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Late Cenozoic structure and tectonics of the northern Mojave Desert

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Abstract. In the Fort Irwin region of the northern Mojave desert, late Cenozoic east striking sinistral faults predominate over northwest striking dextral faults of the same age. Kinematic indicators and offset marker units indicate dominantly sinistral strike slip on the east striking portions of the faults and sinistral-thrust slip on northwest striking, moderately dipping segments at the east ends of the blocks. Crustal blocks ∼7-10 km wide by ∼50 km long are bounded by complex fault zones up to 2 km wide at the edges and ends of each block. Faulting initiated after ∼11 Ma, and Quaternary deposits are faulted and folded. We document a minimum of 13 km cumulative sinistral offset in a north-south transect from south of the Bicycle Lake fault to north of the Drinkwater Lake fault. Paleomagnetic results from 50 sites reveal two direction groups in early and middle Miocene rocks. The north-to-northwest declinations of the first group are close to the middle Miocene reference pole. However, rock magnetic studies suggest that both primary and remagnetized directions are present in this group. The northeast declinations of the second group are interpreted as primary and 63.5° ± 7.6° clockwise from the reference pole and suggest net post middle Miocene clockwise rotation [e.g., Gaffunkel, 1974; Luyendyk et al., 1962; Jennings, 1992] as east striking as opposed to northwest striking faults. In contrast, Dokka and Travis [1990a] named this apparently interrelated northwest striking domain-bounding faults. Our estimates of ∼11 Ma, and Quaternary deposits are faulted and folded. We document a minimum of 13 km cumulative sinistral offset in a north-south transect from south of the Bicycle Lake fault to north of the Drinkwater Lake fault. Paleomagnetic results from 50 sites reveal two direction groups in early and middle Miocene rocks. The north-to-northwest declinations of the first group are close to the middle Miocene reference pole. 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west striking faults with minor left slip and little rotation on east striking faults. In this paper we describe geologic mapping and structural and paleomagnetic analysis in the Fort Irwin National Training Center (Figure 1). This study was designed to address the question of how the plate motion is partitioned within and across this part of the plate boundary zone, specifically to determine the geometry, kinematics, and timing of faulting and the role and distribution of vertical-axis rotations. We also consider the question of the relation between fault slip and rotation of blocks and the size, shape, and rigidity of crustal blocks, as well as implications of the data for models of the Mojave region.

Geologic Background

Geological and geophysical studies of the Mojave desert block have recognized three important types of Cenozoic deformation. During early Miocene time, the central Mojave region experienced large-scale, northeast directed extension [e.g., Dokka et al., 1988; Glazner et al., 1988; Dokka, 1989; Glazner et al., 1989; Walker et al., 1990], locally accompanied by clockwise rotation [Ross et al., 1989; Ross, 1995]. Later strike-slip faulting along northwest striking dextral faults apparently began during late Miocene time [Dibblee, 1961, 1967; Dokka, 1983; Dokka and Travis, 1990a]. In addition, north-south shortening has been recently recognized as playing an important role in the Miocene and younger deformation of the Mojave region [Bartley et al., 1990; Glazner and Bartley, 1994].

Previous work in the Fort Irwin region of the Northeast Mojave Domain consists of reconnaissance mapping for the Trona 1:250,000 sheet [Jennings et al., 1962], together with more detailed recent work related to the present study [Miller et al., 1994; Yount et al., 1994] and studies in areas bordering Fort Irwin [Ryder, 1960; Brady, 1984a, b; Spencer, 1990a, b; MacConnell et al., 1994; Sabin et al., 1994]. Our new mapping and geochronology documents the following pre-Tertiary geologic history of the Fort Irwin region. The oldest rocks consist of Precambrian basement (~1.4 Ga) and probable Late Precambrian and Paleozoic miogeoclinal metasedimentary rocks that occur as screens in Jurassic and Cretaceous plutonic rocks. Plutonic and volcanic rocks were deformed in Middle Jurassic time, cut by the 148 Ma Independence dike swarm, and deformed again at ~105 Ma [Stephens et al., 1993; Schermer et al., 1994; Stephens, 1994]. The Mesozoic events left a pervasive mylonitic foliation and lineation in pre-Late Cretaceous rocks in much of the Fort Irwin region. Deformed rocks were intruded by Late Cretaceous (~80 Ma) granitoids [Miller and Sutter, 1982]. A period of uplift and erosion occurred following Late Cretaceous plutonism and prior to deposition and eruption of Miocene sedimentary and volcanic rocks.

Tertiary volcanic rocks in Fort Irwin and surrounding regions range in age from ~21 Ma to 5 Ma and consist of silicic to mafic volcanic rocks, including several vent complexes [Spencer, 1990b; Sabin et al., 1993, 1994; Keith et al., 1994; Sabin et al., 1994; Schermer, 1994]. Most of the units dip gently and range in...
Figure 2. Generalized geologic map of the Fort Irwin region, modified from Jennings et al., 1962 and Spencer, 1990a. Fort Irwin National Training Center is outlined by dashed box; China Lake Naval Weapons Center is area west of Fort Irwin. Abbreviations not defined in Figure 1 are AV, Alpine Valley; ASF, Arrastre Spring fault; BL, Bicycle Lake; BS, Bitter Spring; CCF, Coyote Canyon fault; CR, Coyote Ridge; DD, Dacite Dome; DKSF, Desert King Spring fault; FI, Fort Irwin town; GL, Goldstone Lake; GSF, Garlic Spring fault; LL, Leach Lake; LWF, Langford Well lake; ML, McLean Lake; MLF, McLean Lake fault; MSF, Mule Spring branch of Garlock fault NL, Nelson Lake; NLF, Nelson Lake fault; NWR, Northwest Ridge; OMF, Old Mormon Spring fault; PC, Pink Canyon; RPF, Red Pass fault; RPL, Red Pass lake; SR, Stone Ridge; SWR, Southwest Ridge. Locations of Figures 3b-9 are outlined by boxes.

age from 19 to 16 Ma [Sabin et al., 1994; Schermer, 1994]; however, locally younger (~12 Ma) rocks occur at China Lake to the west [Sabin et al., 1994] and Alvord Mountain to the south (A.F. Glazner, written communication, 1995) (Figures 1 and 2). The typical Tertiary sequence consists of thin silicic tuff and tuff breccia overlying basement, followed by thick rhyolite lavas then basalt. The thicknesses of units are highly variable owing to erosional paleotopography on the pre-Tertiary basement and paleotopography created by silicic flows and domes. Mafic (basalt and basaltic andesite) and silicic (rhyolite and dacite) magmatism are coeval; however, basalts predominate at the top of the section [Keith et al., 1994; Schermer, 1994]. Volcanism largely ceased in this region by ~12 Ma [Sabin et al., 1994]; however, small-volume basalt lavas of latest Miocene age (5.6 Ma [Schermer, 1994]) and silicic air fall tuffs of Pliocene age (~3.5 Ma (D. M. Miller written communication, 1995)) occur locally intercalated within sedimentary sequences that lie unconformably above older rocks.

Miocene sedimentary rocks are sparse and dominantly crop out in eastern Fort Irwin and the Avawatz Mountains (Figure 2) where Spencer [1990a, b] documented early to middle Miocene extension along high-angle normal faults along with basin formation and filling. Tertiary deposits in Fort Irwin include gently to moderately dipping medial to distal alluvial fan and fluvial deposits of middle Miocene age and alluvial and playa deposits of Pliocene to Quaternary age, with local intercalations of silicic air fall tuff [Sobieraj, 1994; Sobieraj and Schermer, 1994; Yount et al., 1994].

The presence of subhorizontal bedding (except where locally affected by strike-slip faults) and the relative abundance of volcanic rocks and sparseness of sedimentary rocks suggest that little extension occurred in most of the study area. This is in
### Table 1. Fault slip in the Ft. Irwin region

<table>
<thead>
<tr>
<th>Fault</th>
<th>Orientation</th>
<th>Lateral Slip km³</th>
<th>Vertical Separation sense</th>
<th>Quality</th>
<th>Offset Feature</th>
<th>Age of Movement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle Lake</td>
<td>E-W to NW</td>
<td>&gt;4.7</td>
<td>+, S</td>
<td>1</td>
<td>1 Jfg, Tyb(T)</td>
<td>1, -18Ma Tb</td>
<td>marble intersects fault at high angle, plus subhorizontal slicks; offset includes drag folding and slip on strands 1-3; offset of Jfg is on all four strands; Tyb apparently offset 3-8 km but probably originally flowed west from vent near Bitter Spring, so offset is nonquantitative</td>
</tr>
<tr>
<td>Coyote Canyon</td>
<td>E-W</td>
<td>4.1</td>
<td>+ S in E; N in W</td>
<td>2</td>
<td>1, -Tb</td>
<td>1, -18Ma Tb</td>
<td>Tyb offset along northern strand, Tyb offset along 2 northern strands; Tyb offset is nonquantitative; eastern end strongly deforms ~3 Ma paludal deposits, trace marked by uplifted Qja and Pleistocene(? ) spring mounds; central portion forms north facing scarps in Qja on the south flank of Coyote Ridge</td>
</tr>
<tr>
<td>Tiefert Mountain</td>
<td>E-W</td>
<td>0.75</td>
<td>0.12 S</td>
<td>1</td>
<td>1, Qoa</td>
<td>1, Qoa</td>
<td>shutterridge with distinctive metamorphic clasts in faagglomerate; strands farther north offset Tertiary(? ) rhyolite dike ~700 m</td>
</tr>
<tr>
<td>(north)</td>
<td></td>
<td>&gt;1.4</td>
<td></td>
<td>1</td>
<td>2, Qja, Qya?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiefert Mountain</td>
<td>E-W</td>
<td>&gt;2.7</td>
<td>+ S</td>
<td>1</td>
<td>1, T(? ) dike</td>
<td>1, T(? ) dike</td>
<td>T(? ) dike cuts Cretaceous granitoids south strand more topographically subsided than north strand</td>
</tr>
<tr>
<td>(south)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2, Qoa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined north and south</td>
<td></td>
<td>&gt;3.4</td>
<td></td>
<td>1</td>
<td>3, Qja(?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fort Irwin (four strands)</td>
<td>E-W to NW</td>
<td>&gt;3.7</td>
<td>0.16 S</td>
<td>1</td>
<td>1, Tib, Tl(?)</td>
<td>1, Tib, Tl(?)</td>
<td>Tcf/Tl contact appears to be offset ~1 km along strand 2 (Figure 6), but correlation of units is not certain; Tcf/Tl/Tcs sequence is also offset ~0.5-1 km along strand 3; these amounts are similar to Tib/Qja offset, suggesting initiation of faulting post 11.7 Ma. Strands 1-2 may be older, as Qoa may not be cut, and topographic expression is more subdued. Strand 6 does not laterally offset Mx units but may terminate in uplifted Q(? ) playsa deposit adjacent to strand 5; slip on strand 5 is unconstrained and could be large</td>
</tr>
<tr>
<td>McLean Lake (west)</td>
<td>E-W</td>
<td>1.67</td>
<td>S</td>
<td>2</td>
<td>1, Tb+Tl</td>
<td>1, Tb+Tl (18-16 Ma)</td>
<td>Qof uplifted south of fault, suggesting most recent motion south side up, but higher topography north of fault may suggest reversal of dip-slip component; west segment does not deform Qja, Qya; east segment may cut Qja and shows stronger topographic expression</td>
</tr>
<tr>
<td>(three strands)</td>
<td></td>
<td>1.0</td>
<td>0.3 S</td>
<td>1</td>
<td>2, Qoa, Qja(?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alpine Valley</td>
<td>ENE</td>
<td>1.7</td>
<td>N</td>
<td>2</td>
<td>1, Qym</td>
<td></td>
<td>steepsly dipping contact between Mesozoic metabasalt and metasediments is offset similar amount to Qym/mnzv contact; fault cuts and folds Miocene(?) and younger fluvial and lacustrine strata near east end</td>
</tr>
<tr>
<td>Drinkwater Lake</td>
<td>EW to NW</td>
<td>1.7</td>
<td>+, S</td>
<td>1</td>
<td>1, Jqm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1. (continued)

<table>
<thead>
<tr>
<th>Fault</th>
<th>Orientation</th>
<th>Lateral Slip km&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Vertical Separation sense&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Quality&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Offset Feature</th>
<th>Age of Movement&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldstone Lake&lt;sup&gt;e&lt;/sup&gt;</td>
<td>NW</td>
<td>-3-4</td>
<td>3</td>
<td>south margin of Cretaceous pluton/wall rock contact; Tertiary volcanic/Cretaceous granite contact</td>
<td>1, Kmg, T Tb 2, Qia 3, Qya</td>
<td>RRF: apparent dextral and west side down offset at south end; lateral slip &lt;50 m, with fault scarps up to 4 m high in Qol. OSF: Tb offset ~150 m down to west but scarp in Qia shows ~1 m east side up [Yount et al., 1994, Miller et al., 1994]</td>
<td></td>
</tr>
<tr>
<td>Garlic Spring</td>
<td>NW</td>
<td>n/a</td>
<td>+, E</td>
<td>no markers along main strand marble layer, western strand</td>
<td>1, Pre-Tertiary? 2, Qia 3, Qya</td>
<td>several subparallel fault strands, only local outcrops of fault surfaces with subhorizontal striae; minor subsidiary structures include WNw to west striking reverse and sinistral faults, suggesting dextral-sense displacement on main fault strand; correlation of marble unit is uncertain; evidence exists for Mesozoic sinistral slip (see electronic supplement Appendix 1).</td>
<td></td>
</tr>
<tr>
<td>Desert King Spring</td>
<td>NW</td>
<td>&lt;5</td>
<td>W</td>
<td>intruded southern boundary of dike swarm</td>
<td>1, Kqm 2, Qoa 3, Qya, Qia</td>
<td>most of fault zone in brecciated Qjm and Kqm; Qol cut by fault and Qia locally unconformably overlies deformed Qol</td>
<td></td>
</tr>
</tbody>
</table>

Total left slip is 13.5-14.2 km (minimum includes quality 1 offsets only and assumes Coyote Canyon and Tiefort Mountain are segments of the same fault, and McLean Lake and Drinkwater Lake are segments of the same fault, with an average of 1.7 km slip; larger estimate includes offsets of lesser precision and certainty); total right slip is <8.2 km.

<sup>a</sup>Horizontal slip based on piercing points or combination of horizontal slickenlines and separation of planar contacts. Positive values indicate left slip; negative values indicate right slip.

<sup>b</sup>Quantitative estimate of dip separation not typically available due to lack of marker units; where given, estimated from relief on Quaternary or late Tertiary fan surfaces of similar age, except for one strand of McLean Lake fault where net slip is measured. Positive indicates reverse, negative indicates normal separation; upthrown block indicated.

<sup>c</sup>Quality indicators of strike-slip estimate: 1, offset of linear feature or subvertical contact that intersects fault at high angle or offset of geomorphic feature such as channel or shutter ridge, combined with information from slickenline orientations; 2, offset of moderately to steeply dipping contact, combined with information from slickenline orientations; 3, offset of gently dipping contact or estimate of offset of fan from source area, combined with information from slickenline orientations.

<sup>d</sup>Age constraints indicated by 1, youngest unit fully offset by fault; 2, youngest unit cut by fault; and 3, oldest unit that overlaps or is not deformed. Unit symbols shown in Figure 3a. Ages from Schermer, [1994] and Yount et al., [1994]; approximate ages of Quaternary units from fan morphology and soil development [Yount et al., 1994, Miller et al., 1994]; Qya, 8000-0 years B.P.; Qia, 180,000-20,000 years B.P.; Qoa, >250,000 years B.P. Ages of other units discussed in text and shown in Figure 3a.

<sup>e</sup>Goldstone Lake fault data from southern to central segment of the fault, includes Rifle Range (RRF) and Old Stable (OSF) faults and Goldstone Lake East fault of Dokka [1992].
contrast to the large-magnitude extension in the central Mojave desert [Dokka, 1989; Glazner et al., 1989] and in the Avawatz Mountains [Spencer, 1990b]. Extension in the Avawatz Mountains was followed by late Cenozoic east vergent reverse faulting and folding that may be related to the eastern termination of the Garlock fault, or to right shear along northwest striking faults possibly connected to the southern Death Valley fault zone (Figures 1 and 2) [Brady, 1984b; Brady and Verosub, 1984; Brady and Dokka, 1989; Spencer, 1990a, b].

Geometry and Kinematics of Faulting

The Mojave block has long been recognized to contain at least two different Late Cenozoic structural domains, one containing northwest striking dextral faults and the other containing east striking sinistral faults [Garfunkel, 1974; Luyendyk et al., 1980, 1985; Carter et al., 1987]. More complex models of the domain structure have been proposed [Dokka and Travis, 1990a; Dokka, 1992], but in general, northwest or east striking strike-slip faults predominate in all models. Fort Irwin is located in a domain of east striking faults bounded to the east and west by north-northwest and northwest striking faults (Figure 2), but detailed structural studies have not been previously conducted in the region.

A summary of observations of faulting in Fort Irwin is shown in Table 1. Detailed maps and structural data are in Figures 3-9, and detailed fault zone descriptions are given in electronic supplement Appendix 1. In general, east striking faults are typically subvertical to steeply south dipping, relatively continuous across Fort Irwin, and curve to northwest strikes at their east and west ends. Left-lateral strike-slip with a small reverse component occurs on east striking segments, and thrust or left-oblique slip occurs on the northwest striking end segments. The major east striking fault strands (Drinkwater Lake fault to McLean Lake fault; Fort Irwin fault; Tiefort Mountain fault to Coyote Canyon fault; and Bicycle lake fault; Figure 2) define four relatively coherent elongate crustal blocks. The east striking faults do not follow preexisting structural weaknesses (e.g., compare the trends of Mesozoic contacts and fabrics with faults on Figures 3, 4, and 5). Relatively continuous northwest striking faults are most important in western Fort Irwin and possibly at the eastern boundary of the domain, where they are less well exposed (Figure 1). A dextral component of slip is observed along northeast striking faults in northern and western Fort Irwin, including the Goldstone Lake, Desert King Spring, and Garlic Spring faults, but a dip-slip component is also present.

The relative quality of features used to estimate fault slip and separation is shown in Table 1, together with description of offset features. Few linear features are available to provide true piercing points; however, for planar features, we combine information from slickenlines and kinematic indicators on brittle fault planes together with measurement of separation on planes to assess the strike-slip and dip-slip components. If the slickenlines do not reflect the long-term fault history, this interpretation could be in error.

Detailed Structural Geology of Fault Zones

Because of the complexity of many of the fault zones and the importance of distributed deformation within many of the fault blocks, we describe here in some detail the deformation along two of the major east striking fault zones, the Coyote Canyon-Tiefort Mountain fault system, and the Fort Irwin fault zone, and two of the northwest striking fault zones, the Goldstone Lake fault and Desert King Spring fault, which exemplify the most important features. Detailed maps of all the faults (Figures 3-9) and a summary of the age and nature of displaced units (Table 1) is supplemented by descriptions of deformation along the other faults in Appendix 1. The distributed deformation appears to play an important role in producing large rotations determined from paleomagnetic analysis relative to the amount of fault slip observed, as discussed below. We use subdivisions of Quaternary units following the criteria described by Yount et al., [1994] and Miller et al., [1994]; locations of the detailed maps are shown in Figure 2, and brief descriptions of widespread lithologic units are provided in Figure 3a.

Coyote Canyon Fault. The Coyote Canyon fault strikes approximately east and extends from the Pink Canyon area in the west, across Coyote Ridge, to a likely connection with the Tiefort Mountain fault to the east (Figures 2 and 4). A distinct Miocene volcanic sequence of intercalated tuffs and basalts is offset across the fault zone. Cumulative strike separation on a contact between basalt and tuff near the base of the sequence is 4.1 km (Table 1 and Figure 4). Deformation along the Coyote Canyon fault is distributed in a zone ~1.5 km wide that includes most of Coyote ridge and Coyote Canyon and includes northwest plunging folds and reverse faults (Figure 4).

The western termination of the Coyote Canyon fault occurs where it is truncated by the Goldstone Lake fault (Figure 9). In this region the several fault strands curve into a more northwesterly orientation, suggesting dextral drag related to the Goldstone Lake fault [MacConnell et al., 1994]. At its east end, the fault is buried beneath Holocene alluvium.

Tiefort Mountain fault (north and south). The Tiefort Mountain fault strikes east from the northern margin of Tiefort Mountain and bifurcates into northern and southern strands at eastern Tiefort Mountain (Figures 2 and 5). Abundant steeply dipping brittle fault planes with subhorizontal slickensides demonstrate dominantly strike slip (Figure 5). East trending folds are common adjacent to the northern strand, and there appears to be a significant component of south-side up reverse faulting near the eastern end (Table 1). To the west, the sense of vertical separation appears to change to south-side down normal faulting. The change from reverse to normal dip-slip component may be related to the presence of a relaxing bend in the area of North Tiefort Ridge, where the main strand of the fault changes strike ~10° (Figure 5 and Table 1). Offset markers include irregular pre-Tertiary intrusive contacts and a vertical Tertiary(?), rhyolite dike (solid triangle pattern on Figure 5), indicating sinistral slip of >3.4 km on the major north and south strands, but the northernmost strand on the north flank of North Tiefort Ridge may accommodate additional slip (Table 1 and Figure 5). An offset Quaternary alluvial fan deposit with distinctive metamorphic clasts forms a shutter ridge along the northern strand that indicates 750 m sinistral slip since early Pleistocene time (Figure 5). This evidence, together with the strong topographic expression of the north strand, suggests that the northern
**EXPLANATION OF MAP SYMBOLS**

- Strike and dip, horizontal bedding
- Strike and dip of volcanic flow layering
- Strike and dip of tectonic foliation
- Depositional or intrusive contact: dashed where approximate, dotted where inferred or covered
- Fault contact: dashed where approximate, dotted where inferred or covered
- Fault plane attitude; ball shows dip, arrow shows trend and plunge of striae
- Anticline
- Syncline
- Paleomagnetic sites
- Piercing point or separation marker; white and shaded triangles used for other markers along same fault

**EXPLANATION OF MAP UNITS**

- **Qya** Holocene wash and alluvial fan deposits (Qya) and playa deposits (Qp)
- **Qia** Pleistocene alluvial deposits showing desert pavement and rock varnish development, moderately developed soils. Qia/Qoa indicates younger fan surface developed on older deposits. Age probably 20-180ka (Yount et al., 1994)
- **Qoo** Pleistocene alluvial fan deposits showing well developed or eroded soils, moderately incised and eroded fan morphology. Age probably >250ka (Yount et al., 1994).
- **Qti** Pleistocene and Pliocene(? alluvial fan deposits, moderately indurated, with strongly eroded soils and highly dissected fan morphology; locally probably older than Tyb. Age >500 ka (Yount et al, 1994).
- **Qyb** Younger basalt: Latest Miocene (5.6 Ma) andesitic basalt
- **Ts** Tertiary (Miocene) sedimentary rocks: Fanglomerate (Tc), sandstone and siltstone (Ts), and lacustrine deposits including shale, siltstone, evaporites, and limestone, with local silicic tuffs dated at 11.7 Ma (Tf).
- **Tb** Tertiary volcanic rocks: Miocene basalt and andesitic basalt (Tb), andesite (Ta), dacite and rhyodacite (Td), rhyolite (Tr) and silicic tuffs (Tt). Dates in local area from 19-16 Ma.
- **Ta** Tertiary(? aphanitic rhyolite dikes
- **Kg** Cretaceous granitic dikes; granitoids, including granite (Kg) and quartz monzonite (Kqm)
- **Jkg** Jurassic or Cretaceous granitoids, including granite (Jkg) and quartz monzonite (JKqm); used where mapping and geochronology are insufficient to determine probable age
- **Jg** Late Jurassic Independence dikes: mafic and felsic
- **Jm** Jurassic granitoids, generally unfoliated (Jqm); locally fine-grained, strongly foliated (Jfg)
- **Ji** Jurassic intermediate to mafic plutonic rocks, generally foliated; includes granodiorite to quartz monzodiorite (Ji), dark-colored granodiorite and monzodiorite (Jm), diorite (Jdi), and gabbro (Jgb)
- **Ms** Triassic or Jurassic metavolcanic rocks, including rhyolite ignimbrite and andesite, with locally intercalated volcaniclastic sedimentary rocks
- **Mr** metamorphosed sedimentary rocks (ms), typically mica schist, marble with local schist intercalations (mr)

**Figure 3a.** Explanation of map units and symbols used in Figures 3b-9. Only lithologic units that are present on more than one map are shown here; units of restricted importance are identified in individual figures. Ages based on Ar/Ar data from Schermer [1994, also unpublished data, 1994]; subdivision of Quaternary units after Yount et al. [1994].
Figure 3b. Map of the Bicycle Lake and Garlic Spring fault zones; location on Figure 2. Beacon Hill geology from Yount et al. [1994]. Inset shows equal-area lower hemisphere stereonet projection of fault data, with slickenline orientations shown by dots. Dashed curves indicate conjugate fault planes. (All stereonets plotted using program Stereonet by R.W. Allmendinger.) Units not identified in Figure 3a are Jpg, Jurassic porphyritic granite to granodiorite; gn, Proterozoic augen gneiss. Paleomagnetic sites 89-10 and 11 are immediately south of Bicycle Lake.
Figure 4. Map of the Coyote Canyon fault zone, location on Figure 2. Quaternary geology largely from Yount et al. [1994]. Insets show equal-area stereonet projection of fault data for (left) main fault strands and (right) conjugate and subsidiary fractures, with dextral slip directions shown by open circle symbols. Outcrop area north of Coyote Canyon is Coyote Ridge. Units not identified in Figure 3a are Tys, Pliocene? younger sands with minor gravel intercalations; grades into Tyg, consisting mostly of gravel, and Tp, consisting of paludal deposits (fine sand to mud, evaporites, local silicic tephra). Tog, Pliocene? older gravel underlying Tys, Tp, and Tyb. Tb1, Tb2, etc., indicate stratigraphy within Tertiary volcanic units, which is defined by basalt or andesite units that alternate with silicic tuffs (Tt), but numbers not shown after tuffs for clarity. From the base, the sequence is Tb1 (basaltic andesite)-Tt1-Tb2 (basalt, with local intercalations of thin tuff, Tt)-Tt2-Tb3 (andesite)-Tt3-Tb4 (basalt)-Tb5 (basaltic andesite). Unit Tb3 is probably equivalent to unit Ta on Figure 9 (E.R. Schermer, unpublished data, 1994). Paleomagnetic sites 89-5, 6 and 90-5, 6, 10 are located south of the main fault zone.
Figure 5. Map of the Tiefort Mountain fault zone, location on Figure 2. Geology of Tiefort Mountain simplified from Stephens [1994]. Insets show equal-area stereonet projection of fault data for (left) main fault zones and (right) older, NW striking breccia zone, located on East Tiefort Ridge. Alluvial deposits of QTf of uncertain age, but postdate unit Tc.g. Unit not identified in Figure 3a is Tc.g, coarse sand to gravel, with local megabreccia blocks (described in text). Overlies fine sand to mud, evaporites, and local silicic tephra of unit Tvp, dated at ~10 Ma (D. M. Miller, written communication, 1995). Line with triangle pattern shows outcrop of Tertiary (?) rhyolite dike that was used to calculate offset on the fault zone.
Mountains. The fault was first recognized [Jennings et al., 1962] major topographic relief bordering a basin east of Tiefort Mountain fault may once have curved to northwest strikes but Tiefort Mountain, suggesting the presence of an older south strand to have -2 km left separation of a contact between a Tertiary? These deposits were derived from East Tiefort Ridge and eastern older, unrelated feature or that earlier strands of the Tiefort Mountain fault may once have curved to northwest strikes but were later crosscut by east striking strands. Coarse fanglomerate and breccia dated at <19 Ma [Sobieraj, 1994] and megabreccia sheets interpreted as landslide deposits overlies ~10 Ma fluvial and lacustrine deposits south and east of the Tiefort Mountain fault (D. Miller, written communication 1995) (unit Teg, Figure 5). These deposits were derived from East Tiefort Ridge and eastern Tiefort Mountain [Sobieraj, 1994] and suggest the presence of major topographic relief bordering a basin east of Tiefort Mountain. Because faults are not exposed at either margin of the basin, it is difficult to determine whether these landslide deposits are related to normal, thrust, or strike-slip faulting (see Appendix 1, "Red Pass faults" for further description of the Tertiary deposits).

Fort Irwin fault. The Fort Irwin fault extends from just west of the Avawatz Mountains to west of Nelson Lake (Figure 2). Details of the western extent in the Nelson Lake area are uncertain because the fault is covered by alluvium and land has been extensively modified (due to military activity), so the area described herein includes only the segment east of the Granite Range fault, together with reconnaissance observations along the Goldstone Lake fault (Figure 9) [also see Dokka, 1992; Miller et al., 1994; Yount et al., 1994]. The Goldstone Range fault, Main Gate fault, and Old Stable Fault are likely related. strands of the Fort Irwin fault (Figure 9), one that strikes approximately east with dextral kinematic indicators and the other that strikes northwest with poorly developed sinistral kinematic indicators. Net slip on the fault is poorly constrained due to lack of distinctive marker units and presence of similar Cretaceous granite on both sides of the fault. A crude estimate of ~4 km of dextral separation is provided by the offset of the gently dipping contact between Tertiary volcanic rocks and Cretaceous granite, but this is not a unique contact relation. A contact between Cretaceous muscovite-garnet granite and Jurassic quartz diorite mapped west of the area of Figure 9 by Miller and Sutter [1982] may be the offset equivalent of the contact east of the Main Gate fault, which suggests ~3 km dextral separation (Figure 9), but the plutonic rocks may not be equivalent, as Yount et al., [1994] suggested the Cretaceous granite is offset in a sinistral sense.

Figure 6. Map of eastern Fort Irwin fault zone, location on Figure 2. Subdivisions of Tertiary units modified from Sobieraj [1994]. Inset shows equal-area stereonet projection of fault data: main fault planes and slickenline orientations shown with solid lines and solid symbols; conjugate and subsidiary faults and slickenline orientations shown by dashed lines with open symbols. For clarity, not all folds are shown by fold symbols, but can be identified from bedding attitudes. Bold numbers indicate different strands of fault referred to in text. Tertiary lacustrine deposits (unit T1) north of strand 4 dated at 11.7±0.1Ma [Sobieraj, 1994]. Units not identified in Figure 3a are Qop, older(?) Quaternary playa deposits, incised by modern wash; Tcs, Tcg, interfingering finer (sandstone to cobble conglomerate) and coarser (pebble to boulder conglomerate) Miocene alluvial fan deposits; Tof, conglomerate with different clast compositions from Tcs, Tcg [see Sobieraj, 1994]; Tib, hypabyssal intrusive basaltic andesite.
Figure 7a. Map of western segment of McLean Lake fault, location on Figure 2. Paleomagnetic sites 91-9p to 12p are shown at the west edge; these are labeled “Gary Owen” in Tables 2 and 3, and Figures 10, 11, and 12.
Figure 7b. Map of eastern segment of McLean Lake fault (Alpine Valley segment) and southern segment of Desert King Spring fault, location on Figure 2. Only some of Independence dikes are shown for clarity. Contacts between Jurassic and Cretaceous granitic rocks are approximate and based on reconnaissance mapping. Insets show equal-area stereonet projection of fault data for (left) both western and eastern McLean Lake fault and (right) Desert King Spring fault; subsidiary faults shown with dashed lines. Unit not identified in Figure 3a is QTp, Quaternary or Tertiary(?d) playa deposits.
Figure 8. Map of Drinkwater Lake fault zone, location on Figure 2. Inset shows equal-area stereonet projection of fault data. Units not identified in Figure 3a are mvr, rhyolitic metavolcanic rocks; mbb, basaltic metavolcanic rocks. Unit QTF is of uncertain age, and its outcrops north and south of the fault zone are not correlatable. Unit ms in this figure consists of Mesozoic volcaniclastic sedimentary rocks that are not correlatable with unit ms in other figures. See Brady, [1984a] for more detail north of the fault zone.
Figure 9. Map of southern end of Goldstone Lake fault zone, location on Figure 2. Inset shows equal-area stereonet projection of fault data. Unit not identified in Figure 3a is Kmg, Cretaceous muscovite granite, which ranges from biotite-muscovite granite to muscovite-garnet granite. Paleomagnetic sites are shown on Southwest Ridge (89-1 to 89-8), Northwest Ridge (90-19 to 90-23), and Goldstone Mesa (89-12 to 89-17). Paleomagnetic sites of MacConnell et al. [1994] are on Goldstone Mesa and northeast of Pink Canyon in the block north of the Coyote Canyon fault.
Dokka [1992] proposed ~2.5 km dextral slip on the Goldstone Lake fault but did not indicate the offset units. The Old Stable Fault strikes north-northwest and curves to more northerly strikes in several splays at its southern end (Figure 9). Yount et al., [1994] interpret the splays as either a horsetail splay at the termination of a dextral fault or curved due to the margin of a rhyolite plug southwest of the fault. The Rifle Range fault consists of several strands with minor lateral and dip-slip displacement (<100 m [Miller et al., 1994; Yount et al., 1994]).

Farther to the northwest, the Goldstone Lake (east) fault appears to cut the Coyote Canyon fault. MacConnell et al., [1994] report ~28° of clockwise rotation of Miocene volcanic rocks north of the Coyote Canyon fault and east of the Goldstone Lake fault and attribute the rotation to dextral bending along the Goldstone Lake fault, consistent with our observations of the change in strike of volcanic rocks (Figures 4 and 9). Strands of the Goldstone Lake fault that cut Goldstone Mesa (Figures 2 and 9) show evidence for ~0.5 km of right separation and ~100-150 m vertical separation (northeast side down) of the gently north dipping contact between the basalt and Cretaceous granitic rocks.

**Desert King Spring fault.** The Desert King Spring fault (Figure 7b) was interpreted to be a right-lateral fault by Dokka and Travis, [1990a] and Dokka, [1992], though no evidence was cited for amount or sense of displacement. The fault is marked by a breccia zone that cuts through Jurassic and Cretaceous rocks, but no markers exist in the Quaternary units cut by the fault (Figure 7b and Table 1). Slickenlines and small-scale kinematic indicators are sparse. Because the fault zone juxtaposes identical granitic rocks cut by the Independence dike swarm on either side and does not appear to significantly displace the southern, intruded boundary of the dike swarm, dextral slip is likely <5 km (Figure 7b). Moreover, the Desert King Spring fault is clearly cut by several small-displacement splays of the Alpine Valley fault (Figure 7b), which has <2 km of cumulative left-lateral slip on it. Thus if the Desert King Spring fault is a long, continuous fault, its offset continuation south of the Alpine Valley fault should appear farther southeast in the Granite Mountains. Although no detailed mapping has been done in that part of the Granite Mountains, no evidence for the fault can be seen on aerial photos, on Landsat TM images, or in reconnaissance mapping. A northwest striking fault with subhorizontal slickensides occurs just west of the Desert King Spring fault and has apparent left separation of a contact between Jurassic and Cretaceous granite (Figure 7b); however, the kinematics and timing of this fault and its relation to the Desert King Spring fault are uncertain. Thus the 24 km dextral slip on the Desert King Spring fault predicted by Dokka, [1992] remains unverified. Part of the basis for the large slip value was the purported existence of a large sphenochasm basin northeast of the fault. However, we have mapped outcrops of basement rocks in small hills and gullies within the alluvial fan complex northeast of the fault (Figure 2; also shown by Jennings et al., [1962] ), and limited gravity data [Nilsen and Chapman, 1971; Saltus and Jachens, 1995] show no evidence for a low. These observations suggest that the area northeast of the Desert King Spring fault contains a thin veneer of alluvium or pediment over shallow granite basement rather than a large deep basin.

**Discussion of Geometric Characteristics of Faulting**

**Size of fault blocks.** The detailed mapping of the fault zones and areas between major faults described above and in Appendix 1 reveals that deformation is distributed over several kilometers adjacent to each fault zone. The five major east striking faults, the Garlock, Drinkwater Lake-McLean Lake, Fort Irwin, Tiefert Mountain, and Bicycle Lake faults, divide the region into blocks ~7-10 km wide by 40-50 km long, which we term "crustal blocks" (Figure 2). Typically, ~0.5-1 km of the north and south edge of each block is occupied by complexly deformed rocks in the bounding fault zones, but the width of deformed rock increases to 2-3 km adjacent to fault jogs and bends. The faults tend to have multiple strands, and rocks are folded and sheared within the fault zone and adjacent to each strand; these define "local" blocks. Local blocks are also defined by the intersection of subsidiary northwest and northeast striking faults with the main fault zones (e.g., Figures 3, 4, and 6). The east striking faults typically have cumulative sinistral slip of 3-5 km that is distributed between the several fault strands in addition to a significant component of reverse slip (Table 1). Thus, in our consideration of the regional significance of the deformation in the northeast Mojave domain, a simple plane strain model of crustal blocks bounded by discrete, single, strike-slip faults is clearly too simple.

While it is evident from this study that the area of deformed rock is significant relative to the block size, there are still undeformed areas ~5-10 km wide between each fault zone. Although a single marker unit is rarely present in more than one crustal block, nearly all the blocks (with the exception of the block between the Tiefert Mountain fault and the Fort Irwin fault) have geologic features that can be traced the entire width of the block, suggesting that no significant slip is accommodated on unrecognized faults within the blocks. Furthermore, most of the markers used to measure slip have been followed across the deformed block edges; thus the slip values reflect cumulative displacement across the deformed zones. Disappearance of marker units from one fault block to another, however, leaves open the possibility that unrecognized or buried faults exist at the edges of the blocks that could accommodate more slip. We consider this unlikely, however, due to the overall continuity of such features as the belt of Mesozoic metavolcanic rocks, the Independence dike swarm, and the belt of Jurassic mylonitic rocks (Figures 2 and 10). In some areas, however, the width of undeformed blocks appear to be <5 km, for example, in the Nelson Lake area and north of Red Pass Lake (Figure 2). Elsewhere, where Quaternary units cover significant portions of the fault block (e.g., north of Tiefert Mountains), the only constraint on true block size is for the faults that have been active during Quaternary time (all of those in Table 1), and it is possible there was a more complex pattern of faulting during earlier times.

**Fault intersections.** Deformation at the ends of fault blocks occurs at the intersections of northwest and east striking faults. Unfortunately, many of these intersections in Fort Irwin occur in areas of low hills of sedimentary rocks that are poorly exposed. Fairly simple crosscutting relations are exhibited at the intersection of the Goldstone Lake and Coyote Canyon faults (Figure 9) where the Coyote Canyon fault curves to a more northwesterly strike and rocks adjacent to the fault are interpreted to be folded due to dextral drag on the Goldstone Lake fault [MacConnell et al., 1994]. Fault intersections farther north along the Goldstone Lake fault are not well exposed, but both the Nelson Lake fault and McLean Lake fault appear to be crosscut by the Goldstone Lake fault in areas of uplifted Quaternary and Tertiary sedimentary rocks. The intersection of the Bicycle Lake
and Garlic Spring fault is extremely complex and is manifested by a zone of thrusting, folding, and both sinistral and dextral faulting that makes up most of Beacon Hill (Appendix 1 and Figure 3) [Miller et al., 1994; Yount et al., 1994]. At the intersection of the Desert King Spring fault and the Alpine Valley strand of the McLean Lake fault, mapped fault traces indicate that the McLean Lake fault cuts the Desert King Spring fault and splays out into many strands with small (tens to hundreds of meters) displacement (Figure 7b).

At the eastern margin of the domain, the northwest striking faults east of Tiefort Mountain, including the southern strand of the Tiefort Mountain fault and the Red Pass faults (Figure 2) are cut by the north strand of the Tiefort Mountain fault in a zone of intense brecciation and complex faulting (Figures 2 and 5). It is unclear whether the complexity of deformation in this region is related to the intersection of broadly coeval faults. It is also possible that the northwest trending fabrics are related to an earlier deformation associated with the shedding of megabreccias into the adjacent basin. The eastern ends of the other east striking faults bend to northwest strikes and develop a significant thrust or reverse component before they are cut by northwest striking faults (Figures 6 and 8). It is unclear whether any large northwest striking dextral faults exist within or east of the Avawatz Mountains at the eastern boundary (Appendix 1).

In general, the fault intersections in the study area appear to result in transpression and positive relief, as opposed to the

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**Figure 10.** Map of the Fort Irwin region showing the location of paleomagnetic sampling locations, mean declination direction at each location (Table 2), and outcrops of the Independence Dike Swarm. Independence dike trends are used to interpret rotation of Fort Irwin outcrops (arrows) relative to dike outcrops north of the Garlock fault (see text). Site location abbreviations are BL, Bicycle Lake; BS, Bitter Spring; CC, Coyote Canyon; DD, Dacite Dome; FINW, Fort Irwin Northwest (Northwest Ridge); FISW, Fort Irwin Southwest (Southwest Ridge); GM, Goldstone Mesa; GO, Gary Owen; PC, Pink Canyon location of MacConnell et al. [1994]; SR, Stone Ridge. Other abbreviations as in Figure 2. Declination arrow shown for BL and BS is an average for these localities (see text).
formation of extensional basins such as the sphenochasms that have been inferred to mark the ends of blocks [e.g., Luyendyk et al., 1980; Carter et al., 1987; Dokka, 1992]. In eastern Fort Irwin, where low-relief areas are present at the ends of the blocks, any basin formed there may be related to overthrusting of units to the east. Modeling of gravity data [Saltus and Jachens, 1995] suggests that basins exist at the east ends of the fault blocks, and the abundance of Miocene and Pliocene (?) deposits in this area (Figure 2) may indicate that long-lived basins developed at the ends of the blocks. Whether these late Neogene basins are due to extension or shortening is unknown, but they appear to largely postdate the Avawatz formation and its associated extensional event [Sobieraj, 1994; Spencer, 1990b].

**Timing of Faulting**

The major faults in the northeast Mojave domain were active during post-middle Miocene through Quaternary time. Early Miocene volcanic rocks (18-16 Ma) [Schermer, 1994] appear to be displaced as much as Paleozoic and Mesozoic rocks, suggesting faulting began after ~16 Ma. Along the Fort Irwin fault, sediments <11.7 Ma appear to have been offset as much as older rocks [Sobieraj, 1994]. These data are consistent with the

### Table 2. Mean Paleomagnetic directions for Fort Irwin

<table>
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<tr>
<th>Location</th>
<th>Site</th>
<th>Age, Ma</th>
<th>N</th>
<th>I, D, deg</th>
<th>Polarity</th>
<th>α95</th>
<th>k</th>
<th>R</th>
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<tr>
<td>Dacite Dome</td>
<td>84-1, 2; 91-13, 15, 16</td>
<td>17.68 ± 0.24</td>
<td>5</td>
<td>69.1, 332.7, uncorrected</td>
<td>N</td>
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<td>40.5</td>
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<td>Fort Irwin SW</td>
<td>89-1,3,4, 7</td>
<td>17.83 ± 0.2</td>
<td>4</td>
<td>46.4, 3.3, corrected</td>
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<td>36.1</td>
<td>3.917</td>
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<td>Coyote Canyon NW declinations</td>
<td>90-5, 90-6</td>
<td>17.9 ± 1.0</td>
<td>2</td>
<td>54.7, 83.8, corrected</td>
<td>R</td>
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<tr>
<td>Coyote Canyon NE declinations</td>
<td>89-5, 90-10</td>
<td>5.57 ± 0.26</td>
<td>5</td>
<td>8.7, 163.1, corrected</td>
<td>T?</td>
<td>14.2</td>
<td>30.1</td>
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<tr>
<td>Bicycle Lake and Bitter Springs, combined</td>
<td>89-12 to 89-18</td>
<td>17.4 ± 0.4</td>
<td>7</td>
<td>43.6, 357.8, corrected</td>
<td>N</td>
<td>5.7</td>
<td>112.0</td>
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<td>Goldstone Mesa</td>
<td>90-11 to 90-16</td>
<td>18.6 ± 0.2</td>
<td>6</td>
<td>57.9, 59.5, uncorrected</td>
<td>N</td>
<td>5.4</td>
<td>153.0</td>
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<td>Stone Ridge</td>
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<td>18.0 ± 0.2</td>
<td>5</td>
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<td>Fort Irwin NW</td>
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<td>15.85 ± 0.11</td>
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<td>R</td>
<td>14.0</td>
<td>44.2</td>
<td>3.932</td>
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N is number of sites comprising 3 to 6 samples each. Lavas at Dacite Dome, Stone Ridge, and Fort Irwin NW are believed to be flat-lying and no structural corrections were applied. At Fort Irwin SW, the average of site mean directions corrected for fold plunge and bedding dip yields α95 = 15.5° and k = 36.1 (n = 4); the average of uncorrected in situ site mean directions yields α95 = 25.4° and k = 14.0. The mean directions for the northeast declination group and for the north-to-northwest declination group include both structurally corrected and in situ site mean directions. The same group means computed with all uncorrected site mean directions have much higher values of α95 and lower values of k; α95 = 42.0° and k = 2.0 for northeast declination sites, and α95 = 8.4° and k = 14.1 for the north- to northwest-declination sites. These analyses suggest a successful modified fold test indicating magnetization was acquired before structural disturbance.

- Polarity: N, normal; R, reversed; T?, transitional?
- Structural attitudes 221°/31° NW, 89-1; 340°/25° NE, 89-7; -1,-3,-4 plunge 16° at 354°
- Calculated with reversed directions projected through the origin
- K-Ar by Geochron Labs.
- Structural attitudes 111°/53° S, 89-5, plunge 22° at 290°
- Structural attitudes 240°/11° NW, Bike Lake; 349°/6° E, Bitter Springs
- Structural attitudes 290°/10° N, 89-12; 302°/18° NE, 89-14,15; 182°/16° W, 89-16, 17, 18
- Cited by MacConnell et al. [1994]
- Except 91-12 is N.
Table 3. Fort Irwin Mean Directions, Virtual Geomagnetic Poles, and Discordance

<table>
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<th>Site Groupa</th>
<th>N</th>
<th>I, D, deg</th>
<th>$\alpha_{95}$ deg</th>
<th>k</th>
<th>R</th>
<th>VGP</th>
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<td>Translation</td>
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<td>54.2, 59.7</td>
<td>6.6</td>
<td>44.4°</td>
<td>11.750</td>
<td>41.9° N, 315.8° E</td>
<td>63.5° ± 7.6° CW</td>
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<td>North and NW</td>
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<td>53.6, 349.8</td>
<td>6.3</td>
<td>24.4°</td>
<td>22.099</td>
<td>81.5° N, 148.5° E</td>
<td>6.5° ± 7.4° CCW</td>
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<tr>
<td>North</td>
<td>11</td>
<td>44.6, 359.7</td>
<td>5.5</td>
<td>68.7</td>
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<tr>
<td>NW, Remagnetized?</td>
<td>12</td>
<td>61.0, 336.2</td>
<td>8.0</td>
<td>30.2</td>
<td>11.636</td>
<td>70.3° N, 180.6° E</td>
<td>20.0° ± 9.5° CCW</td>
</tr>
</tbody>
</table>

aBitter Springs and Bicycle Lake excluded; n=5 sites. Two dominant directions are selected; northeast or clockwise deflected and northwest or counterclockwise deflected. Northeast sites are Coyote Canyon 89-5, 90-10; Stone Ridge 90-11 to 90-16; and Gary Owen 91-9 to 91-12. North and NW sites are all good sites minus the NE sites above. North sites are Fort Irwin SW 89-1, 3, 4, 7; Goldstone Mesa 89-12 to 89-18. NW, remagnetized? sites are Dacite Dome 84-1, 84-2, 91-13, 91-15 and 91-16; Coyote Canyon 90-5, 90-6; and Fort Irwin NW 90-19 to 90-23.
bCW, clockwise; CCW, counterclockwise. Discordance is relative to early and middle Miocene reference pole of Calderone et al. [1990] at 85.5° N, 108.9° E, $\alpha_{95}$ = 4.4°; $I = 51.4°; D = 356.2°$ at Fort Irwin. Calculated with formulae of Butler [1992] and [Demarest, 1983].

If the means of the locations with NE declinations (Table 2) are averaged together (n=3) the mean direction result has k = 46.0 compared to 44.4. Both of these values are too high for proper averaging of secular variation [Butler, 1992].

Paleomagnetism

Sampling and Results

We obtained oriented drill core samples from 50 sites in Miocene basalts, andesites, and dacites in the region (Figure 10, Table 2, and electronic supplement Appendix 2). All specimens were treated by step-wise alternating field demagnetization (AFDM) and their stable directions were selected by line fitting to orthogonal vector end point diagrams. Two direction groups defining northeast and north-to-northeastward declinations were found in 35 sites that were of acceptable quality (Table 2 and Figure 11). Of these sites, five are reversely polarized and are deflected southwest approximately antipodal to the northeast deflected sites, suggesting a successful reversal test.

At any given location the number of direction results is too few to average secular variation (Table 2). Successful field stability tests include the approximate reversal test mentioned above and modified fold tests indicating that magnetization was acquired before structural disturbance (Table 2).

The stable characteristic paleomagnetic directions do not appear to bear a simple relation to the elongate crustal blocks such as is seen for the California Transverse Ranges [e.g., Carter et al., 1987; Luyendyk, 1991]. The combined north and northwest declinations are close to the expected direction for a middle Miocene North American paleomagnetic pole determined for the southeast California-western Arizona region [Calderone et al., 1990] (Table 3 and Figure 11). However, the mean
AF demagnetization of 90-15.2a from Stone Ridge

\[ \theta_0 = 1.9 \times 10^{-3} \]

\[ d_{iv} = 2.0 \times 10^{-4} \]

AF demagnetization of 90-22.1 from Ft. Irwin NW

\[ \theta_0 = 3.0 \times 10^{-3} \]

\[ d_{iv} = 5.0 \times 10^{-4} \]

Figure 12. Progressive alternating field demagnetization data for representative samples from (a) Stone Ridge (90-15.2) and (b) Northwest Ridge (90-22.1). These samples demonstrate the two classes of demagnetization behavior: hard with a stable characteristic remanent magnetization (Stone Ridge), and soft with streaked directions found at northwest declination sites (Fort Irwin NW).

direction from all the northwest declination sites alone has good precision statistics and is discordant counterclockwise from the Miocene reference pole (Table 3). The northeast directions are 63.5°±7.6° clockwise from the reference pole.

Progressive Demagnetization Studies

Progressive AFDM experiments reveal two classes of behavior: (1) a large amplitude soft component removed by 15 mT or less (150 Oe); and (2) resistance to AFDM with a median destructive field greater that several tens of milliteslas (Figure 12). Most samples from most locations are of type 1. These softer samples have streaked directions on equal-area plots. Soft samples are from a variety of rock types and ages and often show multiple overprint directions. Many harder samples also show a reversed overprint direction on their natural remanent magnetization (NRM) that is removed by 10 mT. The AFDM shows the most resistant samples are from Goldstone Mesa and Stone Ridge where stable characteristic remanent magnetization (ChRM) directions are easily obtained. Moderately resistant sites are Fort Irwin SW 89-1, 90-3, 90-7 and Coyote Canyon 89-5 and 90-10. The softest sites are Coyote Canyon 89-6, 90-5 and 90-6, and all sites at Fort Irwin NW. Samples from Gary Owen have soft behavior and are moderately stable; Dacite Dome samples are soft and less stable.

The AFDM behavior suggests that the northeast and north declination directions are primary because these locations have samples that are most resistant. Northwest declination directions are closely associated with soft AFDM behavior which makes them suspect. Although firm remagnetization evidence is lacking, e.g., in the form of consistent direction overprints removed by progressive demagnetization, demagnetization ratio experiments (below) support this hypothesis. Dacite Dome apparently is in the same fault-bounded crustal block as Stone Ridge (Figure 10). Dacite Dome samples show soft demagnetization, poor direction statistics, and northeast declinations. Stone Ridge has hard demagnetization, clear primary magnetization and clearly northeast deflected declinations. Unless there is an unrecognized fault between these locations, Dacite Dome directions are a remagnetization direction acquired after rotation.

Coyote Canyon samples show both styles of demagnetization behavior and both northeast and northwest declinations. Here we sampled three lavas in stratigraphic order: b3, b4, b5 (Figure 4). Hard remanence at 89-5 and 90-10 (flow sequence b3 and b4) is southwest deflected with upward inclination and is interpreted as a reversed northeast direction; soft remanence at 90-5 and 6 (b5) is northwest deflected. Both directions are not likely to be primary, as this interpretation would require that b4 and b3 were reversely magnetized and that post-b4, they both rotated >90° clockwise, then b5 was deposited, normally magnetized, and then all flows were rotated slightly counterclockwise. This requires a large rotation in a short time period; probably <<1 m.y. (Table 2). Since the northwest direction is in younger units than the northeast direction, there are at least two other possibilities if some of the rocks were remagnetized: (1) b5 was normally magnetized; post-b5 the location rotated ~90° counterclockwise; the lower units b4 and b3 were remagnetized in a south (reversed) direction; then the location rotated ~90° clockwise, or (2) post-b5, all units rotated ~90° clockwise, then b5 was remagnetized normal and there was no further rotation or slight counterclockwise rotation. Explanation 2 is the least complex.
DEMAGNETIZATION OF TRM and NRM versus IRM

Figure 13. Demagnetization ratios for TRM (heated to 625°C then cooled in 0.045 mT field) and NRM versus SIRM of Fort Irwin samples. Demagnetizations were done at 10, 20, 30, 50, and 70 mT. Remagnetized and demagnetized samples such as those shown from Dacite Dome and Fort Irwin NW are indicated by significant differences between their TRM/IRM and NRM/IRM demagnetization ratio curves. See text for details. Abbreviations are DD, Dacite Dome; FINW, Northwest ridge; FISW, Southwest ridge; GM, Goldstone Mesa; GO, Gary Owen; SR, Stone Ridge.

Rock Magnetism

Rock magnetic experiments also suggest that the northwest directions are remagnetized, while the north and northeast directions are primary. A comparison of alternating magnetic field demagnetization behavior of NRM to laboratory-induced saturation isothermal remanent magnetism (SIRM) can aid in distinguishing remagnetized paleomagnetic samples from those that have retained their primary remanence [Fuller et al., 1988]. For this method, a log10/log10 plot of NRM versus SIRM intensity at identical demagnetization levels is employed. For fine grained igneous rocks that still retain much of their primary thermal remanent magnetism (TRM), less altered samples generally display NRM/SIRM ratios of the order of 10^{-2} or above, and their NRM/SIRM demagnetization curves have a concave downward shape. This characteristic demagnetization behavior may result from a mixture of abundant fine, and less abundant, coarser magnetic grains [Cisowski et al., 1990, Figure 6]. In contrast, highly altered (naturally demagnetized and remagnetized) samples generally display lower NRM/SIRM ratios in the range of 10^{-3}, often with linear or concave upward curves [Cisowski, 1992, Figure 8]. As a test of stability we induced some samples with a laboratory TRM and compared the TRM/SIRM demagnetization ratio curves against the NRM/SIRM curves (Figure 13).

Samples from sites displaying north and northeast declinations have different ratio curves than those samples from sites displaying northwest declination (Figure 13). The northeast and north declination samples display concave downward NRM/SIRM demagnetization curves, similar to their TRM/SIRM curves. In contrast, samples from northwest declination sites (Dacite Dome, Fort Irwin NW) have uniformly low NRM/SIRM ratios with demagnetization curve shapes that are strongly dissimilar to their TRM/SIRM curves (Figure 13).

The inference from these observations is that samples from the northeast and north declination sites have retained their primary thermal remanence. The character of the NRM/SIRM curves from Dacite Dome and Fort Irwin NW suggests alteration and remagnetization, so that paleomagnetic evidence for or against tectonic rotation may have been lost. These experimental results suggest that the NRM/SIRM curves may be useful in distinguishing remagnetized sites that appear nonrotated or
counterclockwise-rotated (Dacite Dome and Fort Irwin NW) from sites retaining primary magnetization that have not been rotated since the time of extrusion and magnetic blocking (Goldstone Mesa and Fort Irwin SW). Further evidence for remagnetization was revealed in electron microscopy and microprobe analysis (Appendix 2).

The northwest direction is consistent among the Fort Irwin NW, Dacite Dome, and Coyote Canyon locations (Table 3). All three locations are in different blocks. We interpret the northwest declination as a nonrotated remagnetized direction. The remagnetization process and timing are unknown but apparently occurred after rotation was complete and, in Coyote Canyon, before folding.

Tectonic Implications of Paleomagnetic Results

The north directions from Goldstone Mesa and Fort Irwin SW are interpreted as primary and nonrotated; the northeast directions from Stone Ridge, Gary Owen, and two from Coyote Canyon are also interpreted to be primary and to reflect net clockwise vertical axis rotation: the northwest directions from Dacite Dome, Fort Irwin NW, and Coyote Canyon are interpreted as remagnetized and not usable for tectonic analysis (Table 3). The paleomagnetic directions we interpret as primary indicate that −64ø of net post early Miocene clockwise rotation has occurred (compared to the reference pole of Calderone et al. [1990]). The fact that the Goldstone Mesa sites are nonrotated or possibly slightly clockwise rotated [MacConnell et al., 1994] suggests that the Goldstone Lake fault is a significant tectonic boundary between clockwise rotated (east) and nonrotated (west) crust.

As an independent check of the interpretation of rotated blocks, we observe that the Jurassic Independence Dike Swarm within the elongate fault blocks can be interpreted as rotated relative to the swarm north of the Garlock fault an amount broadly similar to the declination vectors [see also Ron et al., 1995]. Dikes immediately north of the Garlock fault trend 310ø-314ø, while in the Granite Mountains in northern Fort Irwin (Figures 2 and 10) they trend −334ø [Smith, 1962]. This suggests a differential rotation of 20ø-24ø between these locations. Dikes that have been dated at 148 ± 14 Ma [Stephens, 1994] and which may be part of the Independence swarm also occur at South Tiefort Mountain (Figure 3). Here they trend 020ø-030ø suggesting a rotation of 65ø-80ø relative to north of the Garlock fault. Assuming the northern dikes to be a reference trend, we interpret that the dike swarm outcrops in the northeast Mojave domain have been rotated clockwise 24ø-80ø. This comparison between the declinations and dike trends further suggests that the northeast magnetic declinations are primary and caused by tectonic rotation. Both the paleomagnetic directions and the dike trends also suggest that the northern areas are rotated less than the southern areas within Fort Irwin (Figure 10).

If the dikes in the Tiefort Mountains are indeed part of the Independence swarm, it follows that the rotation affected large crustal blocks that include both Tertiary volcanic and sedimentary cover and pre-Tertiary basement. However, if the Tiefort Mountain dikes are not Independence dikes, the large tectonic rotation inferred from the paleomagnetic data could instead represent either rotation of cover rocks detached from the basement or rotation of local fault blocks adjacent to and within the fault zones that bound the coherent crustal blocks. We see no geologic evidence, however, for detaching of the cover rocks from the basement. The nonconformity beneath Tertiary strata is exposed throughout the Fort Irwin area, and no low-angle faults which might cause differential rotation between Mesozoic basement rocks and Tertiary cover have been identified. The second possibility, of local rotations, is discussed below.

Previous Paleomagnetic Studies

MacConnell et al. [1994] studied early Miocene basals from Goldstone Mesa and Pink Canyon (Figures 9 and 10). The AFDM character of their samples also appears to be type 2 (hard) as we found for our Goldstone, Fort Irwin SW, and Stone Ridge sites. They computed clockwise rotations for these sites of 9.6ø ± 7.4ø (Goldstone) and 28.4ø ± 9.0ø (Pink Canyon). These mean directions have high k (187.5 and 55.1) suggesting secular variation was not averaged. They computed discordance relative to the early Miocene reference pole of Diehl et al., [1988]. The Pink Canyon sites are rotated −22.6ø clockwise and Goldstone sites are rotated −3.8ø clockwise with respect to the pole of Calderone et al. [1990].

Ross et al. [1995] found early Miocene clockwise tectonic rotation in a broad swath of the Mojave Desert including the Mojave extensional belt. Rotation in the belt is constrained to be before 18.5 Ma by paleomagnetic studies on the Peach Springs Tuff [Wells and Hillhouse, 1989]. Ross et al. [1989] also studied nine early Miocene flows in the Alvord Mountains (Figure 1). They found a clockwise rotation anomaly of 53.2ø ± 9.9ø with respect to the Miocene reference pole of Diehl et al., [1983] (−48ø with respect to the Calderone et al. [1990] pole). Ross et al. were uncertain as to the age of the rotation because they believed only early Miocene rocks were sampled. However, the Peach Springs Tuff at Alvord Mountain is rotated 56.1ø ± 5.6ø clockwise (R. Wells and J. Hillhouse, written communication, 1994), not statistically different from the Ross et al. result. Further, the andesite flows at Alvord Mountain have been recently dated at 12.8 Ma (K-Ar (A.F. Glazner, written communication, 1995)). Therefore the rotation in the Alvord Mountains can be interpreted as younger than 12.8 Ma.

Immediately south of the Manix fault Pluhar et al. [1991] found a rotation of 8ø ± 2.7ø clockwise over 2 m.y. for the Pliocene-Pleistocene (2.5-0.9 Ma [Nagy and Murray, 1991]) Mojave River Formation in the crustal block between the Cady and Manix faults (Figure 1). MacFadden et al. [1990] sampled the Hector Formation (23-16 Ma) within the northern Cady Mountains (Figure 1) and found a uniform clockwise declination of 18.6ø (I = 45.4ø, α95 = 5.7ø) and no declination change with age within the section. This is interpreted as due to 20.6ø ± 7.6ø clockwise rotation past 16 Ma relative to the pole of Irving and Irving, [1982] (−22.4 ø clockwise relative to the Calderone et al. [1990] pole). The rotation rate of −4ø/m.y. implied for this crustal block by the Pluhar et al. [1991] study permits 22ø of clockwise rotation over a period of 5 or 6 m.y., suggesting that rotation could have started at the end of Miocene time.

Ross [1995] found large clockwise declination anomalies in the southwest Cady Mountains, south of the Cady fault. He interprets an early Miocene rotation associated with extension in the Mojave at that time and a post-14 Ma clockwise rotation that is attributed to local rotation in a northwest oriented dextral shear zone.

Valentine et al. [1993] found −15ø ± 12ø counterclockwise rotation of middle Miocene sites and no rotation of Pliocene sites.
Table 4. Tectonic Rotations Assigned to Crustal Blocks in the Northeast Mojave Domain

<table>
<thead>
<tr>
<th>Fault-Bounded Block</th>
<th>Site Name</th>
<th>Study</th>
<th>Rotation</th>
<th>Age, Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Trending Blocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garlock-Drinkwater</td>
<td>IDS(^a) and Gary Owen</td>
<td>this paper</td>
<td>24°-54° CW</td>
<td>≤15.8</td>
</tr>
<tr>
<td>Drinkwater-Fort Irwin</td>
<td>Stone Ridge, Pink Canyon</td>
<td>this paper, MacConnell et al. [1994]</td>
<td>23°-60° CW</td>
<td>≤17</td>
</tr>
<tr>
<td>Nelson Lake/Fort Irwin-Coyote Canyon/Tiefort Mountain</td>
<td>Coyote Canyon</td>
<td>this paper</td>
<td>≤90° CW?</td>
<td>≤17.1</td>
</tr>
<tr>
<td>Tiefort-Bicycle Lake</td>
<td>Bicycle Lake-Coyote Lake IFS(^a)</td>
<td>this paper</td>
<td>56-60° CW?</td>
<td>post-Jurassic</td>
</tr>
<tr>
<td></td>
<td>Coyote Lake-Manix</td>
<td>Alford Mountains Ross et al. [1989]; J. Hillhouse (written communication, 1994)</td>
<td>48°-56° CW</td>
<td>≤12.8 Ma(^b)</td>
</tr>
<tr>
<td></td>
<td>Manix-Cady</td>
<td>Hector Formation MacFadden et al. [1990]</td>
<td>≤22° CW</td>
<td>&lt;16 Ma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mojave River Formation Pluhar et al. [1991]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwest trending blocks</td>
<td>Goldstone-Blackwater</td>
<td>Goldstone Mesa</td>
<td>this paper, MacConnell et al. [1994], and Valentine et al. [1993]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15° CCW to 4° CW</td>
<td>≤13.5 Ma</td>
</tr>
<tr>
<td>Goldstone-Garlic Springs</td>
<td>Fort Irwin SW</td>
<td>this paper</td>
<td>7° CW</td>
<td>≤17.8 Ma</td>
</tr>
</tbody>
</table>

Rotations relative to the pole of Calderone et al. [1990]
\(^a\)Independence Dike Swarm; see text.
\(^b\)A.F. Glazner (written communication, 1995)

sampled in volcanic rocks between the Blackwater and Goldstone Lake faults (Figure 1). These results are consistent with our findings and those of MacConnell et al. [1994] for the nonrotated sites at Goldstone Mesa. There is a possibility that the Miocene sites to the west of the Goldstone area are counterclockwise rotated about 10° to 15° with respect to the Goldstone sites; but this observation is not statistically robust.

From our studies and these prior studies we conclude that crust in northeast Mojave domain bounded by east striking faults has rotated clockwise in post early Miocene time but not coherently (Figure 10 and Table 4). The strain in the region has not been homogeneous as Luyendyk et al. [1980, 1985] and Carter et al., [1987] suggested, but the evidence for widespread clockwise rotation is substantial.

Discussion

Boundaries of Rotated Domain

Our paleomagnetic results suggest that the Goldstone Lake fault is the western boundary of the rotated domain. However, because the Fort Irwin NW directions appear to be remagnetized, the southwestern boundary of the rotated domain is not well constrained by the paleomagnetic data. Evidence for possible westward extension of the Bicycle Lake fault between Northwest and Southwest Ridges (Appendix 1 and Figure 9) and the lack of evidence for major faults between the Coyote Canyon fault and Northwest Ridge (Figures 4 and 9) suggest that the rotation boundary lies just north of Southwest Ridge. Farther south, significant differences in the trends of Mesozoic foliations and lineations east and west of the Garlic Spring fault (Figure 3 and Appendix 1) suggest relative clockwise rotation of South Tiefort Mountain and that the boundary of the rotated domain lies along the Garlic Spring fault. The eastern and northern boundaries of the rotated domain remain undefined.

Rotation and Fault Slip

Field mapping indicates that the east striking faults are sinistral with typically 3-5 km of offset. Assuming a simple block model wherein 10-km-wide blocks rotate during left slip of ~5 km along each fault [e.g., Luyendyk et al., 1980; Ron et al., 1984; Nur et al., 1989], clockwise rotation of ~23° is predicted (Figure 14), or about one-third that inferred from the paleomagnetic measurements. This "mismatch" between slip and rotation also appears to be true for southern parts of the domain (e.g., Manix, Coyote Lake faults) since the magnitude of slip (~5 km [Meek and Battles, 1990]) and rotation (~23°, Table 4) are similar to those in Fort Irwin. In order to match the observed fault slip with observed rotation, coherent crustal blocks would have to be <5 km wide, a value much smaller than that observed.

The discrepancy between slip and rotation suggests that the simple block model is not appropriate and/or that we have either overestimated the rotation or underestimated the slip. There are several possible explanations for this discrepancy: (1) the measured declination does not simply record rotation but also secular variation (see above); (2) the "deficient" slip occurs on other faults, for example, new faults produced when faults rotate into an unfavorable stress orientation [e.g., Ron et al., 1984; Nur et al., 1989]; (3) the "excess" rotation is produced by mechanisms besides slip on parallel faults; and (4) some or all of the faults rotated partly without slipping, either because younger sinistral faults formed or because the entire domain rotated as a rigid body without slip on the faults within it. We favor an explanation where excess rotation is produced by both ductile deformation at the block ends, and by rigid rotation of the Fort Irwin region without slip on the internal faults (explanations 3 and 4).

Most of our paleomagnetic sites were, by necessity, within a few kilometers of the fault zones and at the western ends of the crustal blocks near the domain boundary, whereas slip estimates are typically from the central segments of the faults (Figures 3-
10). However, local rotations adjacent to sinistral fault strands should be counterclockwise, not clockwise, and thus would not explain the large clockwise declination anomalies. The complex intersection of subsidiary northwest and northeast striking faults with the main east striking fault zones produces blocks that could rotate clockwise (and counterclockwise) during north-south shortening (e.g., Figures 3 and 4). Although we do observe evidence for north-south shortening in the form of east-trending folds and reverse faults rotation on the subsidiary faults would require strike-slip on those structures, and is not consistent with the predominant dip-slip observed.

If the "deficient" slip is taken up on a younger, more favorably oriented fault set that formed after blocks rotated -40 or 45° [e.g., Ron et al., 1984; Nur et al., 1989], we would expect that northwest striking segments of sinistral faults in eastern Fort Irwin are older faults that have rotated. However, all of the studied northwest striking segments have lower dip angles and a larger component of dip-slip than the east striking faults and many, as noted above, are clearly continuously curved from west to northwest strikes (Figures 5, 6, and 8). Throughout the study area, crosscutting relations (e.g., Figures 5 and 6) indicate that the two sets are broadly coeval.

It is likely that all of the rotation was not accommodated by fault slip, but instead some was caused by distributed or ductile shearing [e.g., Reches, 1993], particularly at the ends of fault blocks. The observation that the ends of several of the fault blocks are curved (Figure 2) suggests the possibility that the rocks at the ends of the block may rotate independently and more than the main body of the block (Figure 14).

It is also possible that the entire domain may have rotated as a rigid body without slip on internal faults (Figure 14). In such a case the dextral faults bounding the domain would rotate while the internal faults were locked. The paleomagnetic results from Goldstone permit the interpretation that the area bounding the northeast Mojave domain has rotated clockwise ~10°-15° with respect to areas farther west [e.g., Valentine et al., 1993]. Possible dextral faults in the Avawatz Mountains (Figures 1 and 2 and Appendix 1) bounding the eastern edge of the domain strike more northerly (340°-345°) than faults to the southeast (~325°), and a similar relationship is seen for the Goldstone lake fault at the western boundary of the rotated domain. A rigid body rotation would add to the rotation amount suggested by fault displacement and account for 23° + 15° = 38° of clockwise rotation. The rigid body rotation could have occurred either before the sinistral faults formed or after they locked. A similar interpretation was proposed for the eastern Transverse Ranges by Richard [1993], who noted that the 41° clockwise paleomagnetic rotation found by Carter et al. [1987] could not be explained by the observed slip on sinistral east striking faults. He proposed that part of the rotation occurred during sinistral slip on faults within the domain and part occurred during rotation of bounding faults.

**Figure 14.** Cartoon block model illustrating two mechanisms of rotation to explain discrepancy between fault slip and paleomagnetic data. (a) Before deformation, (b) 5 km of left slip on faults within domain resulting in 23° rotation, 22 km dextral shear. Shaded areas at the ends of blocks are regions where distributed deformation may produce additional clockwise rotation observed in paleomagnetic data. (c) "Rigid-body" rotation of 15° occurring during dextral slip and rotation along bounding faults. Total dextral shear is 33 km. Rotation may not have occurred in two distinct stages.
The available geologic data suggest that the Blackwater fault, with ~8.5 km right slip [Dokka, 1983], is the only significant dextral fault in that area. Of the total of 65 km of dextral shear across the entire width of the Eastern California Shear Zone for the last 10 m.y. [Dokka and Travis, 1990a], approximately half occurs within the Northeast Mojave Domain, and half must occur on dextral faults outside of or bounding the domain.

Conclusions

The major Cenozoic structures in the northeast Mojave domain are northwest and east striking, strike-slip and oblique-slip faults. East striking faults typically have ≤5 km left slip and a component of reverse movement, suggesting an overall transpressional regime. Field studies indicate a minimum of ~13 km cumulative left-lateral shear in the region from south of the Garlock fault to north of the Coyote Lake fault (Figures 1 and 2). Right-lateral slip on northwest striking faults within the domain is less well constrained but appears to be less than ~10 km total. East striking and northwest striking faults appear to be broadly coeval and affect late Pleistocene strata. Block dimensions established by mapping suggest blocks are (were) ~10x50 km, separated by wide fault zones of densely spaced fault strands. Where the east striking blocks intersect the northwest-trending margins of the domain, uplift due to folding and reverse faulting occurs. The age of initiation of faulting is post middle Miocene.

Up to 60° of clockwise vertical-axis rotation inferred from paleomagnetic declination anomalies is constrained to have occurred after 12.8 Ma. No declination anomaly is shown by sites west of the Goldstone Lake fault and west of the Garlic Spring fault (Figure 10). Several sites with northwesterly declination directions appear to be partly or completely remagnetized and thus cannot be used to infer rotations. The combination of geological and paleomagnetic constraints defines the western boundary of the rotated region as the Goldstone Lake fault and the southwestern boundary as the Garlic Spring fault (Figures 9 and 10). The eastern and northern boundaries remain unconstrained.

The mismatch between fault slips determined from geologic data and rotations inferred from paleomagnetic declination anomalies is due to the three-dimensional nature of the deformation in the domain and the apparent nonrigidity of the fault blocks. Simple plane strain rotating block models are not appropriate to predict fault slip from vertical-axis rotations. However, it is also possible that some of the observed clockwise declination anomaly is due to a regional-scale rigid body rotation of the blocks within the Northeast Mojave Domain.

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