesozoic granitoids yields approximately 6.5 km of dextral separation. A northeast-trending margin of distinctive porphyritic granite in the Bristol Mountains is cut by the fault zone. Its counterpart is not well exposed across the fault zone, but the same granite lies as far northwest as 6.5 km within the zone. A belt of hypabyssal and metavolcanic rocks is similarly offset. If the fault underwent oblique slip, the uncertainty of this as a slip estimate is increased substantially, for the geometry of the offset pluton margins is not well known. A component of southwest-side-down movement is suggested by the presence of younger rocks along much of that side of the fault, and thus our 6.5-km estimate of dextral offset is imperfectly constrained.

Bristol-Granite Mountains fault

A northwest-striking fault zone cuts the northern Bristol Mountains and separates the Old Dad Mountains from the Granite Mountains. The fault was termed the Bristol Mountains fault zone (Laird, 1959; Gamble, 1959; Howard and others, 1987; Brady, this volume) but Dokka and Travis (1990a,b) called it the Granite Mountains fault (and used the term "Bristol Mountains fault" for the fault we here term the "south Bristol Mountains fault"). The fault has received attention as a possible southeastern continuation of right-slip faults in Death Valley (Hamilton and Myers, 1966; Brady, 1988) and as the eastern limit of young strike-slip faults that characterize the central Mojave Desert (eastern California shear zone of Dokka and Travis, 1990a). Davis (1973, 1977), Woodward McNeil and Associates (1974b, p. E6-7), and Davis and others (1974) emphasized interpretations that the fault zone is older than the southern Death Valley fault zone

In the northern Bristol Mountains a northern strand of the fault zone cuts "older fan sediments" mapped by Woodward-McNeil and Associates (1974b, fig. E-7). From its expression as dark pavement surfaces on aerial photographs this unit probably correlates with our unit 2 (upper Pleistocene). Small thrust faults at the south margin of the northern Bristol Mountains cut materials as young as Pleistocene (Francke-Loriz and Brady, this volume). South of the northern Bristol Mountains the fault cuts lower Miocene rocks, and exposed units 4, 3, and probably 2 cover it.

Plutonic rocks in the northern Bristol Mountains are intensely brecciated along strands of the 2-km-wide fault zone, where vertical, reverse, and thrust faults are reported (Davis,1973; Brady, this volume; Francke-Loriz and Brady, this volume). In contrast, between the Old Dad and Granite Mountains the fault zone is less than 5 m wide; it dips 70-80° northeast and places topographically higher Mesozoic plutonic rocks in the hanging wall over Tertiary supracrustal rocks (Howard and others, 1987). South of the Granite Mountains, linear northwest-striking fronts of the Marble and southern Bristol Mountains suggest a southeastward continuation of the Bristol-Granite Mountains fault zone.

Small-displacement faults that we interpret as splays of the Bristol-Granite Mountains fault zone cut east through the Marble Mountains at highway I-40 (Glazner and Bartley, 1990). A roadcut on I-40 in the eastern Marble Mountains exposes an east-striking, reverse fault dipping 70° north and a southeastward-overturned fold that place plutonic basement rocks over basal Miocene tuff. Dissected highstanding alluvium assigned to unit 1 laps across the fold. The fold and the reverse separations imply a shortening component along the main Bristol-Granite fault zone compatible with reverse, right-lateral, or right-oblique slip.

Displacement on the fault zone is unknown. Dokka and Travis (1990a) proposed 21.5 km of right slip on the fault in a reconstruction of plutons and volcanic rocks shown on the state geologic map. Our mapping in this area (Miller and others, 1982, 1985; Howard and others, 1987; and unpublished) indicates that the plutons are of diverse types, and the proposed reconstruction (Dokka and Travis, 1990a) does no better at aligning related plutons and volcanic rocks than does the present map pattern. Lower Miocene flow-banded rhyolite lava flow crops out on opposite sides of the fault in the Bristol Mountains and Van Winkle Mountains without clear offset. This unit crops out in an east-trending belt from vents in the western Bristol Mountains (Miller, submitted). Its distribution limits dextral offset on this part of the fault zone to between 0 and 10 km. Metavolcanic rock crops out in a pendant in the Granite Mountains across the fault from a belt of metavolcanic rock in the Bristol and Old Dad Mountains. The map patterns limit any right separation on the Bristol-Granite Mountains fault to less than 10 km and perhaps less than 2 km. Reverse-sense separation exceeds 1 km where the fault juxtaposes deep-seated Cretaceous granite in the Granite Mountains onto Miocene volcanic rocks and their substrate of Jurassic granitoids in the Old Dad Mountains. Further constraints to possible lateral separations await detailed mapping of plutonic rocks in the northern Bristol Mountains

Fault in Granite Pass

A north-northwest-striking fault in Granite Pass juxtaposes Cretaceous granite in the Granite Mountains and Jurassic quartz monzonite in the southern Providence Mountains. Perched alluvium tentatively assigned to unit 1 but perhaps older overlies the fault. The west wall of the fault is a zone 150 m wide in which the granite is chloritic and cut by abundant outcrop-scale faults. Analysis of 7 measured fault planes and down-dip striations on one suggests that the small faults are conjugate normal faults.

Ranges on both sides of the fault expose distinctive Cretaceous porphyritic granite (described as the granite of Arrowweed by Miller and others, 1985) as well as more widespread Jurassic porphyritic quartz monzonite (Miller and others, 1985; Howard and others, 1987). Consequently no lateral separation along the fault is required, although as much as 5 km is permissible. Greater abundance and mostly coarser grain size of the Cretaceous granite on the west compared to the east side suggests that the east side is downdropped relative to the west side.

DISCUSSION

Faults in this boundary region between the Mojave and Sonoran blocks mostly ceased movement in the early Pleistocene, in contrast to late Pleistocene to historic faulting along parallel faults immediately to the west. Earthquake density also increases westward from the area (Goter, 1988; Zoback and others, 1988). Inception of the faulting probably occurred in the late Miocene if the extrapolated age of Bristol Lake basin is a guide. The exposed Quaternary faults belong to the eastern California shear zone of Dokka and Travis (1990a) at its eastern margin against the Sonoran block. The fault in Granite Pass does not obviously relate to this fault set.

Cessation of strike-slip faulting at the east margin of the Mojave block has migrated west from the early Pleistocene to the present day. Continued subsidence of Bristol Lake suggests that crustal strain has not ceased.

Dokka and Travis (1990a,b) attempted to model block translations and rotations along faults of late Miocene and younger age in the central Mojave Desert. As those authors emphasized, this region may account for a significant fraction of the motion between the North American and Pacific plates. Our studies in the area do not confirm the 21.5-km dextral offset predicted by the model of Dokka and Travis for the Bristol-Granite Mountains fault at the east edge of the belt of faults, nor the 13.5-km dextral offset their model predicted for the south Bristol Mountains fault. In the Dokka-Travis model, those predicted motions had accounted for more than half of the Mojave Desert total that was then used to calculate slip rates and strain as a fraction of the motion between the North American and Pacific plates (Dokka and Travis, 1990a, b). A lesser amount of strain is instead partitioned among the faults we describe, but geologic constraints are lacking to more completely define the block movements.

Wide fault zones, en echelon faults, reverse faults, normal faults, and deep sedimentary basins indicate that fault blocks in the area have not simply slid past each but have deformed internally, collided, and pulled apart. Basin origins remain poorly understood. Basins can form as pull-aparts near the ends of rotating blocks (Dokka and Travis, 1990a), at fault-bend gaps (Crowell, 1974; Dibblee, 1977), or at imbricate fans at fault ends (Woodcock and Fisher, 1986). Basin fills in this area are as deep as 1 to 1.5 km. The basin depths are much shallower than the block thickness if the blocks extend to 5-10 km depths as do earthquakes in the region (Sanders, 1990).

Fault-bounded ranges commonly truncate at the west- to west-northwest-striking Bristol-Danby trough (fig. 1), which crosses much of the Mojave Desert athwart fault trends (Thompson, 1929; Basset and Kupfer, 1964; Gardner, 1980; Glazner, 1981). This trend of coalescing small basins has irregular sides but overall it lies approximately perpendicular to the regional axis of tectonic compression in the area defined by geologic studies (Cummings, 1976; Bartley and others, 1990), strain measurements (Sauber and others, 1986), and stress measurements (Zoback and Zoback, 1980; Sauber and others, 1986; Zoback and others, 1987; Healy and Zoback, 1988). The Bristol-Danby trough is flanked on the south by a parallel belt of highlands (Bullion Mountains highlands), in turn flanked by the parallel Lucerne-Dale trough, in turn flanked to the south by the Transverse Ranges, all trending between west and west-northwest (fig. 1). This orientation of the four alternating highland and lowland belts is suggestive of tectonic waves akin to compressional-folded oceanic lithosphere (McAdoo and Sandwell, 1985; Zuber, 1987) and to fold-thrust belts. Uplift of the Transverse Ranges has been attributed to tectonic compression, and they are locally thrust over the Lucerne-Dale trough (Sadler, 1982; Meisling and Weldon, 1989). By analogy we speculate that the Bristol-Danby trough may also have a compressional component. The individual basins along it such as Bristol and Cadiz may represent a complex interplay between compression and extension related to translating and rotating fault blocks.

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Horizontal Separation of Major Late Cenozoic Strike-slip Faults in the Twentynine Palms Region, Mojave Desert, California

KEITH JAGIELLO
JOHN M. CHRISTIE } *Dept. of Earth & Space Sciences, University of California, Los Angeles, California, 90024*
RONALD G. BLOM *Jet Propulsion Laboratory-Caltech, Pasadena, California, 91109.*

ABSTRACT

This study focusses on the Hidalgo, Bullion, Sheephole, northern Coxcomb, and northeastern Pinto Mountains in the east-central Mojave Desert. The structure in this part of the block is dominated by late Cenozoic, northwest-trending, right-lateral strike-slip faults, which are systems of branching or en echelon features, rather than single continuous breaks. This paper describes the Pisgah-Bullion, Delta, Cleghorn Pass, Cleghorn Lakes, Sheephole and Dry Lakes faults, all of which have more than 1 km of horizontal separation, and several of which were previously unknown. These faults are seismically inactive, and most of the scarps are eroded or covered by younger alluvium, indicating that they are older than the northwest-trending, right-lateral strike-slip faults in the western Mojave Desert. Aggregate right-separation along northwest-trending faults in the study area is 30-45 km.

INTRODUCTION

The Mojave block is bounded by the San Andreas fault, the Garlock fault, and the Soda-Avawitz-Granite Mountains fault systems (Fig. 1). This study focusses on the portion of the block north of the Pinto Mountain fault, where the structure is dominated by late Cenozoic, northwest-trending, right-lateral strike-slip faults. The faults analyzed in this study are located in the southeastern part of this area, consisting of the Hidalgo, Bullion, Sheephole, northern Coxcomb, and northeastern Pinto Mountains (Fig. 2). Much of the study area lies within the Twentynine Palms Marine Corps Base.

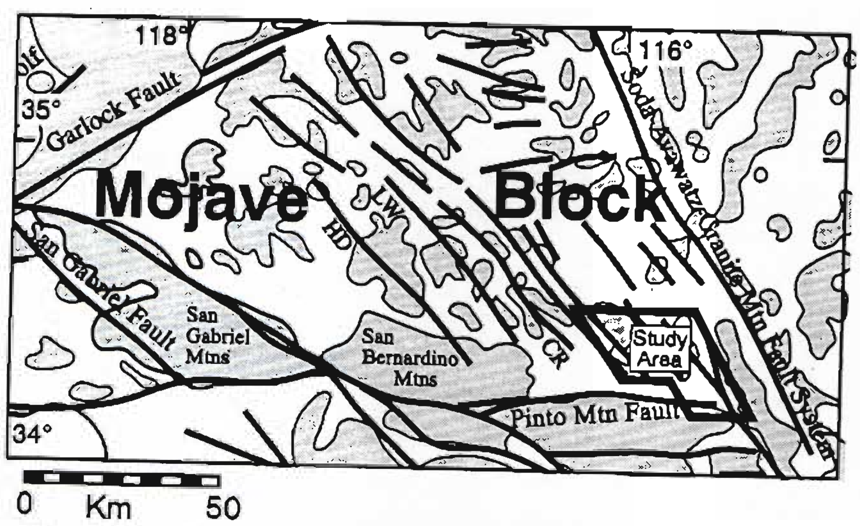

Figure 1. Generalized bedrock and fault map of southern California showing the study area within the Mojave Block (modified from Garfunkel, 1974). Labelled faults are the Helendale (HD), Lenwood (LW), and Camprock (CR).

These faults are systems of branching or en echelon features rather than single continuous breaks. Due the lack of piercing points, the offsets listed below are horizontal separations, based on displaced surficial rock units and structural features, rather than the actual net slip. The following discussion refers to faults with greater than 1 km of horizontal separation.

East-West Trending Right-Lateral Strike-Slip Faults

The only east-west trending, right-lateral strike-slip fault in the study area is the previously unmapped Segundo fault. It is here informally named after Segundo Peak in the western Bullion Mountains on the Twentynine Palms Marine Corps Base. Segments of it are found in the western, central, and southeastern Bullion Mountains, where it is offset right-laterally by the northwest-trending Delta, Cleghorn Pass, and Cleghorn Lakes faults (Fig. 3). This fault has not been found in the easternmost range of the Bullion Mountains or the Sheephole Mountains. In the southeastern Bullion Mountains, the fault is a prominent feature, consisting of a steeply-dipping gouge zone up to 20 m wide. In the east, the right-lateral horizontal separation is 3-5 km, based on the offset of the Cleghorn Pass pluton (Jcp) in the central and southeastern Bullion Mountains. Slickensides, where present, overwhelmingly indicate nearly horizontal movement. To the west, the gouge zone narrows to only 2-3 m, and the horizontal separation in the westernmost Bullion Mountains is no more than 2.3 km.

Northwest-Southeast Trending Right-Lateral Strike-Slip Faults

The northwest-southeast trending, right-lateral strike-slip faults described in this section are seismically inactive. Most of the scarps along these faults are eroded or covered

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by younger alluvium, indicating that they are older than the northwest-southeast trending, right-lateral strike-slip faults further west, such as the Helendale, Lenwood, Camprock, and Calico-Mesquite Lake faults (Morton and others, 1976) (Fig. 1).

Pisgah-Bullion Fault. The Bullion fault forms the western boundary of the Bullion Mountains (Fig. 3). To the north, outside the study area, it bifurcates into the Rodman Mountains fault and the Pisgah fault. The Pisgah fault runs through the late Cenozoic Pisgah volcanic field. In fact, several craters are centered on this fault. The Rodman Mountains fault is farther west, and based on mapping by Dibblee (1966), and field excursions during the course of this study, offset along this fault is considered negligible.

Dokka (1983) correlated the east-west trending Kane Springs fault with another east-west trending fault system in the northwestern Bullion Mountains north of the study area. This possible correlation leads to a right-lateral horizontal separation of 6.4-14.4 km on the fault system in this area.

Delta Fault. This fault runs along a valley separating the two ranges in the westernmost Bullion Mountains (Fig. 3). It is prominent in the southern part of the range, where it offsets plutonic rock units, but dies out to the north in Miocene volcanic and sedimentary rocks of the northern Bullion Mountains. It is here informally named the Delta fault after the "Delta Range" as designated by the Twentynine Palms Marine Corps base. A right-lateral horizontal separation of approximately 3.5 km was determined based on the offset of the east-west trending Segundo fault, which extends through the western and central Bullion Mountains. The only outcrop of the Delta fault is in the central part of the valley, where it is exposed as a nearly vertically dipping gouge zone 2-3 m wide. No indications of recent movement were found.

Cleghorn Pass Fault. This fault separates the ranges in the central Bullion Mountains (Fig. 3). Although this fault has been mapped in reconnaissance fashion (Bishop, 1963), it has never been named; therefore, it is here informally designated as the Cleghorn Pass fault after its exposure in Cleghorn Pass of the central Bullion Mountains. The only surface expression of this fault is in Cleghorn Pass, where it is actually a series of five faults. The faults are steeply-dipping gouge zones 2 to 10 meters wide, and are partially covered by younger alluvium. Although this fault deforms older alluvium, no indicators of recent movement have been found. Unlike the Delta fault, this fault does not die out in the Miocene volcanic field of the northern Bullion Mountains, and may be the southern continuation of the Ludlow fault (Fig. 3). If this fault is a continuation of the Ludlow fault, the right step between the two faults would result in a pull-apart basin. Extension in this area may have led to the extrusion of the basalts in the northern part of the study area.

Right-lateral horizontal separation of 16 km is determined based on the offset of the Segundo fault and the Cleghorn Pass (Jcp) pluton. The Cleghorn Pass pluton is found in the central Bullion Mountains, west of Cleghorn Pass. It is truncated to the north by the Segundo fault.

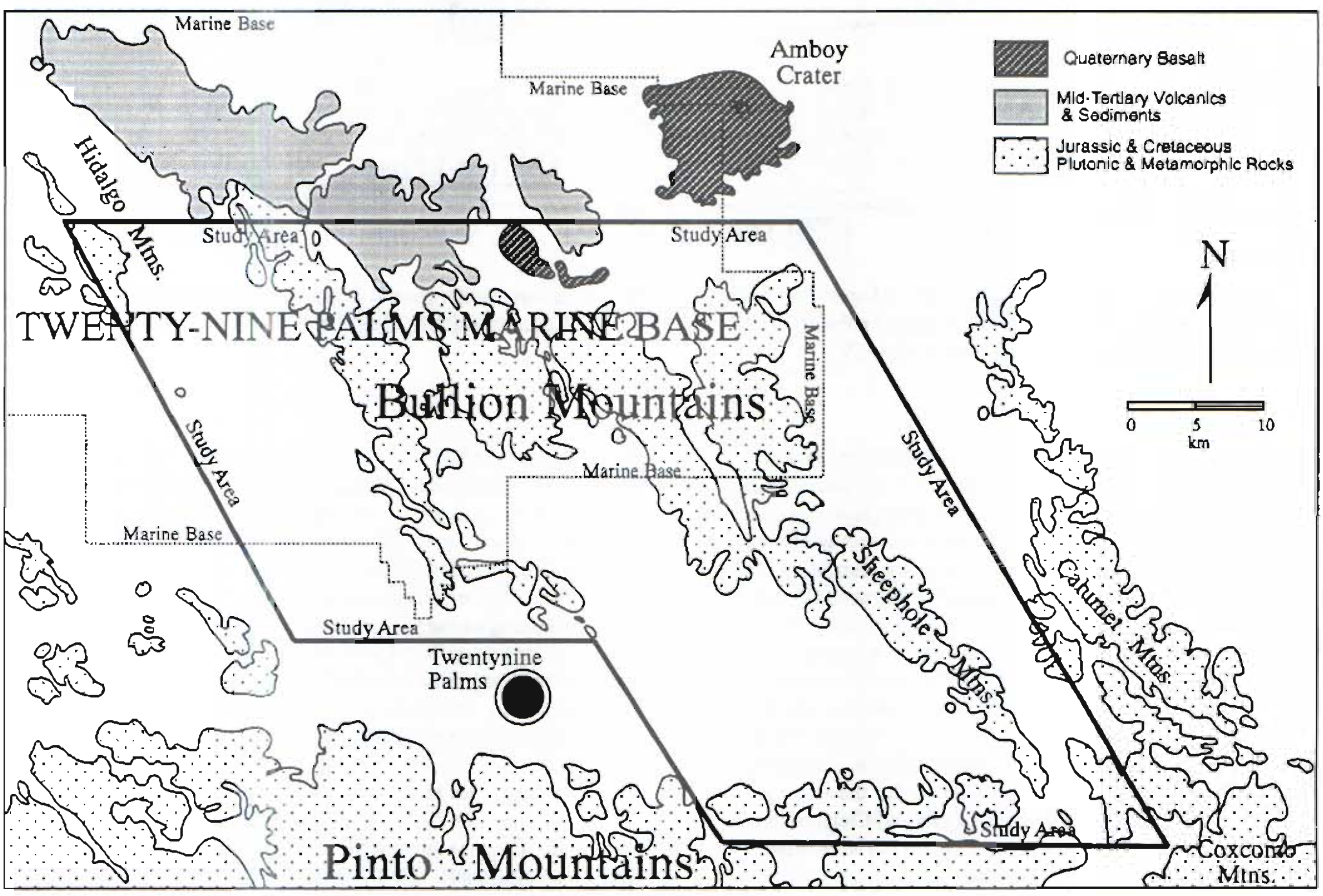

Figure 2. Generalized geologic map of the Twentynine Palms area.

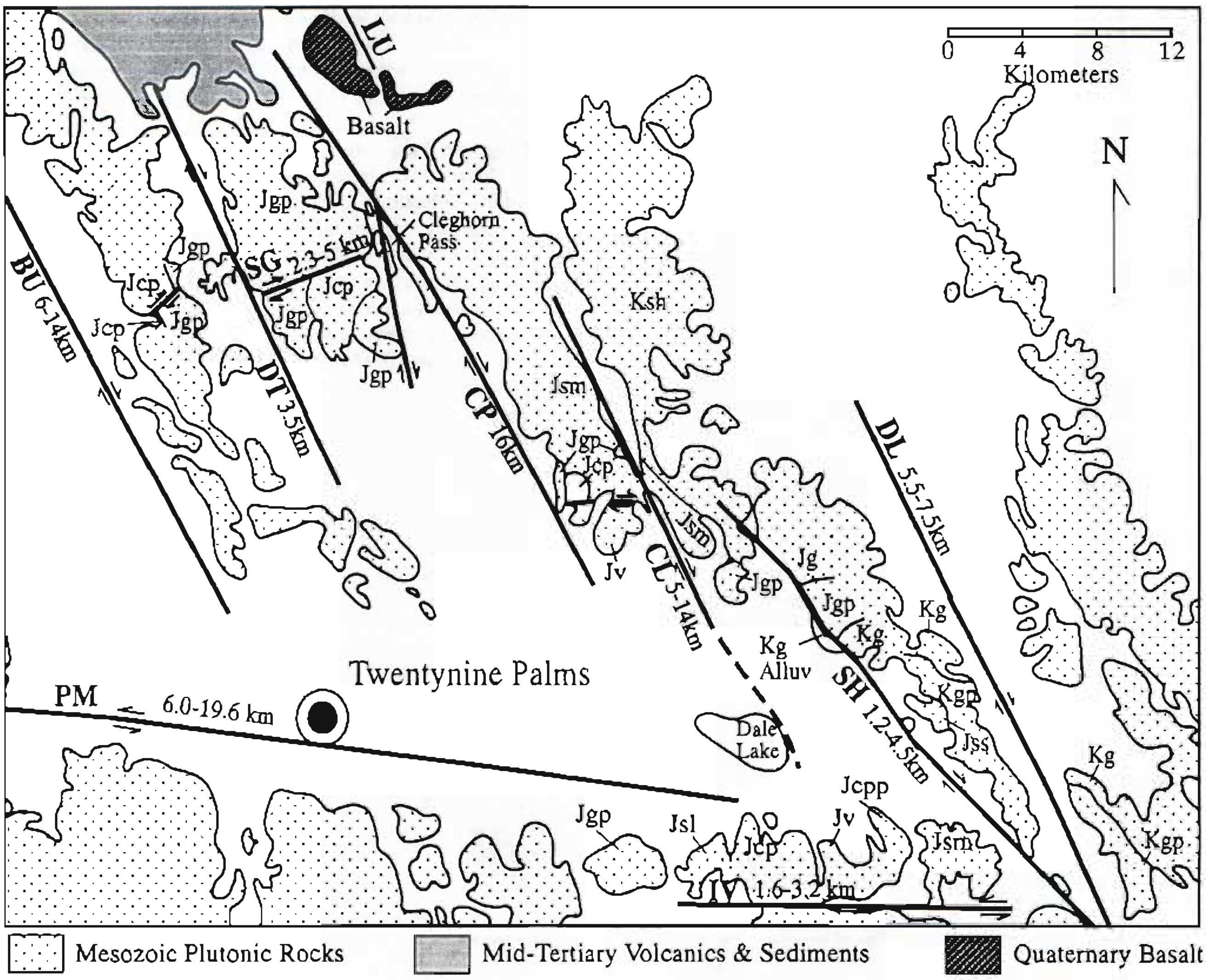

Figure 3. Generalized map of the the major faults and their estimated right-lateral horizontal separation within the study area. The faults are the Bullion (BU), Delta (DT), Cleghorn Pass (CP), Cleghorn Lakes (CL), Ludlow (LU), Sheephole (SH), Dry Lakes (DL), Segundo (SG), Pinto Mountain (PM), and the Ivanhoe (IV).

Enhanced TM images located a pluton with the same spectral signature in the southeastern Bullion Mountains. Here, the pluton is truncated by a fault to the south. Field observations, petrography, geochemistry, and TM images all confirm that this pluton is in fact an offset segment of the Cleghorn Pass pluton and the southern truncating fault is an extension of the Segundo fault. Figure 4 is a structural model for the development of faults in the area. The Cleghorn Pass pluton was most likely emplaced (Fig. 4a) in the Late Jurassic based on its mafic composition and cross-cutting relationships with the surrounding Late Jurassic rocks. In the late Cenozoic, this pluton was offset by the E-W trending, right-lateral, strike-slip Segundo fault (Fig. 4b), so that the northern portion was offset approximately 3 km to the east relative to the southern portion. During the late Cenozoic, the area was then cut by the NW-SE trending, right-lateral, Delta and Cleghorn Pass faults. The Segundo fault and the Cleghorn Pass pluton were offset approximately 16 km to the southeast to their present location (Fig. 4c).

Cleghorn Lakes Fault. This fault separates the two easternmost ranges of the Bullion Mountains (Fig. 3). The northern extension of this fault is covered by alluvium, but a magnetic survey (Mariano and Gauch, 1988) shows it extending to the east side of Dale Lake. This fault has been mapped in reconnaissance (Bishop, 1963), but is unnamed, and it is here informally designated the Cleghorn Lakes fault. Although predominantly covered by alluvium, it is exposed just south of the Cleghorn Dry Lakes, where it consists of a complex series of faults forming a zone 0.4 km wide. Surface expressions are steeply-dipping, gouge zones 3 to 15 meters wide. The Cleghorn Lakes fault separates the Cadiz Valley batholith to the east from Jurassic plutons in the west, and the easternmost fault of this system exploits the foliated zone on the western edge of the Cadiz Valley batholith. Where slickenslides are present, they are horizontal or gently plunging, indicating strike-slip motion.

Although unique offset rock units or structural features have not been found, there is evidence for considerable displacement along the Cleghorn Lakes fault. First, the alignment of magnetic lows is the strongest anomaly reported in the area (Mariano and Gauch, 1988), and extends to the east side of Dale Lake almost to the Pinto Mountain

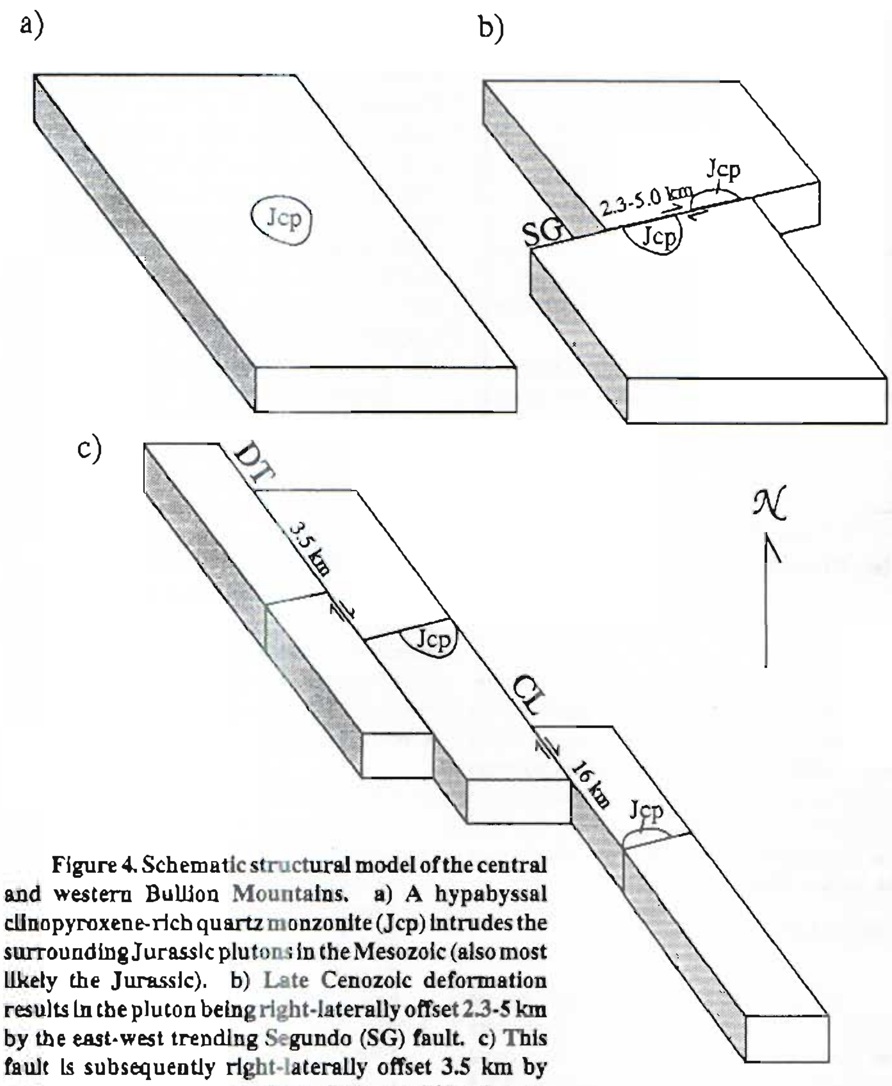

Figure 4. Schematic structural model of the central and western Bullion Mountains. a) A hypabyssal clinopyroxene-rich quartz monzonite (Jcp) intrudes the surrounding Jurassic plutons in the Mesozoic (also most likely the Jurassic). b) Late Cenozoic deformation results in the pluton being right-laterally offset 2.3-5 km by the east-west trending Segundo (SG) fault. c) This fault is subsequently right-laterally offset 3.5 km by northwest-trending Delta fault (DT) and 16 km by the Cleghorn Lakes (CL) fault.

fault. Second, rocks on the two sides of the fault are quite different. Extensions of the Cadiz Valley batholith (Ksh) are absent west of this fault in the southern portion of the range, although Howard and Miller (1991) reported small granite (Ksh) enclaves to the north. Furthermore, Jurassic plutons on the west side of the fault correlate with rocks in the southern Sheephole and northeastern Pinto Mountains, but are lacking in most of the easternmost Bullion Mountain range immediately opposite the fault. Howard and Miller (1991), on the other hand, report partially-recrystallized quartz monzonite (Jsm) in the northern portion of the easternmost Bullion Mountain range.

There are some possibly displaced rock units, which may give an estimate of right-lateral separation on the Cleghorn Lakes fault. Howard and Miller (1991) estimate an offset of 2.5 km in the northern Bullion Mountains based on displaced granitoids, but this offset is poorly constrained. On the other hand, the porphyritic quartz monzonite (Jgp) of the southeasternmost Bullion Mountains south of Sheephole Pass is found in fault-bounded slivers south of Cleghorn Lakes, and as outcrops in the Bullion Mountains west of Cleghorn Lakes. This potential offset results in a net horizontal separation of approximately 8 km. In addition, isolated outcrops and clasts of white quartz monzonite (Jg) associated with the uplifted older alluvium south of Cleghorn Lakes is offset from a possible source in the northwestern Sheephole Mountains, giving a cumulative right-lateral separation of 5-6 km across both the Sheephole and Cleghorn Lakes faults. Furthermore, if the rock units of Jsm, Jcp, and Jv of the southeastern Bullion Mountains on the west side of the Cleghorn fault are connected to their counterparts in the southernmost Sheephole and northeastern Pinto mountains, an offset of up to 20 km is possible; although model reconstructions constrain the offset to a maximum of 14 km.

Sheephole Fault. The northwest-trending, Sheephole fault bounds the western edge of the Sheephole Mountains (Fig. 3) (Howard and John, 1984). To the north, it cuts the southeasternmost Bullion Mountains and may join the Cleghorn Lakes fault. Based on correlative geologic rock units, the displacement along this fault is not great. First, dikes and fingers of the Sheephole Granite (Ksh) in the easternmost Bullion Mountains are found in the adjacent northern Sheephole Mountains. Second, partially-recrystallized quartz monzonite (Jsm) of the southernmost Sheephole Mountains is located in the adjacent northeasternmost Pinto Mountains (Howard and Allen, 1988). Third, a porphyritic quartz monzonite (Jgp) in the southeastern–most Bullion Mountains is also found in the northern Sheephole Mountains, giving a maximum right-lateral, horizontal separation of 4.5 km. Finally, an older alluvial fan with clasts dominated by Cretaceous Granite (Kg) clasts is offset from its source area by only 1.2 km. No indications of recent movement have been discovered on this fault.

Aeromagnetic data (Simpson et al., 1984) of the Sheephole fault shows that it is well-defined in both the extreme northern and southern Sheephole Mountains. Between these two areas, on the other hand, is a series of magnetic highs and lows that obscure the fault.

According to Powell (1981) and Biehler and others (1964), the Sheephole fault continues south and separates the Coxcomb Mountains from the Pinto and Eagle Mountains. Conversely, the small amount of offset of 1.2 to at most 4.5 km in conjunction with correlative rock types between the Pinto and Sheephole Mountains indicates that this fault is only a minor splay of that system, and the main branch of the fault most likely extends up the Calumet Valley on the east side of the Sheephole Mountains.

Dry Lakes Fault. This fault trends northwest-southeast, and runs along the valley that separates the Sheephole Mountains from the Calumet and northern Coxcomb Mountains (Fig. 3). In past publications (Jagiello and Blom, 1991), this fault was referred to as the Calumet fault. Upon recent review of the literature it was discovered that Howard and John (1984) had named a fault farther to the east the Calumet fault. Therefore, based on the convention introduced by Howard and

Fault	Previous Studies	This Study
NW-SE Trending Right-Lateral		
Pisgah-Bullion (BU)	6.4-14.4[d]	-
Delta (DT)	-	3.5
Cleghorn Pass (CP)	-	16
Cleghorn Lakes (CL)	-	6-14
Sheephole (SH)	-	1.2-4.5
Dry Lakes (DL)	-	5.5-7.5
Total		32.2-45.5
E-W Trending Right-Lateral		
Segundo (SG)	-	2.3-5.0
E-W Trending Left-Lateral		
Pinto Mountain (PM)	6.0-19.6[a,b]	--
Ivanhoe (IV)	1.6-3.2[c]	-

[a] Dibblee, 1967, [b] Bachellor, 1978, [c] Hope, 1966, [d] Dokka, 1983

Table 1. Horizontal separation of major late Cenozoic strike-slip faults in the east-central Mojave Desert region.

Miller (1991), this fault is now referred to as the Dry Lakes fault. No outcrops of this fault were located within the study area, but the northwest alignment of the dry lakes in conjunction with gravity and magnetic data (Simpson et al., 1984; Mariano and Gauch, 1988) delineate the trace of the fault. Both the gravity and the magnetic data show an alignment of low anomalies paralleling the trend of dry lake beds in this valley. Although not as well defined, the magnetic data indicates that the Dry Lakes fault continues to the north along the eastern margin of the Sheephole Mountains. The gravity data, on the other hand, does not show this continued alignment, and indicates that the fault may adopt a more northerly trend through the valley north of the dry lakes. Both gravity and magnetic data show the Dry Lakes fault to be better defined than the Sheephole fault to the west.

No indicators of recent movement on this fault have been found. A maximum right-lateral horizontal separation of 7.5 km is possible based on the offset contact of porphyritic granodiorite (Kgp) and granite (Kg) in the southern Sheephole and northern Coxcomb Mountains (Fig. 3). This contact is quite diffuse and it is impossible to determine if it is vertical to give a reliable offset, but it does establish that these ranges are displaced. A more conservative offset of 5.5 km is based on alignment of the topographic dog-leg in the southernmost Sheephole Mountains to the depression in the northern Coxcomb Mountains. The fit is very good, and brings similar rock types together.

The larger offset, the geophysical anomalies, and the consistent trend indicates that the Calumet fault is the main northern projection of the fault that bounds the western Coxcomb Mountains. Therefore, we propose that the fault separating the Coxcomb Mountains from the Pinto and Eagle Mountains also be known as the Dry lakes fault.

CONCLUSION

Estimates of horizontal separation on major strike-slip faults within the study area are summarized in table 1. The horizontal separations are: for the Segundo fault, 2.3-5 km; Delta fault, 3.5 km; Cleghorn Pass, 16 km; Cleghorn Lakes fault, 5-14 km; Sheephole fault, 1.2-4.5 km; and Dry Lakes fault, 5.5-7.5 km. The cumulative right-lateral horizontal separation on these faults is 30-45 km, which is unaccounted for in previous structural models of the northern Mojave Desert.

If the Ludlow and Cleghorn Pass faults are offset segments of the same fault system, a pull-apart basin would result at the right-step between the two faults. Extension in this area may then tap mafic magma reservoirs at depth resulting in the extrusion of late Quaternary basalts in the area.

Previous authors have speculated that the northwest-trending fault on the west side of the Coxcomb Mountains is a continuation of the Sheephole fault. On the other hand, the Dry Lakes fault on the eastern side of the Sheephole Mountains is the probable main northern continuation of this fault, on the basis of its consistent trend and greater offset.

These faults do not show any recent indications of movement, and are relatively seismically inactive compared to faults in the western Mojave Desert (Helendale, Lenwood, Camprock, etc.). In addition, these faults display greater offset (up to 16 km) than their western Mojave counterparts (< 3 km). Moreover the lack of recent indications of movement supports the observations of other authors (Morton et al., 1976; Bortugno and Spittler, 1986; Dokka and Travis, 1990; Howard and Miller, 1991) that fault activity has shifted westward in the Mojave Desert, where it is significantly more active at present.

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Paleomagnetic data from Neogene rocks in the region of the Eastern California Shear Zone (ECSZ)[1]

BRUCE P. LUYENDYK *Institute for Crustal Studies, University of California, Santa Barbara, CA, 93106-1100*

INTRODUCTION

Numerous paleomagnetic studies follow the trend of the Eastern California Shear Zone (ECSZ) from the Death Valley Fault Zone to the lower Colorado River and environs. Paleomagnetic results from rocks older than the shear zone may reveal the age and nature of activity in the zone. The amount and sense of translation can be estimated by both anomalies in paleomagnetic inclination and declination. A comparison of inclinations on opposing sides of the zone can give a direct estimate of the north-south component of translation. Declination anomalies from rotated blocks can be interpreted in terms of fault displacements given the geometry of rotated blocks.

PALEOMAGNETIC STUDIES

East of the ECSZ

A comprehensive review and study of middle Miocene volcanic rocks east of the zone is found in Calderone and others (1990). They discuss results from 16 mountain ranges in the northeastern Mojave Desert and western Arizona (Fig. 1). They studied 179 basalt lavas which post-date early Miocene detachment faulting and tilting. From these lavas they estimate that they found 50 or 60 independent measurements of magnetic field direction. They believe that these data adequately average secular variation. A paleomagnetic pole calculated from these data is in agreement with North American reference poles. Based on this data, they infer that there has not been any rotation or translation of any of the ranges immediately east of the ECSZ since the end of early Miocene time.

Calderone and others (1990) included the previously published data of Calderone and Butler (1984), Acton (1986) and Calderone (1988). Several studies in southeast California and southwest Arizona have been done by masters students at San Diego State University. Veseth (1985) and Butterworth (1984) studied tilted Oligocene and early Miocene and flat lying middle Miocene and younger volcanic rocks from the vicinity of the Kofa and Castle Dome Mountains. No declination anomalies were found in either groups of rocks which might suggest crustal rotations. However, Veseth (1985) noted that paleomagnetic inclinations in the older rocks are lower than expected and could indicate about 9° of northward translation for the Kofa and Castle Dome Mountains. Oliver (1984) studied 23 sites in early Miocene volcanic rocks from the Ajo Range in south-central Arizona. She found low inclinations suggesting about 8° of northward translation.

Of all the studies east of the ECSZ, probably only Calderone and others (1990) have successfully averaged secular variation. A tectonic explanation for the low inclination anomalies is possible but, other causes such as undersampling of secular variation and improper structural corrections due to undetected initial dips of flows, are equally valid.

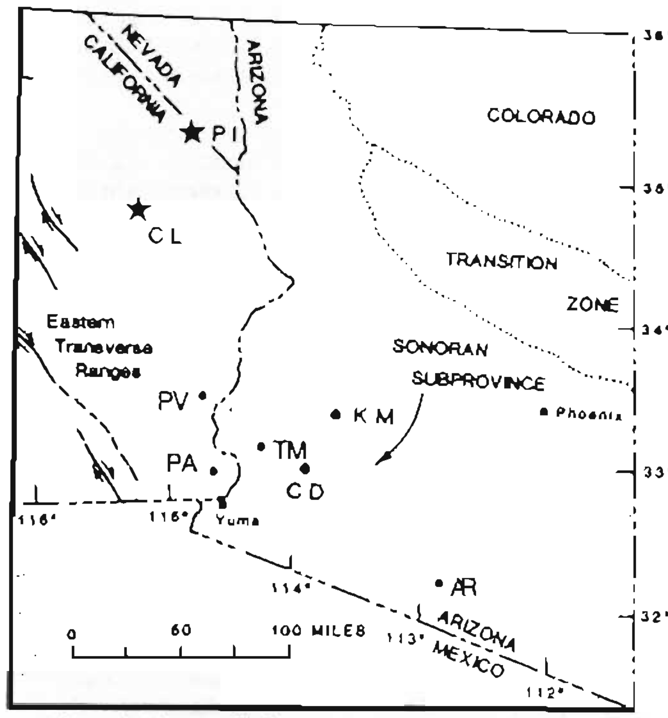

Figure 1. Geographic features in eastern California and southwestern Arizona. Abbreviations are as follows: AR--Ajo Range; CD-- Castle Dome Mountains; CL-- Clipper Mountains; KM--Kofa Mountains; PA--Picacho Area; PI-- Piute Range; PV-- Palo Verde Mountains; TM--Trigo Mountains.

West of the ECSZ

West of the ECSZ several studies have documented clockwise rotation of early Miocene rocks in the central and western Mojave Desert (Ross and others,1989; Golombeck and Brown (1988); Morton and Hillhouse, unpublished, reported in Ross and others, 1989). Paleomagnetic results from Early Miocene volcanic rocks of the Pickhandle Formation (> 19 Ma) near Barstow indicate significant counterclockwise rotation (Burke and others, 1982; Valentine and others, 1987, 1988) which Valentine and others (1991) attributed to deformation associated with a transfer fault between the Waterman and Edwards extended terranes of Dokka (1987). No significant inclination anomalies have been documented in early Miocene volcanic rocks from the Mojave desert area.

Wells and Hillhouse (1989) performed paleomagnetic studies on the Peach Springs tuff (18.5 Ma, Nielson and others, 1990), and report localized rotations of up to 13° and variable clockwise and counterclockwise sense for outcrops of the tuff between Barstow and the Bristol Mountains. MacFadden and others (1990b) report negligible

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or slight counterclockwise rotation of the Barstow Formation (17.6-13.4 Ma) from the Mud Hills. However, MacFadden and others (1990a) have documented post-early Miocene clockwise rotation of 20.6° in the Hector Formation (23-16 Ma) in the northern Cady Mountains.

These data indicate that significant, mostly clockwise, rotations are limited to early Miocene (22-18 Ma) rocks located in the Mojave Extensionsal Belt of Dokka (1990). Post-early Miocene rocks (<18 Ma) show variable and generally small rotations both within and outside the extended terrane, except in the northern Cady Mountains (Ross and others, 1989; Dokka and Travis, 1990).

Tertiary rocks in the eastern Transverse Ranges (ETR) south of the Pinto Mountain Fault have been studied by Terres (1984), Carter and others (1987), and B. Adams (unpublished, 1990; Figure 3). Terres (1984) found extreme clockwise declination anomalies over 160° in volcanic rocks of the early Miocene Diligencia Formation in the Orocopia Mountains adjacent to the Clemens Well Fault. He attributed these to dextral shear on the fault. Terres' (1984) data also show dramatic flattening of inclination of 14° to 17°. Luyendyk and others (1985) do not believe these to be due to tectonic effects.

Terres (1984) and Carter and others (1987) also presented data from middle Miocene and younger volcanic rocks from the ETR. An average of 41° of clockwise rotation and no significant flattening was found. The timing of this rotation is unclear. Some K-Ar ages reported by them may be in error. Lavas from the Palen Mountains show a 31° declination anomaly and were reported by Carter and others (1987) to be 13.7 ± 1.6 Ma. The same lavas were dated at 6.4 ± 0.2 by the U.S.G.S. (Stone and Kelley, 1989). Lavas showing no anomaly on the west side of Pinto Wash were dated at 7.8 ± 0.7 Ma by Carter and others. Two kilometers east across the wash, a lava was dated at 4.5 ± 0.29 Ma by Calzia and others (1986). These lavas are west of the Sheephole fault. Adams (unpublished, 1990) has correlated the lavas across Pinto Wash and believes they all originated from the west. He also obtained paleomagnetic results which mostly agree with Carter and others (1987) data on the west side of the wash and and show little or no clockwise declination anomaly.

The younger revised ages, if accepted, infer that most of the ETR clockwise rotation occurred in Pliocene time. This interpretation would also imply that the younger episode of rotation in the northeast Mojave is also of Pliocene age (Luyendyk, 1991).

In southeastern California paleomagnetic studies on Tertiary volcanics have been made by Costello (1985) and Callian (1984) as masters projects at San Diego State University. They sampled 32 units from three formations described by Crowe and others (1979) in the Palo Verde and Trigo Mountains, and also the Picacho region of the Chocolate Mountains. The rocks comprise rhyolite, andesite, and basalt flows and tuffs varying from 35 to 13 Ma. The southeast Chocolate and southern Trigo Mountains have a clockwise declination anomaly of 40° ±15°. The Palo Verde and northern Trigo Mountains do not have a declination anomaly. The clockwise declination anomaly is interpreted as a rotation which began after 13 m.y.b.p. - this permits it to be interpreted as simultaneous with the ETR rotation to the north. An inclination anomaly suggesting 7° of northward translation was also found. Costello (1985) interpreted this to represent northward translation of the region of Arizona and California west of the Aubrey lineament of Lucchitta (1977) which trends NW-SE through Arizona and passes east of the study by Oliver (1984).

The Peach Spring tuff study of Wells and Hillhouse (1989) spans the region from the west edge of the Colorado Plateau to Barstow in the Mojave Desert. This study provides a structural and stratigraphic marker to assess relative motions after about 18.5 Ma. The work includes results from 41 localities including 6 west of the ECSZ. No sites were studied in the northeast Mojave Block, believed to have rotated in Pliocene time by Luyendyk (1991). The inclination data are too noisy to resolve relative N-S translation over their study area. Declination anomalies suggest a minor amount of clockwise rotation of small blocks associated with dextral faults in the Mojave Desert Block. No significant declination anomalies were found in the Basin and Range Province. In the Colorado River extensional corridor, significant clockwise and counterclockwise declination anomalies are interpreted to be due to rotation of the upper plate blocks of mid-Tertiary detachment fault systems.

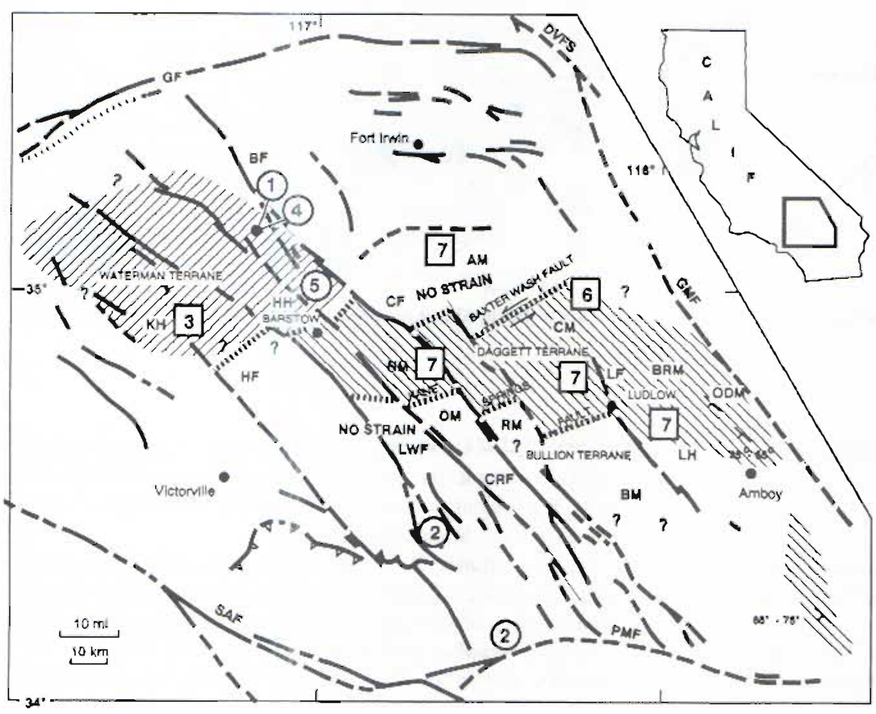

Figure 2. Generalized map of the Mojave Desert showing major faults, early Miocene extensional terranes of Dokka and Travis (1990), and locations of paleomagnetic studies discussed in text. Squares indicate studies yielding clockwise declination anomalies, circles indicate counterclockwise anomalies (modified from Dokka and Travis,1990; Ross and others, 1989). 1--Burke and others (1982); 2-- Morton and Hillhouse (unpublished, In Ross and others, 1989); 3--Golombek and Brown (1988); 4--Valentine and others (1987, 1988); 5--MacFadden and others (1987, 1988); 6--MacFadden and others (1989); 7--Ross and others (1989). DVFS--Death Valley fault zone; BRM--Bristol Mountains; CM--Cady Mountains; PMF--Pinto Mountain Fault.

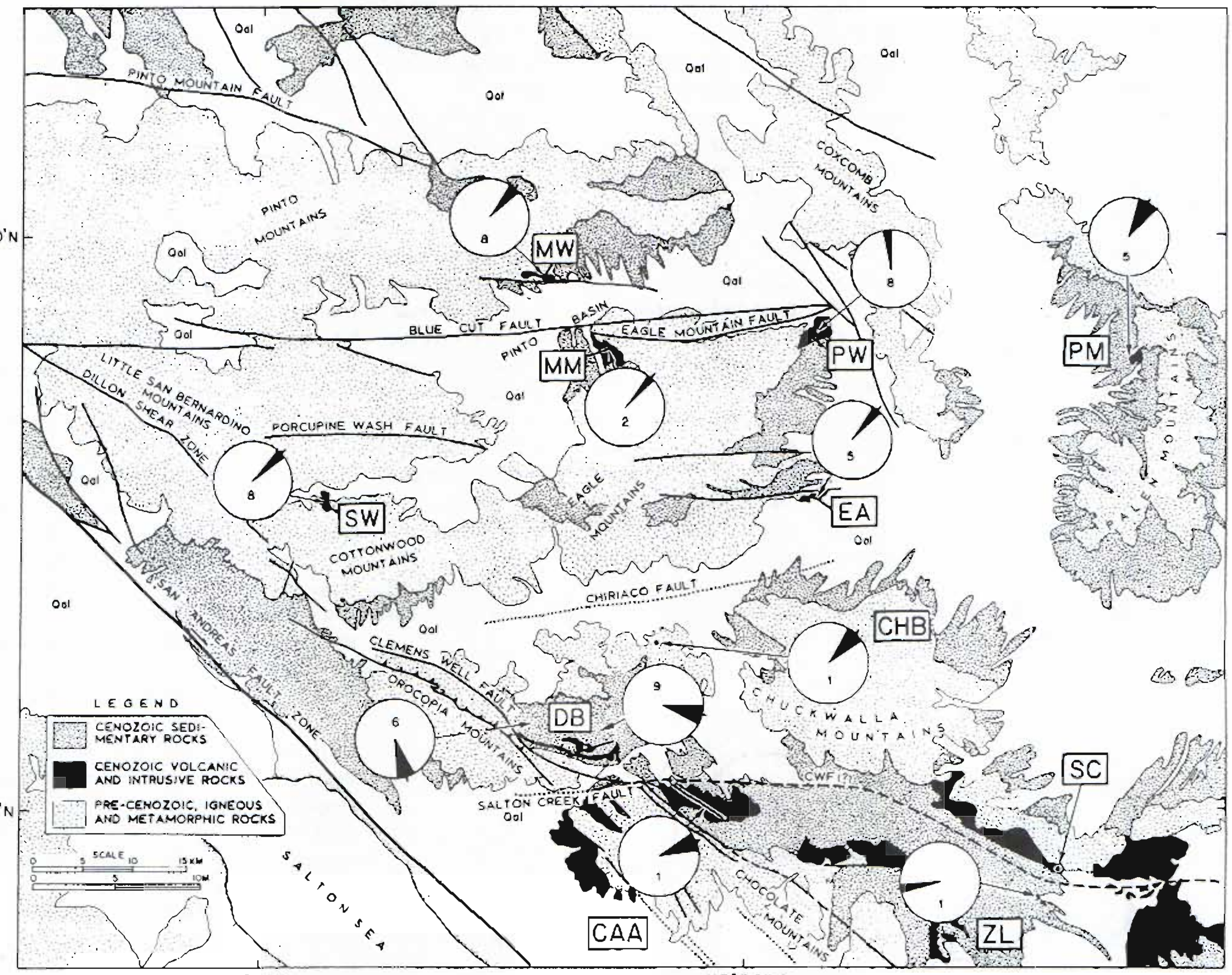

Figure 3. Geographic features in the Eastern Transverse Ranges and adjacent area, along with paleomagnetic data. From Carter and others (1987).

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Late Quaternary Deformation In The Manix Basin Region, Central Mojave Desert, California

NORMAN MEEK *Department of Geography, California State University, San Bernardino, CA 92407.*

In comparison to much of the Mojave Block, the Manix basin has been the focus of unusually active late Quaternary tectonic deformation. In historic time the Manix basin has also been the center of greatest seismicity within the Mojave Block (Goter, 1988). Six potentially active fault zones have been documented within the basin (i.e. the Manix, Calico, North Coyote, Southwest Coyote, Lake Dolores and Afton Exit faults; see Meek, 1990, p. 151-173 for a review of the evidence). There is also abundant evidence of deformed Quaternary deltaic and alluvial fan deposits in many other areas of the basin, but rapid late Quaternary sedimentation has obscured most traces of the faults probably responsible for the deformation.

In general, the northwest-trending faults display right lateral strike-slip separation, and minimal vertical separation where they cross broad plains in the basin. However, it would be premature to believe that vertical deformation is absent along these faults, because the plains are underlain by very thick upper Quaternary sediments, and attempts at subsurface correlation of distinctive strata across the faults have been unsuccessful. On the other hand, the east-trending faults commonly display evidence of substantial vertical deformation, probably caused by north-south compression of the Mojave Block. Interestingly, there is little evidence of significant late Quaternary lateral displacements along either the east-trending or northwest-trending faults in the Manix basin.

It has been proposed that a period of long-term landscape stability was interrupted by Pliocene and Quaternary diastrophism in one, and perhaps two, pulses (Meek, 1990, p. 179). A Pliocene to middle Pleistocene episode of predominantly lateral displacements on both the northwest- and east-trending faults was followed by an episode of mostly vertical displacements on the east-trending faults beginning in the middle Pleistocene. It is possible that these phases may be related to tectonic pulses evident in distant locations such as the San Bernardino Mountains (e.g., Meisling and Weldon, 1989).

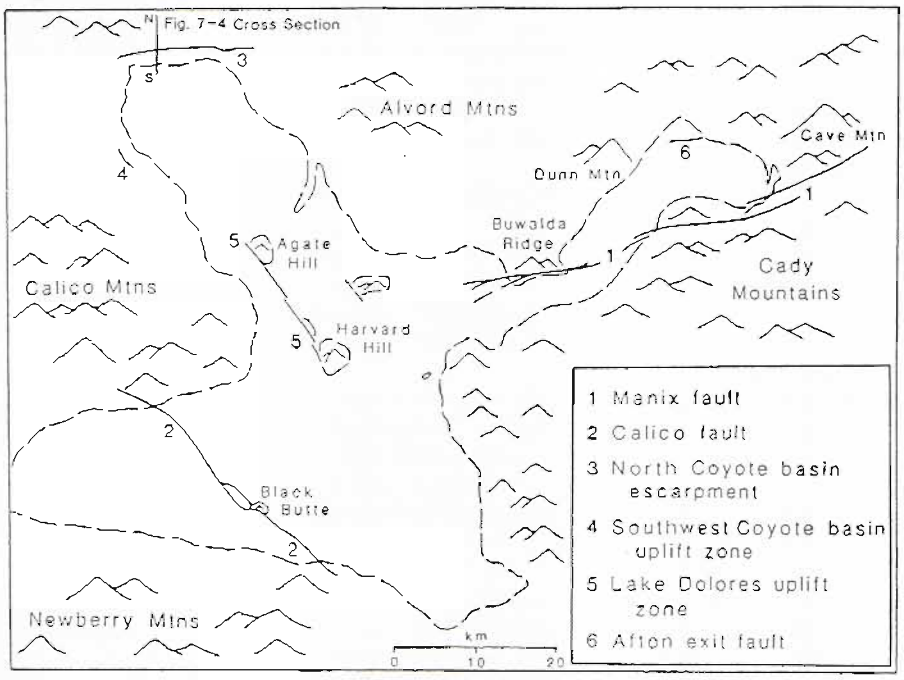

Figure 1. Potentially active tectonic zones in the Manix Basin.

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Distribution of contemporary slip in the Mojave Desert and Walker Lane: A Global Positioning System (GPS) experiment

M. MEGHAN MILLER
MATTHEW P. GOLOMBEK } *Jet Propulsion Laboratory 183-501, California Institute of Technology, Pasadena, CA 91109*
ROY K. DOKKA *Department of Geology, Louisiana State University, Baton Rouge, LA*
STEVE FISHER *Jet Propulsion Laboratory 238-600, California Institute of Technology, Pasadena, CA 91109*

ABSTRACT

Late Cenozoic deformation in the Mojave Desert, east of the San Andreas fault in southern California, is characterized by north-westward dextral displacements along strike-slip faults, and sinistral deformation along lesser, E-W striking faults. Localized extension and contraction are related to variations in fault geometry and areas of offset between the ends of strike-slip faults. Dextral deformation in the Mojave Desert is kinematically related to transform motion on the San Andreas fault and to faulting farther north, in the Death Valley - Furnace Creek and Owens Valley fault zones (Walker Lane). The exact amounts of slip within the Mojave block and the transfer of motion northward into the Walker Lane are poorly understood. We are using high precision space-based geodesy to characterize the distribution of active slip in the Mojave Desert region and structural domains to the north. This study uses the Global Positioning System (GPS) for high precision geodetic measurements in a network that will be occupied on an annual or biannual basis over a period of five years. This paper presents the rationale for the experiment and summarizes the first GPS field campaign, performed in May 1991.

INTRODUCTION

Transform motion between the North America and Pacific plates has resulted in a broad zone of deformation in southern California. The plate boundary is not an ideal transform fault in that motion is not restricted to a single discrete fault zone and the plate margins are not internally rigid on a regional scale (Crowell, 1975). Cenozoic deformation related to the plate boundary includes major right-slip faulting along NW-striking faults (e.g., Hill and Dibblee, 1953), rotation of large crustal blocks about vertical axes (e.g., Luyendyk and others, 1980; Golombek and Brown, 1988), and the creation of sedimentary basins and block uplifts at dilatational and restraining bends respectively (e.g., Crowell, 1974). The actively deforming zone spans the southern California and northern Baja California continental borderland, and also includes extensional deformation to the east, in the Basin and Range province. About 75% of the dextral relative plate motion is accommodated on the San Andreas fault, and lesser components are partitioned along faults in the California Borderland (Weldon and Humphreys, 1986). Much of the relative plate motion can be accounted for in this manner, although the role of active NW-striking dextral faulting and E-striking sinistral faulting east of the San Andreas fault, both in the Mojave Desert Block and east of the Sierra Nevada (Figure 1), has recently been recognized as a kinematically important feature of the plate boundary zone (Garfunkel, 1974; Stewart, 1988; Dokka and Travis, 1990a; Saucier and Humphreys, in review). As much as ~9-29% of the total relative plate motion is accommodated in the Mojave Desert region (Dokka, 1983; Sauber and others, 1986; Golombek and others, 1988). How specific faults in the Mojave Desert accommodate strain and the transfer of slip to temporally related faults to the north is uncertain, although it may occur via east-west striking left-lateral faults of the northeastern Mojave block (Dokka and Travis, 1990a; Schermer and others, 1991). NASA's Crustal Dynamics Project MOJAVE base station for space-based geodesy lies in this area, and its kinematic relation to regional deformation is not well understood, yet critical to deciphering the meaning of decade long Very Long Baseline Interferometry (VLBI) measurements from this site (Golombek and others, 1988).

Recent geologic studies indicate that between 65 and 80 km of right slip has occurred along the eastern California shear zone in the southern Mojave Desert since the Neogene (between the Helendale and Granite Mountains faults, Fig. 1; Dokka and Travis, 1990a). This family of faults, along with coeval, strike-slip faults of the Death Valley region (Furnace Creek and Death Valley fault zones, Owens Valley fault, and other faults of the Walker Lane of Stewart, 1988) constitutes a regional zone of dextral shear in eastern California (Dokka and Travis, 1990b; Savage and others, 1990). Because faults of the south-central Mojave Desert intersect and capture slip from the San Andreas system, these faults must accommodate a portion of Pacific-North American transform motion. As much as 10 mm/a is accommodated in this fashion, and is apparently transferred northward into the Walker Lane.

We are carrying out a series of Global Positioning System (GPS) experiments that will monitor fault motions both within the Mojave Desert and between the Mojave Desert and adjacent areas over a five year period that began in 1991. These studies will: 1) measure slip along many faults within the Mojave Desert, 2) observe the relation between tectonism in the Mojave Desert and adjacent structural domains, and 3) provide local strain nets that will clarify ambiguities of local displacements around NASA's Crustal Dynamics Project MOJAVE and OVRO base stations. The first measurements were made during May, 1991. This paper briefly describes the geodetic method, the network and first occupation, and the specific geological problems that will be addressed by this experiment.

METHOD

Techniques that use the Global Positioning System to measure crustal deformation have recently been summarized by Dixon (1991) and Hager and others (1991). In GPS geodesy, an array of navigation

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 59-63.

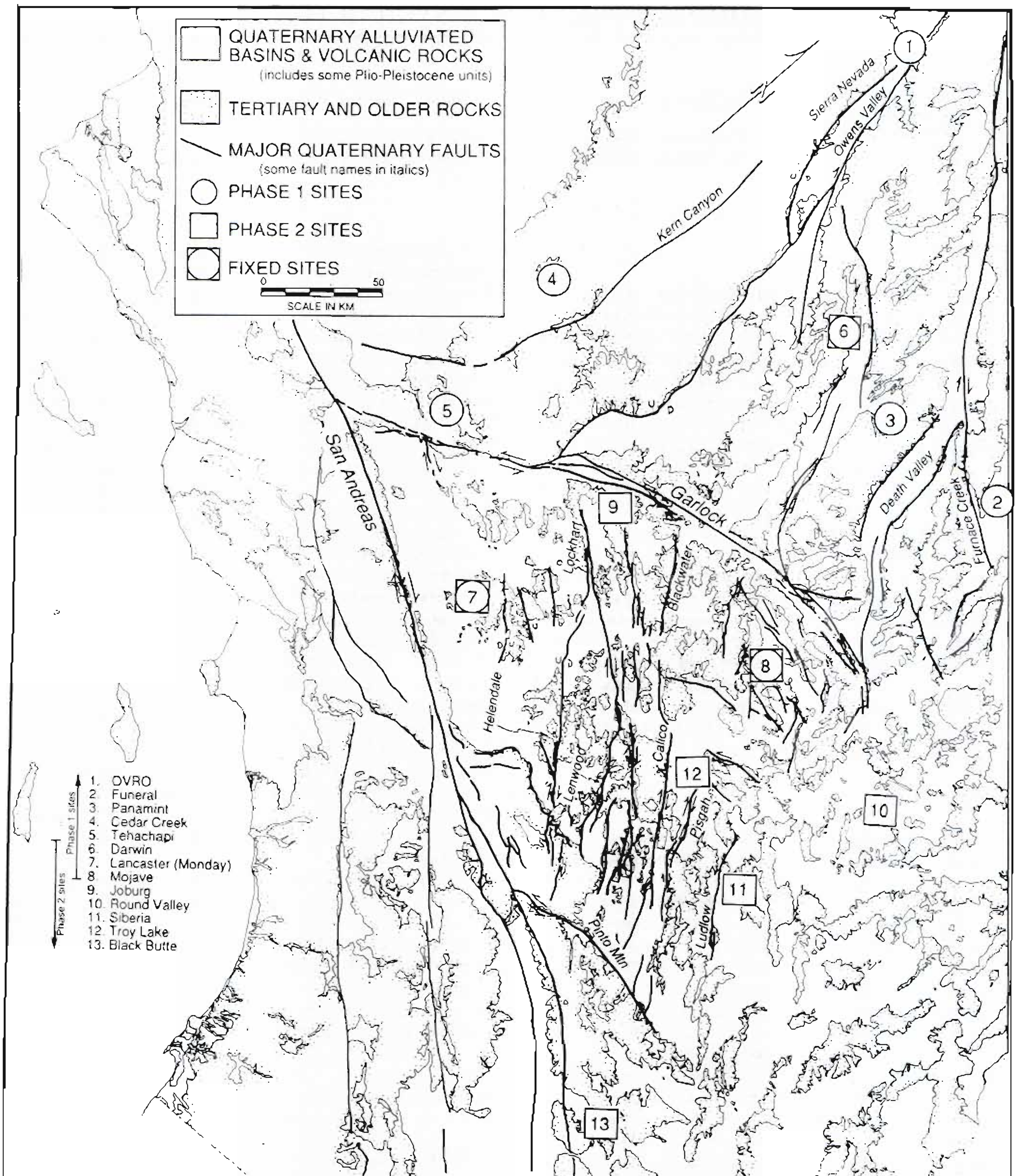

Figure 1. Location of GPS sites in the Mojave-Walker Lane network with respect to active faults east of the San Andreas fault in southeastern and east-central California. Geologic base from Jennings (1977), Mojave Desert faults simplified from Dokka and Travis (1989), active faults north of the Garlock fault simplified from Stewart (1988).

satellites (the Global Positioning System) determines high-precision locations for a network of ground survey points. Receivers at ground stations simultaneously range to three or more satellites to determine their location in a inertial reference frame. Repetition of an experiment after an interval of strain accumulation allows direct measurement of regional surface deformation. The time interval required is limited by strain rate and measurement precision. The largest sources of error in GPS geodesy are variable signal path delays due to variations in the wet troposphere and uncertainties in the satellite orbits (Dixon, 1991). These effects are minimized by simultaneous occupation of a global network of stations whose positions are known (fiducial sites) allowing accurate solutions of orbit paths. Geodetic experiments with the Global Positioning System have achieved position precisions of several mm plus 1-2 parts in 10^8 of baseline length (Tralli and Dixon, 1988; Dong and Bock, 1989; Blewitt, 1989; Dixon and others, 1991).

Southern California is a benign environment for GPS geodesy. The wet tropospheric path delay is both small and uniform for much of the year. Moreover, numerous fiducial sites, whose positions are well known by some independent space-based geodetic technique such as Very Long Baseline Interferometry or Satellite Laser Ranging are available, enabling acquisition of high resolution tracking data for the GPS satellites and subsequent estimation of high precision satellite ephemerides. In addition, baselines within this network are relatively short and satellite constellations were robust over North America during the period of observations, and are likely to remain so in subsequent years, further minimizing errors.

Geodetic precision is commonly expressed by the equation:

$$\sigma_h = (a^2 + b^2 l^2)^{1/2}$$

where σ_h is horizontal precision, l is baseline length, and a and b are 5 mm and $1 * 10^{-8}$, respectively (Dixon, 1991). These constants represent the length-independent (a) and length-dependent (b) sources of error. For GPS, a is affected by receiver noise, while b is dominated by tropospheric and orbit effects (beyond baseline lengths of several hundred km, orbit effects dominate). Vertical component repeatability is significantly worse, but these measurements are not critical to our experiment.

Baseline lengths in the Mojave - Walker Lane net vary from 40 km to 350 km. Shorter baselines cross faults with expected slip rates as small as 1-3 mm/a (for summary of expected strain rates, see Saucier and Humphreys, in review). Regional strain across longer baselines occurs at the centimeter-per-year level. Estimates for day-to-day repeatabilities (precision) using the equation given above range from about 5.0 to 6.1 mm for baselines of these lengths. Thus, regional deformation expected within the network as a whole at the centimeter-per-year level should be detectable after two occupations at a two-year interval. Both precision and accuracy should substantially improve with subsequent occupations. Slower rates across shorter baselines will be resolved over a longer time interval, perhaps as long as a decade

MOJAVE REGIONAL NETWORK

Network Design and Site Selection

The Mojave - Walker Lane GPS network (Fig. 1) was designed to measure slip along NW-striking dextral faults and related families of faults in eastern California. In addition, it will relate deformation within the Mojave block and Walker Lane to the San Andreas fault zone and the Basin and Range. In particular, it will monitor 1) the potential transfer of slip from the San Andreas fault into the Mojave block, 2) cumulative deformation across the eastern California shear zone, 3) the difference between slip along the Helendale, Lenwood, and Calico faults and possible slip to the east on the Pisgah, Ludlow, and Granite Mountains faults, 4) deformation within the Goldstone area and its relation to the rest of the Mojave block, 5) slip rates across the eastern and western ends of the Garlock fault, 6) slip rates of specific faults within the Walker Lane (the Furnace Creek - Death Valley fault zones and Panamint and Owens Valley faults) and within the Sierra Nevada block (e.g., the White Wolf and Kern Canyon faults), and 7) regional strain distribution.

The network was designed to be occupied in two phases, with three common (fixed) stations and five additional stations occupied during each phase (Fig. 1). The network of thirteen stations consists of three Crustal Dynamics Project stations (OVRO, Mojave, and Black Butte), one Cal Trans station (Cedar Creek), four U. S. Geological Survey stations (Darwin, Joburg, Lancaster, and Tehachapi) and five new marks set by the Jet Propulsion Laboratory (JPL) specifically for this project where pre-existing ground survey points were not suitable (Funeral, Panamint, Round Valley, Siberia, and Troy Lake).

Careful site selection was used to minimize noise sources and improve the accuracy of geodetic position estimates. Specifically, we 1) avoided areas of spurious ground motion (such as unstable slopes and alluvium where settling, landsliding and the cyclic effects of temperature and ground water fluctuations pose threats to site stability) by selecting sites on bedrock, 2) maximized sky coverage for visibility of satellites, and 3) minimized multipath potential (reflection of the GPS signal due to ground level obstructions). These issues are important to detection of motion within the five year period of this project.

All stations were set in bedrock, except three existing Crustal Dynamics Project (CDP) and one Cal Trans station. The three CDP stations used pre-existing monuments set in alluvium. They were selected to address ambiguities from previous CDP geodetic campaigns, and to maximize the sharing of common baselines with other California geodetic networks and data bases. All three of these stations have been previously occupied with GPS and VLBI. In addition, OVRO and Mojave have both been occupied with Satellite Laser Ranging. The Cal Trans station is in a carapace of grus on a rounded knob of granitic bedrock that is free from potential hazards associated with alluvium sites. This mark was recently installed as part of the Cal Trans California high precision GPS network. The four U. S. Geological Survey (USGS) stations are all first order triangulation stations in bedrock (one in subsurface bedrock), and two of them have been subsequently occupied using GPS by USGS, Cal Trans, Caltech, and the County of Los Angeles. New stations installed by JPL are steel rods in epoxy set in drilled bedrock approximately 30 cm deep. Reference marks within about ten meters of the station mark were installed at all of the new JPL stations for reconstruction of base station location in case of vandalism. Where no reference marks were present for existing marks, new reference marks were installed.

1991 Network Occupation

The network was occupied from May 12 - 23, 1991, in two phases of eight sites each. Mobile teams began in the north, operating at the Funeral, Panamint, OVRO, Cedar Creek, and Tehachapi stations from May 12 - 17, 1991. Field teams made the transition to phase two stations in one day and operated at the Joburg, Troy Lake, Siberia, Round Valley, and Black Butte stations for the period of May 19 - 23 (Fig. 1). Three stations, Lancaster (Monday), Darwin, and Mojave, were occupied during both phases to tie the northern and southern parts of the network and were occupied on the day that other teams were in transition to allow for better orbit solutions. Seven hours (~ 18:00 -

1:00 UTC (Coordinated universal time)) of GPS data were collected daily at each station with Trimble 4000 SST receivers. The observation schedule took advantage of the time period when as many as six satellites were visible simultaneously. Surveys between station and reference marks at each site were performed using spare receivers at all stations except for the three CDP stations where precise survey ties had already been made to local recovery networks.

A number of global fiducial sites that were operating with ROGUE or CIGNET (Minimacs, TI-4100, and Trimbles) receivers during the project provide satellite tracking for orbit determination and reference frame control. Data collected during the May 1991 Mojave campaign is currently being processed and analyzed at the Jet Propulsion Laboratory (JPL) using GIPSY (GPS Inferred Positioning System), a software package developed at JPL for GPS data reduction.

Future network occupations

The regional network will next be reoccupied in the spring of 1993, after a two year interval of strain accumulation. Several sites will be added, primarily to differentiate slip on the Kern Canyon fault from faults to the east, and to differentiate slip on the Death Valley fault from that on the Furnace Creek fault. Equipment limitations prevented these sites from being occupied during the 1991 campaign. In 1992, tectonic footprint networks will be installed across the Owens Valley and Garlock faults. These local networks will use short baselines across segments of specific faults to determine their local slip rates with high precision. The local nets will be occupied concurrently with the regional net again in 1993, and in subsequent occupations.

DISCUSSION

Reconstructions of fault slip and block motions in the Mojave Desert indicate that the locus of faulting in this broad zone has not remained fixed, but has shifted westward with time (Dokka and Travis, 1990a). The distribution of earthquakes (Goter, 1988; C. Jones in Dokka and Travis, 1990a) and distortion of the Mojave regional strain net (Sauber and others, 1986), indicate that displacements of approximately 7 mm/a are now concentrated in the south-central Mojave along the Helendale, Lenwood, and Camp Rock faults (Fig. 1; Dokka and Travis, 1990a). Gravels that are late Quaternary in age overlie the Granite Mountains (Davis, 1977), Bristol Mountains (Brady, 1988), and Broadwell Lake (Ford and others, 1990) faults, implying that the westward shift occurred quite recently. The geometry of modern slip within the Mojave block will be tested by baselines between Lancaster (Monday), Troy Lake, Siberia, Round Valley, and Mojave (Fig. 1).

Active deformation is not apparent immediately north or west of the currently active right-slip faults (King, 1985; Goter, 1988), indicating that dextral shear is not transferred directly through these areas to Death Valley. Dextral strike-slip faults are well known, however, in the Death Valley region (e.g., Stewart, 1983) and farther north (e.g., Owens Valley, Beanland and Clark, 1987; Lubetkin and Clark, 1988). These faults form part of the regionally extensive Walker Lane belt, consisting of differing Cenozoic structural domains that separate regionally extensive, basin-and-range style faulting to the east from the large Sierra Nevada block to the west (Stewart, 1988). Diverse tectonic styles characterize different domains, and include NW-striking dextral faults, oblique sinistral faults, and families of normal faults with differing orientations. Strike-slip faults from any one domain do not connect directly to those of adjacent domains, although the region as a whole appears to transfer dextral slip from the Mojave Desert region, and thus must play an important role in Pacific-North America plate interaction. Because most of the regionally important strike-slip faults do not physically connect, slip is likely transferred between faults by localized finite strain and(or) subsurface faulting along shallowly dipping structures. Such deformation must be present in the area of the MOJAVE base station, which lies at the juncture of regions of differing structural style, contributing to uncertainties in the location of the Crustal Dynamics Project MOJAVE base station with respect to active structural domains and to tectonically stable North America. VLBI geodesy indicates about 1 cm/a of northwestward motion of the MOJAVE and OVRO sites with respect to sites east of the Basin and Range (Ward, 1990). The geometry of how slip is transferred across the northeastern Mojave block and into the Walker Lane will be recorded by baselines connecting Round Valley, Mojave, Rand, Funeral, Panamint, Darwin, OVRO, and Cedar Creek (Fig. 1).

Saucier and Humphreys (in review) have derived a regional kinematic model for southern California using finite-element analysis that incorporates fault orientation data and geologically and geodetically (VLBI) determined fault slip rates. Their model predicts a probability distribution for long-term present-day motion. It indicates different slip rates on the eastern and western ends of the Garlock fault (7 mm/a and 3 mm/a respectively) resulting from Basin and Range extension north of the Garlock and east of the Sierra Nevada. In addition, it predicts slip rates for specific faults within both the Mojave block and the Walker Lane. These slip rates will be independently determined by our GPS experiment. In the case of the Garlock fault, baselines between Tehachapi, Cedar Creek, Rand, Lancaster (Monday), Funeral, Mojave, and Round Valley (Fig. 1) will resolve differential motion. Conversely, when rates are determined from the Mojave-Walker Lane GPS network, the results may be used to refine such regional model.

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Quaternary Movement on the Calico Fault, Mojave Desert, California

ROBERT E. REYNOLDS   *Division of Earth Sciences, San Bernardino County Museum, Redlands CA 92374*

ABSTRACT

Late Pleistocene faunas and radiocarbon dates indicate that the Mojave River was ponded between 12-9,000 y.b.p. west of the Calico Fault. Faunas in fractures and their mode of preservation suggest early Holocene faulting on the Coon Canyon Fault which lies northwest along the projected trace of the Calico Fault. This data suggests the need for review of the late Pleistocene/early Holocene activity along a "Calico Fault Zone".

Ponti (1985) described the Tylerhorse series of soils as commencing development at approximately 500,000 y.b.p. on existing alluvial topography in the west central Mojave Desert. Reynolds (1989) described fossil assemblages from these alluvial sediments that indicate a corresponding late Irvingtonian Land Mammal Age (LMA) (1.3-0.7 y.b.p.). The soils and sediments support a flat topographic surface and both have been cut by erosion of the Mojave River drainage and by northwest-trending faults that roughly parallel the San Andreas Fault. The Helendale Fault, for example, cuts and deforms the late Irvingtonian topographic surface from a point east of Kramer to Wilde Wash, a distance of >33 km (20 miles). The Calico Fault cuts the Irvingtonian surface and uplifts sediments that contain Irvingtonian fossil mammals (<1.3 Ma) to an elevation of 770 m (2500 ft) near Calico Ghost Town (Reynolds, 1989).

LACUSTRINE DEPOSITS

The late Pleistocene/early Holocene Mojave River ponded west of the Calico Fault in the Daggett-Yermo area (Reynolds, 1987; Reynolds and Reynolds, 1985). Lacustrine deposition is indicated by a 1.7 m (5 ft) section of fine-grained silty sand that crops out on the north side of the Mojave River Valley and by a 2 m (6 ft) thick sequence of silt on the south side of the valley.

These pond sediments contain late Pleistocene taxa including *Equus occidentalis* (extinct horse), *E. conversidens* (extinct horse), *Camelops hesternus* (extinct large camel), *Hemiauchenia macrocephalus* (extinct llama), and *Mammuthus* sp. (extinct mammoth). Aquatic organisms include mollusks (*Anodonta, Pisidium, Lymnaea, Gyraulus, Planorbula,* and *Physa*) and fish (*Gasterosteus aculeatus* and *Gila bicolor mojavensis*). A Pleistocene age is consistent with radiocarbon dates of 12,000-10,000 y.b.p. on the south side of the river valley and 12,000-9,000 y.b.p. on the north side (Reynolds and Reynolds, 1985). The highest levels of Manix Lake, to the east of the Calico Fault, predate and were at a lower elevation than the lacustrine sediments in the Daggett-Yermo area (Jefferson, 1985; Meek, 1989; Reynolds, 1987).

The sedimentary section southwest of the Calico Fault in the Daggett-Yermo area suggests the following sequence of events:

a) Prior to 12,000 y.b.p., the Mojave River meandered over a broad river valley. Depositional facies included fanglomerates, overbank deposits, and coarse, well-sorted channel sands, respectively, from river margins to the central drainage course.

b) The Mojave River was tectonically dammed at approximately 12,800 y.b.p., after which silts and green lacustrine sands were deposited north of I-40 and south of I-15. Silt deposited east of the Daggett solar sites suggest that the minimum height of the dam was 2 m (6 ft) or more. Aquatic taxa suggest that fresh water extended from near the Calico fault at Minneola Road approximately 6.5 km (4 miles) southwest to the Daggett solar sites. The Calico Fault or a compressional rise on the west side of the scarp most likely accounts for damming of a small body of water west of Minneola Road.

c) The Mojave River breached the Calico Fault dam and began downcutting into lacustrine sediments between 9,050 and 7,350 y.b.p. The breach point may have been near I-15 and the intersection of the Calico Fault. Subsequent downcutting left a series of erosional benches on the north side of the river, south of Yermo. The south bank of the river is an abrupt 6 m (20 ft) cliff. This suggests that downcutting has shifted laterally from north to south through the Holocene.

d) River downcutting, starting from the north at Yermo, swinging south along the trace of the Calico Fault, and now trending easterly toward Afton Canyon causes a jog in the river course that may reflect structures developed along the right lateral Calico Fault.

e) On the north side of the river valley, west of the Calico Fault, lacustrine 12,800 and 9,050 y.b.p. sediments are at elevations between 1902 and 1906 feet above sea level. On the south side, fine-grained 12,200 and 10,910 y.b.p. sediments are at elevations between 1932 and 1934 feet above sea level. Differences in present-day elevations between coeval sediments may indicate compressional structural activity in the Mojave River Valley after 9,000 y.b.p.

THE CALICO FAULT ZONE

Previous mapping by Dibblee (1970) and McCulloh (1965) shows that the Calico Fault strikes northwesterly but bends westerly on the north side of the Mojave River, approximately where it would be intersected by the Manix Fault (Dibblee, 1970; Keaton and Keaton, 1977; Jefferson and others, 1982). Mapping by Dibblee (1970) suggests that branches of the Calico Fault lie within the Miocene rocks of the Calico Mountains. However, a continuation of this structure along the southwest flank of the Calico Mountains is supported by uplift of middle Pleistocene fans. Bortugno and Spittler (1985) and Dibblee (1970) infer faults on the southwest margin of the Calico Mountains. Dibblee (1970) did not connect the Calico Fault along its projected trace (from the Daggett 15' quadrangle to the Opal Mountain 15' quadrangle) into the Coon Canyon Fault. However, he mapped fold hinges in middle Pleistocene sediments that trend subparallel to the postulated fault trace. Deformation of middle Pleistocene sediments

in Richard, S. M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, CA., San Bernardino County Museum Special Publication, p. 64-65.

suggest that the trace of a late Pleistocene/early Holocene fault zone continues along the southwest margin of the Calico Mountains and along the southwest margin of the Mud Hills, where it is expressed as the trace of the Coon Canyon Fault and places Pleistocene sediments against Miocene sediments. Filled fractures along the trace of the Coon Canyon Fault contain vertebrate fossils of early Holocene age (Reynolds and Fay, 1989; Bell and Reynolds, 1991).

Entombment on the Coon Canyon Fault and ponding of sediments on the west side of the Calico Fault were contemporaneous, suggesting that these faults were part of a continuous, active "Calico Fault Zone" during late Pleistocene/early Holocene time. A local apparent vertical component on the east side of the Calico Fault is suggested by east-side-up displacement of late Irvingtonian sediments near Calico Ghost Town (Reynolds, 1987; Reynolds and Reynolds, 1985, 1991). Right lateral movement is suggest by a southeast bend in the Mojave River on the east side of the Calico Fault. Damming of the Mojave River was probably accomplished by right lateral movement of a topographically high area.

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Cibola Pass Fault, Southwestern Arizona

STEPHEN M. RICHARD *Institute for Crustal Studies, University of California, Santa Barabara, CA 93106*
DAVID R. SHERROD
RICHARD M. TOSDAL } *U. S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025*

INTRODUCTION

The Cibola Pass fault zone encompasses faults that strike southeast through a low divide between the Trigo Peaks and Trigo Mountains, southwestern Arizona (Fig. 1). The fault zone is buried at its northwestern end by Pliocene(?) and Pleistocene alluvium of the Blythe basin. To the southeast, it links with normal faults that bound the Middle Mountains on the west and east; extension on these range-bounding faults is probably transferred to faults of the Cibola Pass fault zone. We have mapped the fault zone in the Trigo Peaks and northern Trigo and Middle Mountains. Some areas have restricted access, however, because they lie within the Yuma Proving Ground. For these areas, our few field observations have been supplemented by interpretation of Landsat Thematic mapper images (processing described in Crippen and others, in press and Crippen, in press).

Consistent separation of west-dipping normal faults in the Cibola Pass area and east-dipping stratigraphic contacts in the northern Middle Mountains are interpreted to indicate that the Cibola Pass fault zone is a strike-slip fault zone with approximately 7 km of right separation. Faulting predates deposition of the youngest, basin-filling alluvium, which probably is similar in age to the youngest part of the upper Miocene and lower Pliocene Bouse Formation.

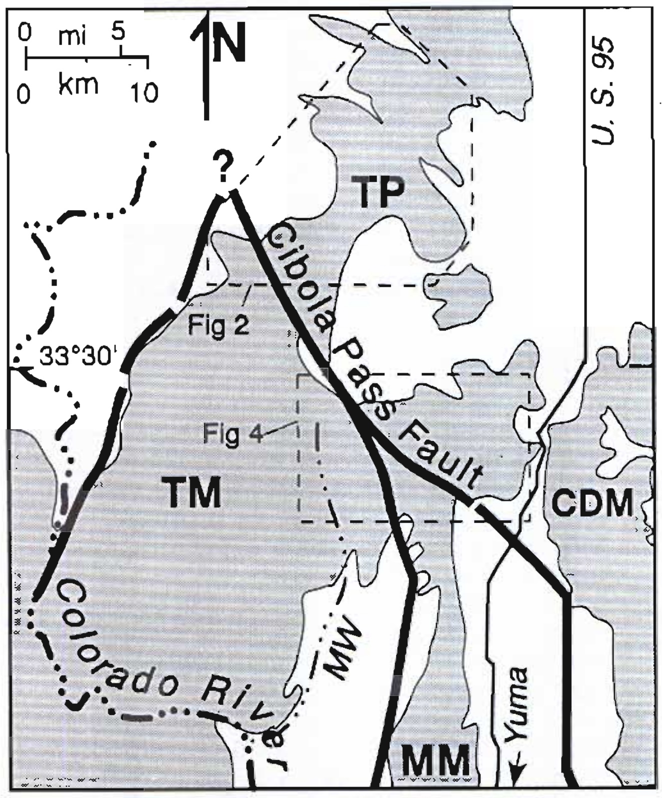

Fig 1. Map showing location of Cibola Pass Fault zone. Abbreviations are for: CDM- Castle Dome Mountains; MM- Middle Mountains; MW-McAllister Wash; TM-Trigo Mountains; TP-Trigo Peaks.

GEOLOGIC SETTING

The Cibola Pass fault zone cuts mostly Tertiary volcanic and sedimentary rocks. These rocks are underlain by Triassic and Jurassic crystalline rocks in the northern Trigo Mountains [Barth et al., 1991]; the base of the Tertiary section is not exposed in the northern Middle Mountains. The Tertiary rocks are part of a stratigraphically complex series of lava flows interbedded with pyroclastic and epiclastic rocks along the northern boundary of the Tertiary volcanic province of southwestern Arizona and southeastern California [Richard and Sherrod, in press]. They range in composition from andesite in the west (Palo Verde Mountains, Calif.) to rhyolite in the east (northern Castle Dome and Kofa Mountains, Ariz.). Volcanic strata thicken dramatically across a highly disrupted hinge line located just south of Cibola Pass. To the north, relatively thin volcanic sequences, overlie the Jurassic crystalline rocks [Sherrod and Tosdal, 1991]; whereas to the south are thick accumulations of intermediate to silicic lava flows and domes. The hinge line probably resulted from greater subsidence to the south and minor down-to-the-south faulting.

The volcanic rocks are overlain by gently dipping to untilted conglomerate that postdates displacement on the Cibola Pass fault zone. The age of the conglomerate is poorly known but can be inferred from some geomorphic criteria: the conglomerate is widespread in the drainage divides at the headward extent of south-draining washes (e.g. McAlister Wash, Fig. 1), and underlies the highest and oldest geomorphic surfaces along the divide. The headward erosion of these washes has occurred in response to base level drops along the modern lower Colorado River, probably entirely since the deposition of the Bouse Formation in a late Miocene and early Pliocene marine embayment along the Colorado River trough [Buising, 1991; Metzger, 1968]. Therefore, deposition of conglomerate along the drainage divides occurred before or during Bouse time, when the regional base level would have been at its highest. Some of the youngest parts of the conglomerate may have been deposited during Bouse time or slightly thereafter.

RECONSTRUCTION AND SLIP

The volcanic rocks are cut by a series of north- to northwest-striking normal faults that tilt strata to the northeast in the Cibola Pass area. These faults, many inferred by the relationships between scattered outcrops, have been used as the principal markers to reconstruct the younger west- and northwest-striking faults.

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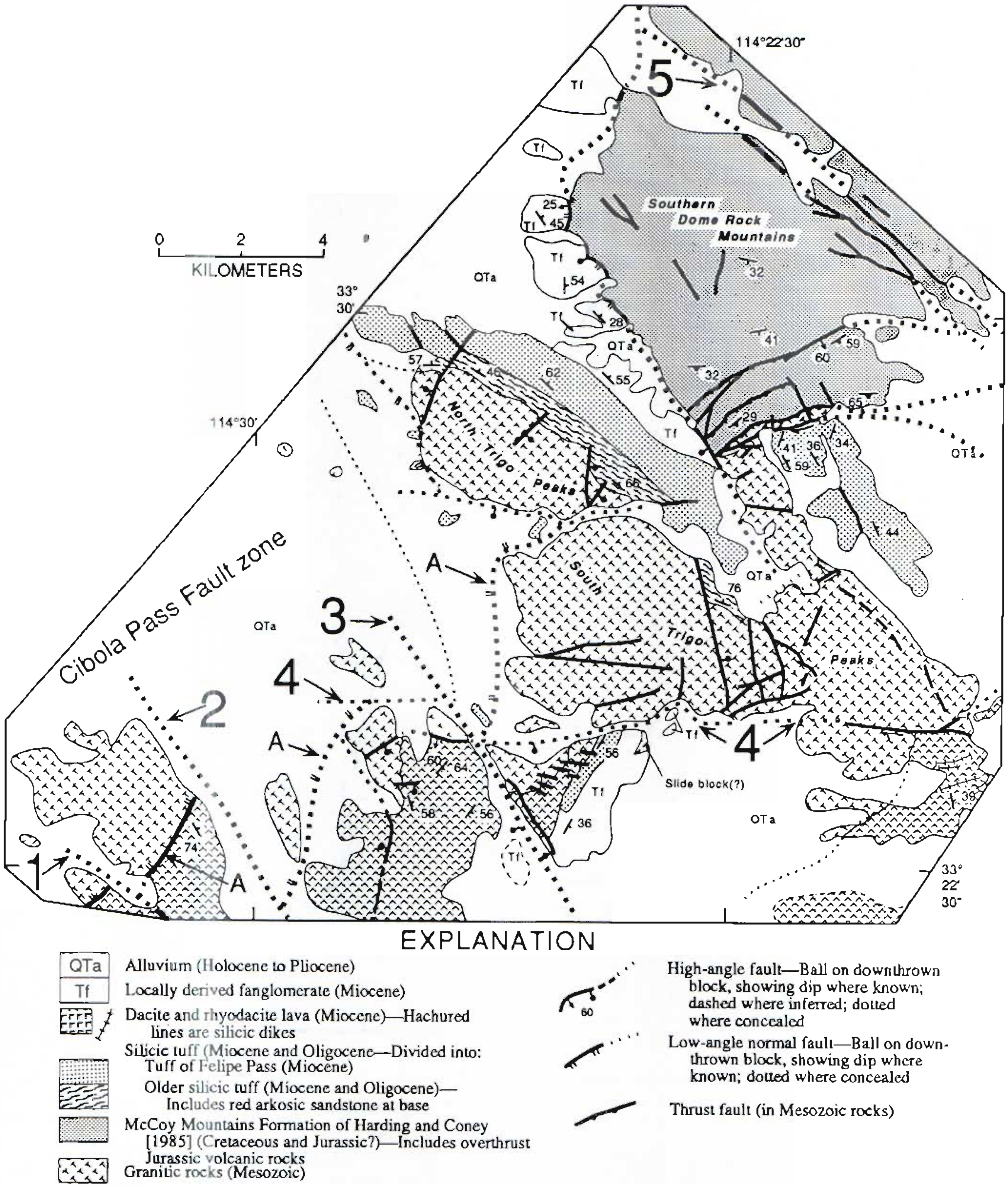

Figure 2. Geologic map of the Cibola Pass area, southwestern Arizona. Mapping by D. R. Sherrod and R. M. Tosdal.

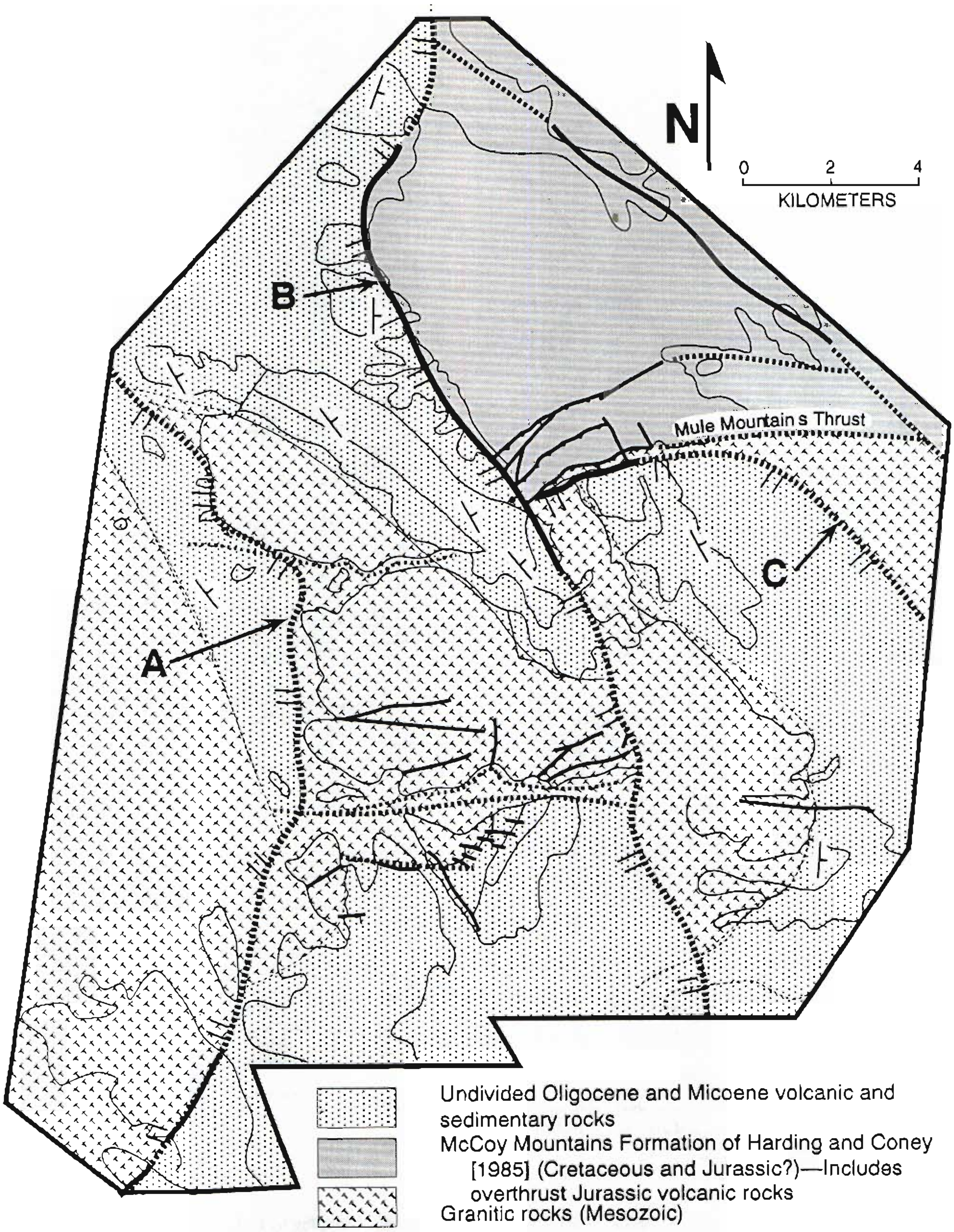

Figure 3. Palinspastic reconstruction of late Miocene and younger faults in the Cibola Pass area. Outcrop outlines from Fig. 2 are provided for reference. Faults A, B, and C are hypothesized major early Miocene normal faults used to reconstruct the Cibola Pass Fault zone.

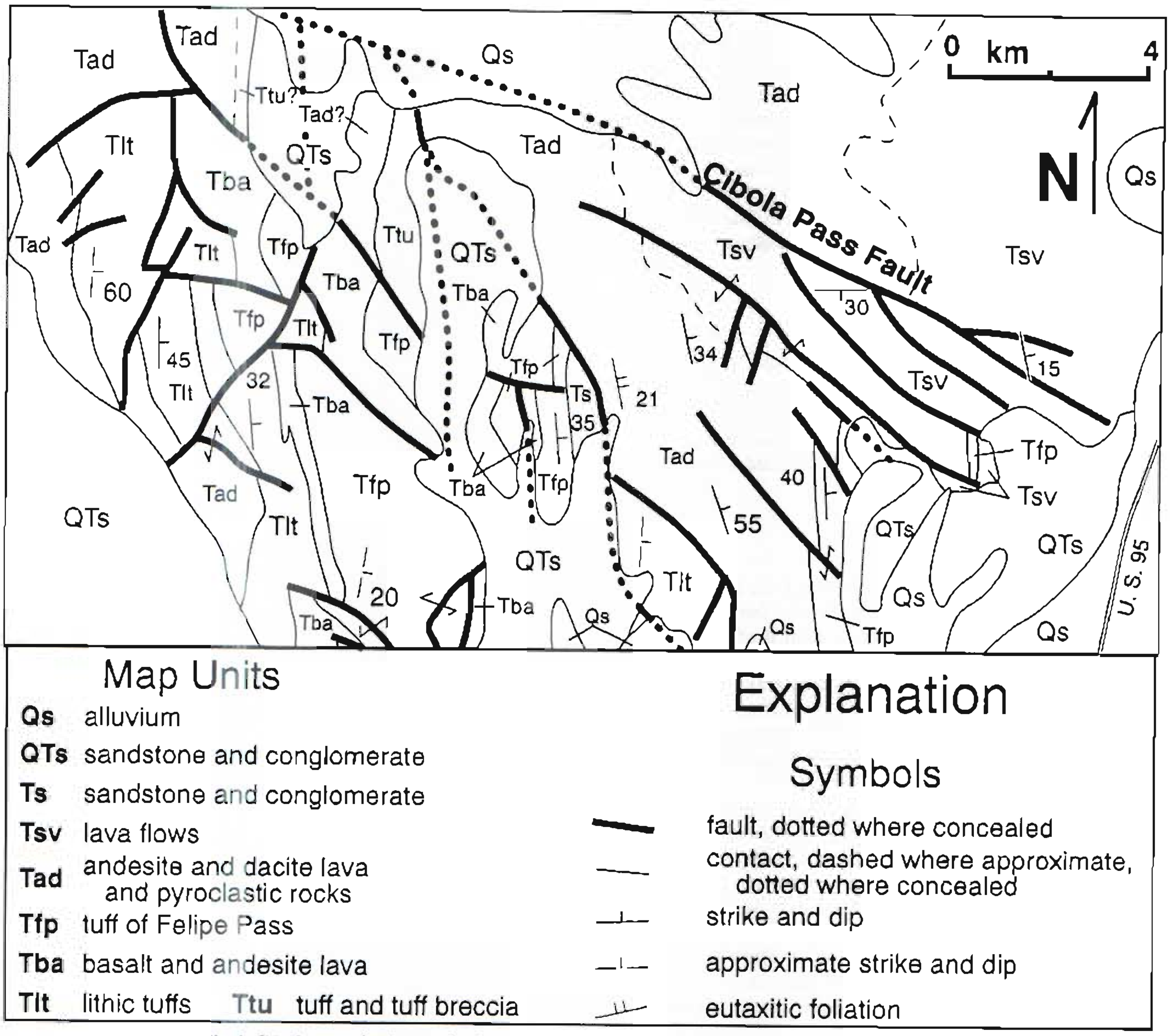

Fig 4. Cibola pass fault zone in the northern Middle Mountains. Mapping by S. M. Richard.

Faults that cut the normal faults associated with tilting of the Tertiary volcanic rocks are inferred to be middle Miocene or younger. These younger faults are generally associated with prominent lineaments. In the Cibola Pass area, two generations of post-early Miocene faults are inferred. The younger faults (nos. 1-3 on Fig. 2) strike about 150° and have net right separation of 6 km across the three faults, estimated by aligning segments of inferred early Miocene fault A (Figs. 2, 3). Faults of an older west-trending fault zone follow the south side of the stratigraphic hinge mentioned above (Fault 4 on Fig. 1). This fault zone is interpreted as a zone of faulting and oroclinal bending approximately 3 km wide. At the east end of the area, the base of the Tertiary section is offset progressively across two fault segments, whereas in the central part the basal contact is bent to a northeast strike and offset by numerous small faults. At the west end of outcrop the fault zone is shown as a single fault, but other faults may lie buried beneath the alluvium.

The reconstruction of the Cibola Pass area assumes that three major north-northwest-striking, west-dipping normal faults were present before disruption by late Miocene strike-slip faulting (A, B, and C on Fig. 3). The stratigraphic hinge separating thin and thick Tertiary sections coincides with the greatest structural thickness of Jurassic granitoid preserved beneath Tertiary strata and above the bounding normal faults in the central and eastern fault blocks (B and C, Fig. 3). This pattern reflects pre-tilting paleotopography and structure. Normal fault B (Fig. 3) cuts out the Mule Mountains thrust [Tosdal, 1991], whereas normal fault C (Fig. 3) is interpreted to curve into the thrust zone and is truncated by normal fault B (Fig. 3). The northwest-striking fault along Ehrenberg Wash (fault 5, Fig. 2) is interpreted to predate normal fault B (Fig. 3) because the footwall of normal fault B lies at significantly different stratigraphic horizons in Mesozoic supracrustal rocks northeast and southwest of northwest-striking fault 5 (Fig. 2).

The Cibola Pass fault zone is also exposed in the northernmost Middle Mountains. There it consists of west- and northwest-trending faults (Fig. 4) that cut a thick, generally east-dipping sequence of rhyolite domes, lava flows, and minor pyroclastic rocks. These rocks overlie darker, intermediate-composition lavas and pyroclastic rocks. The basal contact of the rhyolite sequence, identified in the field on the northeast side of the fault zone, is prominent on processed TM imagery and is separated by 7 km across the Cibola Pass fault zone. Subhorizontal striations have been observed in outcrops of one fault at its southeast end. Slip on other faults within the zone is unknown, but probably includes minor normal- and right-slip.

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Geology of the Packard Well Fault zone, Southeastern California

STEPHEN M. RICHARD — *Institute for Crustal Studies, University of California, Santa Barbara, CA 93106*
ROY K. DOKKA — *Dept. of Geological Sciences, Louisiana State University, Baton Rouge, LA, 70803*

ABSTRACT

The Packard Well fault (new name) juxtaposes Jurassic granitoid in the northern Palen Mountains against Cretaceous granitoid in the Granite Mountains. A minimum of 10 km of right separation is estimated from offset of the eastern boundary of the Cretaceous Cadiz Valley batholith, but total right-strike-slip is estimated to range from 24 km in the northwest to 12 km in the southeast, based on alignment of Mesozoic structures in the Coxcomb, Palen, McCoy, and Little Maria Mountains. The Packard Well fault is interpreted to be the southeast continuation of a concealed fault in Cadiz Valley, and to continue southeast across the northern end of the McCoy Mountains to terminate in the basin south of the Big Maria Mountains. Slip on the fault decreases to the southeast and is transferred to extension in the basins between the Coxcomb, Palen, McCoy, and Dome Rock Mountains.

GEOLOGIC SETTING

The Packard Well fault is named for exposures in the Packard Well area between the Palen and Granite Mountains (Fig. 1), where two moderatly to steeply north-dipping faults separate a deformed sliver of older alluvium of uncertain age from Cretaceous granitoid on the north and Jurassic granitoid on the south [Stone and Kelley, 1989]. The fault zone is here proposed to project southeast between the McCoy and Big and Little Maria Mountains, but does not continue through the Dome Rock Mountains. Some slip is probably transferred through the basin around Blythe, California to the Cibola Pass fault zone [Richard, this volume] to the southeast. The Packard Well fault is interpreted to continue northwestward through the Cadiz Valley to join the Bristol-Granite Mountains fault zone [Dokka and Travis, 1990a; Howard and Miller, this volume], which Dokka and Travis [1990b] defined as the eastern boundary of the Eastern California shear zone. The some slip may also be transferred by a concealed fault between the Coxcomb and Calumet Mountains to join the Calumet and west Calumet faults along the west side of the Calumet Mountains, which cut old alluvium [Howard and John, 1984; Howard and Miller, this volume].

The Packard Well fault zone cuts through the Maria fold and thrust belt, a zone of highly deformed Paleozoic, Mesozoic and Proterozoic metasedimentary and metaigneous rocks [Reynolds et al., 1986; Tosdal, in press; Ballard, 1990; Knapp, 1989; Hamilton, 1987]. Within the Maria fold and thrust belt, Proterozoic and Mesozoic crystalline rocks have been emplaced south or southwest over strongly folded and sheared Paleozoic and Mesozoic metasedimentary rocks that form a complex synclinorium with a moderately north-dipping hinge surface. A structural culmination

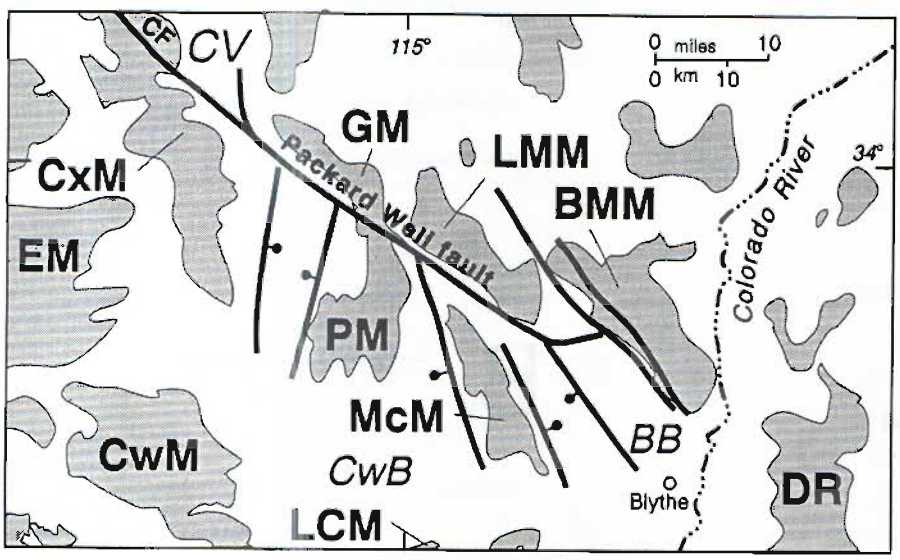

Figure 1. Map showing location of Packard Well Fault and its proposed extensions. Abbreviations are as follows: BB—Blythe basin; BMM—Big Maria Mountains; CV—Cadiz Valley; CF—Calumet fault; CwB—Chuckwalla Basin; CwM—Chuckwalla Mountains; CxM—Coxcomb Mountains; DR—Dome Rock Mountains; EM—Eagle Mountains; GM—Granite Mountains; LMM—Little Maria Mountains; McM—McCoy Mountains.

→

Figure 2. Reconstruction of the Maria Fold and Thrust belt. A. Paleogeologic map for the middle Miocene. Outlines of mountain ranges shown in Fig. 1 are indicated for reference. Inferred outcrop of Cadiz Valley Batholith (patterned units Kg and Klg) is shown, including extrapolation under present Quarternary sediments. Dotted faults and contacts are presently covered by Quaternary sediments. Geologic data from Ballard (1990), Calzia and others (1986), Hamilton (1987), Knapp (1989), Stone and Kelley (1989), Stone and Pelka (1989), and Tosdal (1988). B. Schematic north-south cross sections A and B across southern edge of Maria Fold and thrust belt in the Palen and Dome Rock Mountains. Section lines indicated in part A.

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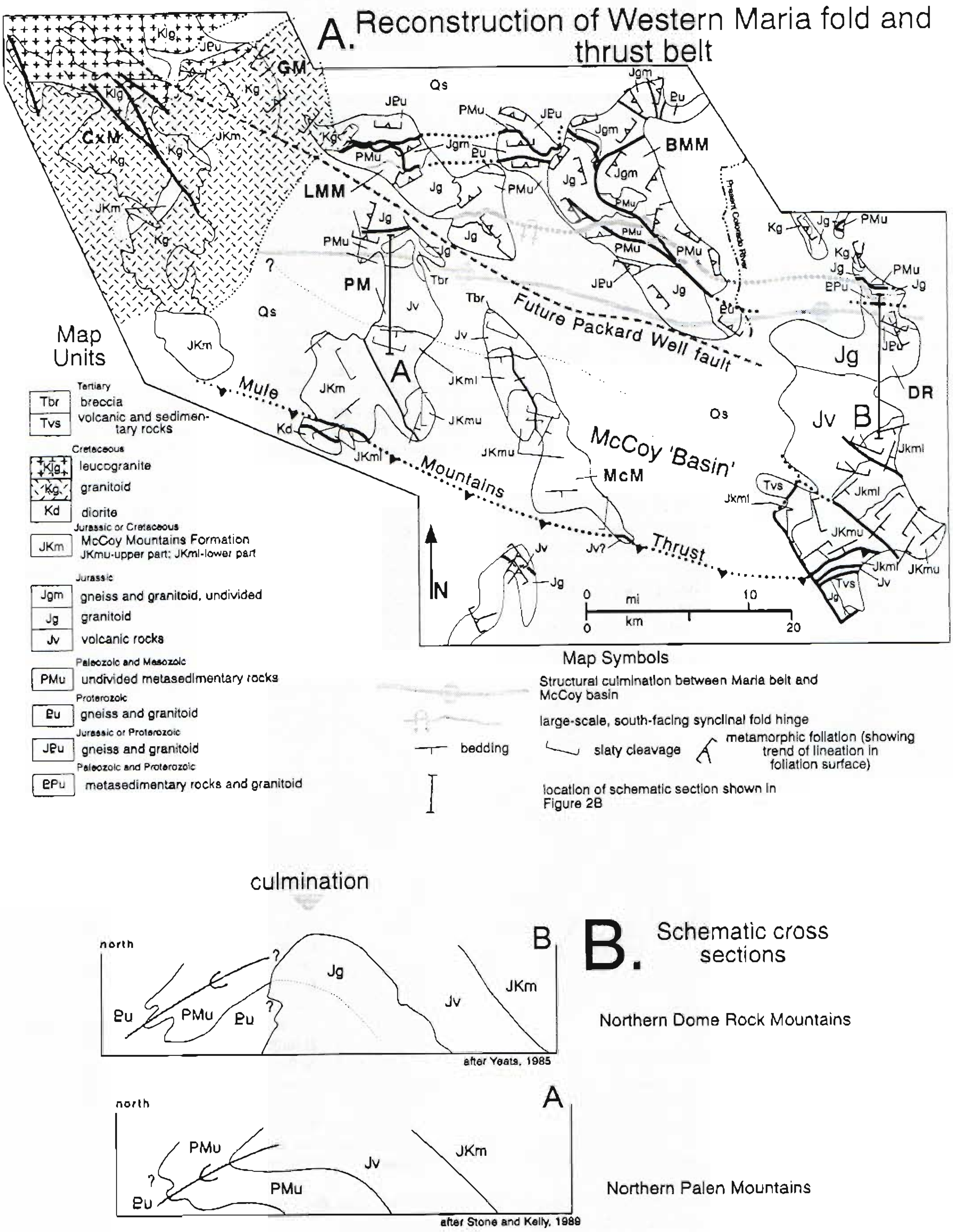
A. Reconstruction of Western Maria fold and thrust belt
Map Units
Tertiary
Tbr breccia
Tvs volcanic and sedimentary rocks
Cretaceous
Klg leucogranite
Kg granitoid
Kd diorite
Jurassic or Cretaceous
JKm McCoy Mountains Formation JKmu-upper part; JKml-lower part
Jurassic
Jgm gneiss and granitoid, undivided
Jg granitoid
Jv volcanic rocks
Paleozoic and Mesozoic
PMu undivided metasedimentary rocks
Proterozoic
Pu gneiss and granitoid
Jurassic or Proterozoic
JPu gneiss and granitoid
Paleozoic and Proterozoic
PPu metasedimentary rocks and granitoid
Map Symbols
Structural culmination between Maria belt and McCoy basin
large-scale, south-facing synclinal fold hinge
bedding
slaty cleavage
metamorphic foliation (showing trend of lineation in foliation surface)
location of schematic section shown in Figure 2B
GM
CxM
LMM
BMM
PM
McM
DR
Future Packard Well fault
McCoy 'Basin'
Mule Mountains Thrust
Present Colorado River
N
0 mi 10
0 km 20
B. Schematic cross sections
culmination
north
B
Northern Dome Rock Mountains
after Yeats, 1985
A
Northern Palen Mountains
after Stone and Kelly, 1989

connects the lower limb of this synclinorium with southward-dipping Jurassic volcanic rocks cropping out to the south (Fig. 2). This culmination or anticline plunges gently to the west and loses amplitude to the west: Proterozoic rocks are exposed on the crest of an upright antiform in the central Dome Rock Mountains whereas Triassic(?) strata are exposed in a structural terrace in the northern Palen Mountains. Jurassic plutons intrude the core of the culmination in the Dome Rock, Big Maria and Little Maria Mountains, and are abundant in the Maria fold and thrust belt, but are absent in the McCoy basin to the south.

The Maria Fold and Thrust Belt is intruded on the west by by the Late Cretaceous Cadiz Valley batholith [John, 1981; Calzia et al., 1986] (Fig. 2). Cretaceous plutons also underlie much of the central Eastern Transverse Ranges [Powell, 1981], but are rare in southeastern California east of the Cadiz Valley batholith and southeast of the Little Chuckwalla Mountains. The southeastern part of the Cadiz Valley batholith consists of a marginal zone of granodiorite and porphyritic monzogranite (Kg in Fig. 2) that is intruded by muscovite granitoids (Klg) to the northwest [Calzia et al., 1986; Stone and Pelka, 1989].

RECONSTRUCTION

The reconstruction places the southern Coxcomb Mountains south of the Granite Mountains to align the contact between muscovite bearing leucogranites (Klg in Fig. 2) and biotite granodiorite (Kg) within the Cadiz Valley batholith. This yields an estimated 24 km of right slip along the northwestern part of the Packard Well fault. Approxmately 10 km of right separation along minor faults within the northern Coxcomb Mountains, apparent in Figure 2, has not been reconstructed; right slip on these faults would link to the Dry Lakes fault [Howard and Miller, this volume] and faults in the Sheephole and Bullion Mountains [Jagiello and others, this volume]. The estimated slip on the Packard Well fault is close to the maximum permissible translation across the Cadiz Valley, estimated by Howard and Miller [this volume] to be 25 km.

The Palen Mountains are reconstructed 16 km southeast to align the structural culmination on the southern side of the Maria fold and thrust belt between the southern Big Maria Mountains and the northern Palen Mountains, and to align the Jurassic plutonic complex in the northern Palen Mountains with the Midland plutons in the southeastern Little Maria Mountains. A minimum 10 km of right separation on the Packard Well fault is required in order for the eastern boundary of the Cadiz Valley batholith to project west of the northern Palen Mountains from the western Little Maria Mountains (Fig. 2). The difference in estimated slip on the Packard Well fault northwest and southeast of the Palen Mountains (8 km) is accommodated by extension in the basin between the Palen and Coxcomb Mountains.

No geologic features can be directly matched between the McCoy Mountains and the Little or Big Maria Mountains. Thus, the position of the McCoy Mountains was determined by closing the basin between the Palen and McCoy Mountains by about 4 km to align the basal contact of the McCoy Mountains Formation [Stone and Kelly, 1989], resulting in 12 km of right slip between the McCoy and Little Maria Mountains. Five km of right slip have been removed between the Big and Little Maria Mountains to better align the trend of gently north-dipping shear zones mapped by Ballard [1990]. The net effect of these reconstructions is to close the basin between the McCoy Mountains and Dome Rock Mountains by 17 km.

DISCUSSION

Our analysis of late Miocene and younger deformation of the Coxcomb, Palen, McCoy, Little Maria, Big Maria, and Dome Rock Mountains relies principally on reconstructing structures in Paleozoic and Mesozoic rocks (Fig. 2). Latest movement on faults used here for reconstructing the Maria fold and thrust belt is constrained only to be younger than the fanglomerate deformed in the Packard Well fault zone, which Stone and Pelka [1989] suggest is older than basalt flows they dated at 6.4 Ma. Unrecognized middle Miocene or older faulting is possible. The available data allow that right shear across the area is late Neogene in age, consistent with studies to the north in the Mojave Desert and Death Valley areas where 66 km of distributed right shear has been proposed on the Eastern California Shear Zone [Dokka and Travis, 1990 a, b]. We assert the Packard Well fault is an important component in the southeastward continuation of this deformation zone.

This proposed reconstruction is based on separations of pre-Tertiary contacts, and as such is permissible, but not a unique solution. The reconstructed geometry of the Maria fold and thrust belt and Cadiz Valley batholith is appealing because it reduces the complexity of the outcrop patterns and we believe represents a reasonable early Tertiary configuration of these rocks. However, significant pre-Late Miocene normal and strike-slip faulting may have contributed to producing the present outcrop configuration. Further testing of this reconstruction is clearly necessary.

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Geologic and Paleomagnetic Constraints on the Timing of Initiation and Amount of Slip on the Rodman and Pisgah Faults, Central Mojave Desert, California

TIMOTHY M. ROSS *Dept. of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, 70803*

INTRODUCTION

Geologic and geophysical studies of the SW Cady Mountains and surrounding area are being conducted to study the Neogene evolution of the central Mojave Desert. These data were collected to evaluate proposed tectonic models and the regional syntheses of the Eastern California shear zone. The results reported here concern the timing and amount of slip on the northern strands of the Rodman-Pisgah fault system and their relationship to the vertical axis rotation of an associated crustal block (Figure 1).

The stratigraphy of the SW Cady Mountains consists of three Miocene volcanic and volcaniclastic units which overlie an irregularly eroded granitic basement (Figure 2; Ross and others, 1989, 1991). The oldest Miocene unit (Tmo) contains various tuffs, flows and laharic deposits which are steeply tilted. This tilting occurred in response to regional early Miocene extension of the Mojave Extensional Belt (Ross and others, 1989, 1991). The overlying unit Tmm contains tuff breccia succeeded by volcaniclastic sandstone and basalt flows which were not affected by this extension. The youngest Miocene unit (Tmy) lies on Tmm and consists of a basal conglomerate followed by bedded sandstone, shale and tuff which interfinger with tuff breccia. Fossil remains of the late Hemingfordian age horse Merychippus cf M. carrizoensis. are found near the base of this section and indicate that Tmy is younger than ~16 Ma. (Ross and others, 1991).

Mapping and earthquake seismicity data suggest that the Calico, Rodman and Pisgah faults are active. A geodetic study by Sauber and others (1986), however, suggests very little shear for this area over ~50 years of observation. The Pisgah fault cuts alluvium as well as the Pisgah and Sunshine Crater basalt flows, all mapped as Quaternary age (Dibblee, 1966; Dibblee and Bassett, 1966a). The Rodman and the Calico faults also cut Quaternary units in the central Mojave Desert (Dibblee, 1964, 1966; Dibblee and Bassett, 1966b) In addition, earthquake data from 1977 to 1989 plot near the surface traces of the Rodman, Pisgah and Calico faults (Dokka and Travis, 1990) suggesting that these faults are active.

DATA

Paleomagnetic studies suggest that two separate tectonic rotations have affected rocks in the SW Cady Mountains since early Miocene time. Paleomagnetic directions from the Tmm basalts suggest that 132° ±12° of clockwise vertical-axis rotation has occurred since their deposition (Ross and others, 1991). Preliminary data from Tmy suggest that 82.8° ± 24° of clockwise rotation occurred younger than ~16 Ma (Ross and others, 1991). Differences in the paleomagnetic directions of Tmm and Tmo indicate that ~50° of rotation occurred prior to ~16 Ma which agrees well with the 50° ± 15.6° of early Miocene regional clockwise rotation documented by Ross and others (1989) in the central Mojave Desert. The younger rotation is most likely due to the interaction of late Miocene to Quaternary movement on the the surrounding faults (i.e., Calico, Rodman and Pisgah faults; Ross and others, 1989, 1991; Dokka and others, 1991). If the SW Cady Mountains is a tectonic block caught in the dextral shear between the Rodman and Pisgah faults, the deflection of paleomagnetic directions observed and the age of the units that have been rotated constrain the timing of faulting and amount of accumulated shear of this system. This implies that movement in the Rodman-Pisgah fault system began after deposition of Tmy strata, constraining the initiation of these faults to be younger than ~16 Ma.

Using the geometric relationships of McKenzie and Jackson (1983, 1986) paleomagnetic data from the SW Cady Mountains can be used to calculate the amount of slip needed to produce the observed tectonic rotation. The amount of rotation is a direct function of the slip across the shear zone and the

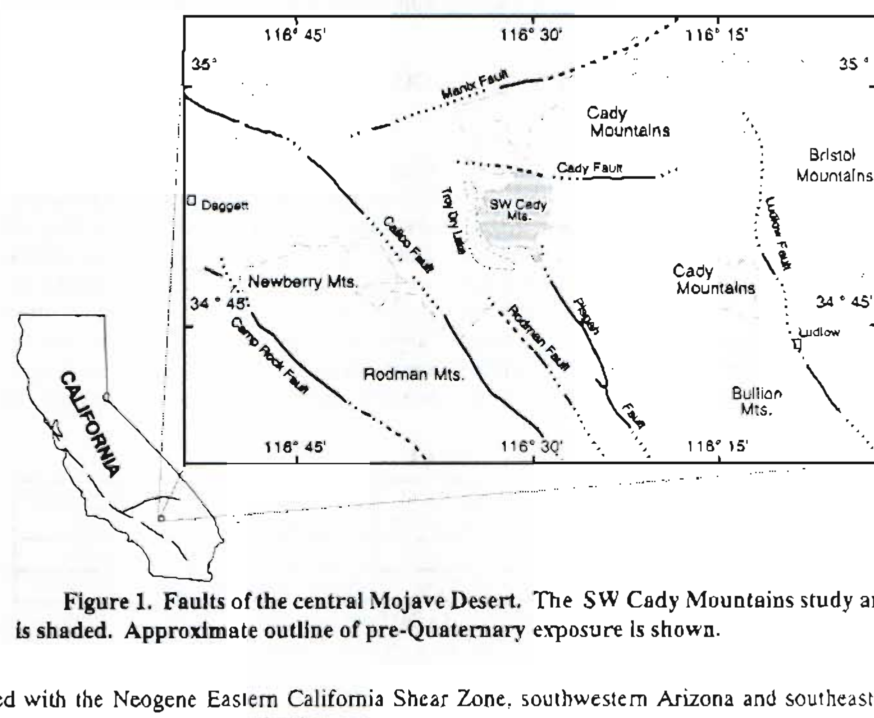

Figure 1. Faults of the central Mojave Desert. The SW Cady Mountains study area **is shaded. Approximate outline of pre-Quaternary exposure is shown.**

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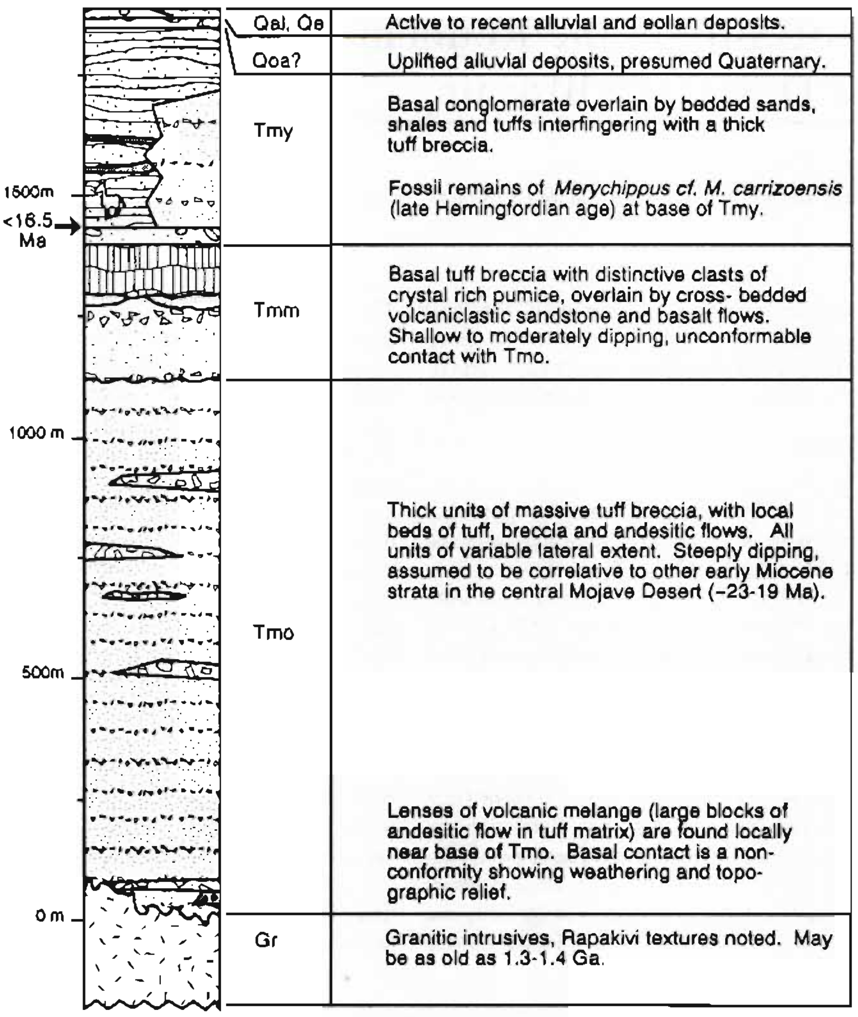

Figure 2. Generalized stratigraphy of the SW Cady Mountains.

width of the zone. Amounts of slip inferred by the McKenzie and Jackson (1983) model have been calculated for "pinned" and "floating" block cases in a manner similar to McKenzie and Jackson (1986). These new constraints for slip on the Rodman-Pisgah fault system are shown in Table 1 along with timing and slip data from Dokka (1983) and Dokka and Travis (1990). The values generated from these calculations are only the amount of shear needed to rotate the block the prescribed amount, and as such are minimum estimates.

DISCUSSION

Calculations from rotation data indicate that the Rodman-Pisgah fault system has accumulated 15.0 ± 4.3 km of dextral slip. By comparing this slip estimate to those of Dokka (1983) and Dokka and Travis (1990), we find that the integrated slip inferred from rotation of "floating" blocks is 2 to 3 times larger than both previous estimates. The estimate using "pinned" blocks is also larger, but not significantly different than that of Dokka (1983). The Dokka and Travis (1990) values have no associated error values, however, if the Dokka and Travis (1990) estimate has an associated error of greater than 0.2 km (~2%), then the slip estimates are also not significantly different. This study indicates that initiation of slip began younger than ~16 Ma which is compatible with Dokka (1983; < ~20 Ma) and inferences from initiation of the Calico fault (< 13.4 Ma; Dokka and Travis, 1990). Data from this geologic and geophysical study indicate that 15.0 ± 4.3 km of dextral slip has occurred younger than ~16 Ma and probably post 13.4 Ma. This new information can help to constrain future model generations for the Eastern California shear zone and Neogene deformation in the central Mojave Desert.

Table 1

Source	Dokka (1983)	Dokka and Travis (1990)	Pinned Block Model	Floating Block Model
Age of initiation	<20 Ma	<13.4 Ma^	<16 Ma	<16 Ma
Amount of slip	6.4-14.4 km	10.5 km	15.0 ± 4.3 km*	30.6 ± 9.0 km*

* Calculations use width = 5.2 km, R = 82.8 ± 24; from Beck (1980), Demarest (1983), with (I= 56.0°, D= 74.6°, a95=16.6°) and reference direction (I=53.3°, D=351.8°, a95=4.0°) calculated from Diehl and others (1983)).

^ Inferred to be equivalent to initiation of slip on the Calico Fault.

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Late Cenozoic Structural and Geomorphic Evolution of the Old Dad Mountain and Cima Volcanic Field as Related to the Eastern California Shear Zone

THOMAS M. SKIRVIN* *Shell Offshore Inc., New Orleans, LA 70161*
STEPHEN G. WELLS *Dept. of Earth Sciences, University of California-Riverside, Riverside, CA 92521*

The Old Dad Mountain-Cima volcanic field-Soda Lake basin area in the eastern Mojave Desert of California lies east of those structures which have previously been kinematically linked to the Mojave Desert Block and its eastern boundary, the Eastern Mojave Shear Zone of Brady and Dokka (1989) (this zone includes the Death Valley and Soda-Avawatz fault zones, and the Bristol-Granite Mountains and south Bristol Mountains fault zones of Howard and Miller, this volume). This paper attempts to place the Neogene and Quaternary geologic evolution of the Old Dad Mountain-Cima Volcanic Field area into a regional structural, tectonic, and landscape evolution context with respect to the Eastern Mojave Shear Zone and Mojave Desert Block.

Regional correlation and mapping of Miocene and Pleistocene sedimentary and volcanic stratigraphic units is used in conjunction with (1) a limited number of kinematic indicators on fault surfaces (n=15), (2) offset of piercing points within boulder conglomerates (n=2), and (3) the sense of separation along fault zones to interpret an oblique (down-to-the-west) right lateral strike slip movement along the major shear/fault zones. The predominant trend of faults ranges between 20^{o} and 60^{o} west of north based upon faults offset of late Cenozoic units that date from approximately 19 Ma to late Pleistocene. Two laterally extensive shear zones were identified and informally named: the Prospect Wash shear zone bounding the eastern flank of the Old Dad Mountain and the Vulcan Wash shear zone along the southwestern boundary of the Cima Volcanic field. Preliminary estimates of the amount of separation along the shear zones suggest that the magnitude of oblique slip decreases eastward from 6 km along faults in the Prospect Wash shear zone to 1 km in the Vulcan Wash shear zone. The Eastern Mojave shear zone, which may exhibit the greatest amount of late Cenozoic slip, lies 20 km to the west of the Prospect Wash shear zone. Timing of latest deformation across the Vulcan Wash, Prospect Wash, and Eastern California shear zones does not differ significantly; all three zones appear to deform mid-to-late Pleistocene alluvial fan and playa sediments. We propose that in the vicinity of the Old Dad Mountain/Cima Volcanic Field area the eastern boundary of structures kinematically related to the Mojave Desert Block is a wide zone (25-35 km) of discontinuous shear and fault zones. We also propose that the variation in landscape evolution across this boundary reflects a progressive change in the style and magnitude of slip and the lateral spacing between shear zones toward the Eastern Mojave shear zone. The transition from (1) pedimented landscapes of Cima Dome, which have been inherited from the late Miocene to (2) transtensional Plio(?)-Pleistocene sedimentary basins, which are commonly flanked by steep linear fronts, in the Old Dad Mountain and Soda Lake Basin areas is interpreted to be a result of a westward increase in long-term slip rates and an increase in oblique slip along faults in the shear zones as well as a decrease in the lateral spacing between these shear zones.

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SAN BERNARDINO COUNTY MUSEUM ASSOCIATION
INFORMATION FOR AUTHORS

The San Bernardino County Museum Association publishes articles and monographs on subjects pertaining to the cultural and natural history of San Bernardino County and surrounding regions. We welcome submissions of such manuscripts.

Subject Matter: articles and monographs pertaining to San Bernardino County, inland Southern California, and surrounding regions, in history, anthropology, archaeology, paleontology, mineralogy, zoology, botany, ornithology, and related disciplines. Manuscripts considered for *Quarterly* publication should be written toward the well-educated non-specialist. Technical research will also be considered for publication. All manuscripts should reflect original work which furthers knowledge in their fields.

Format: Two clear copies of the manuscript must be submitted to the Editorial Board with a letter of transmittal requesting that the manuscript be considered for publication and that it is not presently under consideration elsewhere. Manuscripts should be typewritten, double-spaced, on one side only of 8.5x11" paper. Ample margins should be allowed for editing comments. The first page should contain the title and author(s) name, address, and telephone number. The author's last name and page number should appear at the top of each following page. Include COPIES of figures, tables, and photographs. Do not send original photographs or figures with your initial submission.

Style: Authors should follow the standards for footnotes, citations, headings, and other conventions as applicable to their discipline. The Editorial Board suggests the following:

Anthropology/Archaeology: Society of American Archaeology *(American Antiquity)*
History: American Historical Association *(American Historical Review)*
Geology: Geological Society of America (GSA *Bulletin)*
Paleontology: Society of Vertebrate Paleontology *(Journal)*
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