Basin geometry and cumulative offsets in the Eastern Transverse Ranges, southern California: Implications for transrotational deformation along the San Andreas fault system

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ABSTRACT

The Eastern Transverse Ranges, adjacent to and southeast of the big left bend of the San Andreas fault, southern California, form a crustal block that has rotated clockwise in response to dextral shear within the San Andreas system. Previous studies have indicated a discrepancy between the measured magnitudes of left slip on through-going east-striking fault zones of the Eastern Transverse Ranges and those predicted by simple geometric models using paleomagnetically determined clockwise rotations of basaltic distributions along the faults. To assess the magnitude and source of this discrepancy, we apply new gravity and magnetic data in combination with geologic data to better constrain cumulative fault offsets and to define basin structure for the block between the Pinto Mountain and Chiriaco fault zones. Estimates of offset from using the length of pull-apart basins developed within left-stepping strands of the sinistral faults are consistent with those derived by matching offset magnetic anomalies and bedrock patterns, indicating a cumulative offset of at most ~40 km. The upper limit of displacements constrained by the geophysical and geologic data overlaps with the lower limit of those predicted at the 95% confidence level by models of conservative slip located on margins of rigid rotating blocks and the clockwise rotation of the paleomagnetic vectors. Any discrepancy is likely resolved by internal deformation within the blocks, such as intense deformation adjacent to the San Andreas fault (that can account for the absence of basins there as predicted by rigid-block models) and linkage via subsidiary faults between the main faults.

INTRODUCTION

Large-scale crustal rotations followed by convergence have been proposed as the mechanisms responsible for the anomalous east-west orientation of the Transverse Ranges along the San Andreas fault system in southern California. Such rotations, modeled as rigid blocks, have implications for basin formation along the margins of the rotating domain and the amount and style of fault offset within the domain. For the western Transverse Ranges, abundant paleomagnetic data (Kamerling and Luyendyk, 1979; Hornafius et al., 1986; Luyendyk, 1991) corroborate clockwise rotation of 70°–90° inferred from patterns of disrupted lithotectonic belts (Jones et al., 1976; Crouch, 1979) and sediments of the Eocene Poway Group (Yeats et al., 1974). For the Eastern Transverse Ranges (Fig. 1), a sinistral domain adjacent to the San Andreas fault southeast of its big compressional bend where paleomagnetic data indicate ~40° of clockwise rotation (Carter et al., 1987), direct geologic constraints for the magnitude of rotation within the crystalline basement rocks are few. Although Ron and Nur (1996) suggested dike orientations supported 40°–50° rotation in the Eastern Transverse Ranges, more recent analysis of trends of dikes attributed to the Independence dike swarm is not conclusive (Hopson et al., 2008).

Another way to assess the amount of clockwise rotation is to relate it geometrically to sinistral offset on faults that traverse the domain. This approach assumes that the Eastern Transverse Ranges consist of rigid crustal blocks bounded by east-striking sinistral faults that rotate clockwise in concert with progressive dextral slip on northwest-striking faults (Fig. 2). The amount of offset is a function of the amount of rotation and the width of the blocks. Depending on the boundary conditions and other assumptions of the rotation model and the methods of calculating cumulative offset, the paleomagnetic data match (Carter et al., 1987; Richard, 1993; Dickinson, 1996) or do not match (Powell, 1993; Hopson, 1999) the amount of offset documented on sinistral faults from geologic mapping. To effectively relate this geometric approach to real-world strain requires well-documented fault offsets. Paleogeologic patterns and trends in the eastern province, greatly enhanced by our new geophysical data, yield tightly constrained measurements of displacement on the sinistral faults, perhaps more so than any other fault set in the San Andreas fault system.

A key approach to resolving this discrepancy lies in documenting the evolving infrastructure of basins along the faults, the amount of offset that may be concealed beneath alluvial cover, and internal deformation within the crustal blocks between faults. Here we address this problem with new potential-field geophysical data to constrain basin structure as well as fault offset and geometry. These data lead to discussions of the geological and geophysical implications of rigid versus non-rigid behavior of crustal blocks between faults.

GEOLoGIC SETTING

The Eastern Transverse Ranges block (Fig. 1) is characterized by sinistral and/or left-oblique, east-striking faults that extend east from the Little San Bernardino Mountains for more than 70 km. This sinistral domain interrupts the dominant north-northwest–trending physiography and structure of the Mojave Desert to the north and east and of the Salton Trough and Peninsular Ranges to the west, all characterized by dextral faults. The San Andreas and Pinto...
Figure 1. Index map showing sinistral domains marked by clockwise rotation (gray) modified from Dickinson (1996). BCF—Blue Cut fault; CF—Chiriaco fault; CM—Chocolate Mountains; ECSZ—Eastern California shear zone; PMF—Pinto Mountain fault; SCF—Salton Creek fault; SBM—San Bernardino Mountains; SGP—San Gorgonio Pass.

Figure 2. Schematic model of rigid-block rotation of the Eastern Transverse Ranges (A) before and (B) after 40° of clockwise rotation, simplified from Carter et al. (1987). Striped line represents marker that is sinistrally offset by faults that traverse the domain. Shaded areas are gaps that result from rotation resulting from dextral shear (arrows in B).
Figure 3. Shaded-relief topographic map of study area. Red dots are earthquake epicenters from Shearer et al. (2005). Blue stars denote locations of the 1992 Landers and Joshua Tree earthquakes. Gray lines—main faults from Howard (2002), Powell (1981, 2003), and Jennings (1994); CC—Cottonwood Canyon; EDC—El Dorado Canyon.
Orocopia-like rocks underlie much of southern California (Haxel and Dillon, 1978; Magistrale and Zhou, 1996), including the Eastern Transverse Ranges (Powell, 1981), but Haxel et al. (2002) suggested that the schists were restricted to an east-west–trending belt prior to Neogene displacement on the San Andreas fault system and therefore may not underlie the Eastern Transverse Ranges. The McCoy Mountains Formation in the Coxcomb Mountains consists of phyllitic rocks metamorphosed from nonmarine, clastic rocks.

Mesozoic plutonic suites occur in three north-northwest–trending belts (Powell, 1993, appendix 1). The western belt encompasses Cretaceous tonalite and monzogranite that are intruded by granitic rocks. The central plutonic belt consists of scattered bodies of sparse Triassic monzonite and monzonite accompanied by abundant plutons of Triassic–Cretaceous biotite monzogranite (Powell, 1981; Barth et al., 1997) and Late Cretaceous (Wooden et al., 1994) granodiorite. The eastern plutonic belt spans the boundary between the Eastern Transverse Ranges and Mojave Desert. This belt comprises mafic hornblende-rich plutonic rocks intruded by biotite-hornblende quartz monzonite and monzodiorite, all of Jurassic age. In the Coxcomb Mountains, the Jurassic plutonic rocks and the McCoy Mountains Formation are intruded by Late Cretaceous granitic rocks that constitute part of the Cadiz Valley batholith (Calzia et al., 1986; Howard, 2002; Barth et al., 2004).

Marine Eocene strata (Crowell and Susuki, 1959) and nonmarine Oligocene–lower Miocene strata of the Diligencia Formation (Spittler and Arthur, 1982; Law et al., 2001) are exposed south of the Chiriaco fault in the central Orocopia Mountains (Powell, 1993; Fig. 4). Newly discovered bodies of Eocene strata also crop out at the foot of the Cottonwood Mountains north of the Chiriaco fault (8 in Fig. 4). These strongly deformed Tertiary deposits are now exposed in uplifted and eroded metamorphic basins that crop out in highlands of those mountain ranges.

Middle and upper Miocene nonmarine strata are preserved locally in faulted, tilted, and gently folded sections overlain by olivine basalt. Basalt occurs in necks and restricted near-center flows. In places, basalt directly overlies crystalline basement. Published K–Ar ages on basalts in the Eastern Transverse Ranges province range from 4.5 to 15 Ma (Carter et al., 1987; Calzia et al., 1986), although more recent Ar–Ar ages cluster between 6 and 7 Ma (R. Fleck, 2007, written commun.). The distribution of basalt centers along the sinistral faults may have resulted from early extension along structures that evolved into those fault zones (Powell, 1993).

Faults of Late Miocene and Younger Age

Sinistral Faults

From north to south, spaced ~20 km apart, the main, through-going sinistral fault zones of the Eastern Transverse Ranges province are the Pinto Mountain, Blue Cut, Chiriaco, and Salton Creek fault zones (Fig. 1). Additional subordinate sinistral fault segments include the Ivanhoe fault, which splays off the Pinto Mountain fault zone to the southeast, and the Corn Springs Wash fault, which splays southeast from the Chiriaco fault zone (Fig. 3). Between the Chiriaco and Blue Cut fault zones are two pairs of subordinate faults that do not connect with the main, east-striking, through-going faults or with the bounding San Andreas or Sheep Hole faults. The Porcupine Wash and Substation faults and the Smoke Tree Wash and Victory Pass faults are aligned pairs of faults that are separated by gaps across which geologic units and contacts are not disrupted.

Most maps in the Eastern Transverse Ranges show the sinistral faults as largely concealed continuous features that transect the province (Hope, 1966; Bacheller, 1978; Powell, 1981, 1993). Ongoing geologic mapping has shown, however, that each of these through-going fault zones, despite their great lengths and large displacements, is expressed at the surface as a series of left-stepping fault strands rather than as a continuous fault (Figs. 3 and 4). The locations of these strands are well constrained where they are exposed in basement rocks, moderately well constrained where fault-line scarp occurs in basin fill, and poorly constrained where they are completely concealed by basin fill. Although overall displacement is likely to carry through at depth, displacements measured on the left-stepping surface and near-surface strands appear to diminish toward their ends as displacement is transferred from one strand to the next.

The northern faults show evidence of younger movement than do the southern faults (Powell, 1993, p. 60). The Pinto Mountain, Blue Cut, Porcupine Wash, and Smoke Tree Wash faults are characterized by scars in Pleistocene alluvium (Hope, 1966; Bacheller, 1978) and the latter three (including the aligned Substation and Victory Pass faults) are apparently seismically active (Powell, 1981; Shearer et al., 2005; Fig. 3). Last surface rupture on parts of the Chiriaco fault zone and the subsidiary Corn Springs Wash fault appears to be older because pumice, varnished, and incised Pleistocene fan deposits are not disrupted by the fault (Powell, 1981). The inception of faulting is most likely late Miocene, because there is no evidence for faulting older than Miocene on these faults. For example, the Chiriaco and Salton Creek fault zones truncate Eocene strata and upper Oligocene and lower Miocene rocks (Powell, 1981). Miocene (6–7 Ma, R. Fleck, 2007, written commun.) basalt fields, generally located near the sinistral faults, are displaced by normal faults associated with the Blue Cut fault zone, and are offset sinistrally by the Smoke Tree Wash fault (Hope, 1966; Powell, 1993). These relations demonstrate that faulting postdated volcanism; thus, much, and likely most, movement along the sinistral faults was as young as or younger than 6 Ma (Powell, 1993).

Bounding Dextral Faults

We take the San Andreas fault as forming the western boundary of the Eastern Transverse Ranges block, although the transition between left- to right-slip domains is complex in detail (Powell, 1981). The east-striking sinistral faults that traverse the block, with the exception of the Pinto Mountain fault zone, cannot be mapped all the way to the San Andreas fault zone, but instead lose definition within a broad cataclasitic zone in the Little San Bernardino Mountains that is highly fractured and brecciated. This diffuse boundary coincides with the 1992 Joshua Tree M6.1 earthquake and aftershocks (Fig. 3) and represents a zone where slip from the San Andreas fault zone may be transferred northward onto the faults of the Eastern California shear zone (Rymer, 1997). As mentioned earlier, the eastern boundary of the sinistral domain is considered to be the Sheep Hole fault between the Pinto Mountain and Chiriaco fault zones. The type locality of the Sheep Hole fault is along the western margin of the Sheep Hole Mountains, but this fault has been extended south along the western margin of the Coxcomb Mountains to Chuckwalla Valley, where there is a basement discontinuity between the Pinto and Coxcomb Mountains (Powell, 1981).

Paleomagnetic Studies

Paleomagnetic data on samples from late Miocene basalts from four fields in the Eastern Transverse Ranges and one in the Palen Mountains in the Mojave Desert indicate clockwise rotation of 41.4° ± 7.7° (Fig. 4; Carter et al., 1987). Data from the Pinto Wells basalt field (PW in Fig. 4), however, show no rotation for the sampled flows (Carter et al., 1987) and were not included in their calculation. Although all these sites have abnormally high values of the precision parameter (kappa), suggesting that secular variation is not averaged, the regional value calculated by Carter et al. (1987) should average secular variation. We, however, concur with the analysis of Dickinson (1996) that excludes the Palen Mountains site (PM in Fig. 4) because it is clearly outside the Eastern

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Figure 4. Simplified geologic map of the Eastern Transverse Ranges. Green arrows indicate inferred rotations (relative to north) from paleomagnetic declination data of Carter et al. (1987). Numbers show correlated geologic features discussed in text. Faults, shown in red, are compiled from Jennings (1994), Howard (2002), and Powell (1981, personal observ.); solid lines are well located, dashed lines are concealed, and dotted lines are inferred. Note that more detailed mapping of faults is east of long 116°W. Light gray line is outline of Joshua Tree National Park. Dark gray and blue dashed lines are approximate contact between western and central belt and central and eastern belt plutonic rocks, respectively. CLF—Cleghorn Lake fault; CPF—Cleghorn Pass fault; CWF—Clemens Well fault; CSWF—Corn Springs Wash fault; DWF—Dog Wash fault; EVMF—East Valley Mountain fault; WVMF—West Valley Mountain fault. DB—Diligencia Basin paleomagnetic site; PM—Palen Mountains paleomagnetic site; PW—Pinto Wells paleomagnetic site.
Transverse Ranges domain. The revised amount of rotation is 44° ± 7°.

South of the Chiricahua fault zone, paleomagnetic data from early Miocene flows in the Dili-
genesis Formation indicate clockwise rotation of as much as 164° (Carter et al., 1987). These data from two sites in the Dili-
genesis basin (DB in Fig. 4) sampled a long enough time period to average out secular variations in the Earth's magnetic field. The extreme apparent clockwise rotation of rocks from the Dili-
genesis basin may reflect proximity to the Clemens Well fault rather than a regionally significant rotation (Carter et al., 1987). Paleomagnetic data from Cretaceous (?) microdiorite dikes in the Cottonwood and eastern Orocopia Mountains indicate 40° clockwise rotation (Terres, 1984; Carter et al., 1987).

GEOPHYSICAL DATA

For our study, we concentrate on that part of the Eastern Transverse Ranges north of the Chiricahua fault zone (Fig. 3) because (1) it is this region where paleomagnetic data (Carter et al., 1987; green arrows in Fig. 4) indicate a clock-
wise rotation of 44° (Dickinson, 1996), (2) our gravity data set does not extend with sufficient coverage south of the fault, and (3) heat flow and seismicity suggest a change in the geophysical setting across the Chiricahua fault zone. The Chiricahua fault zone coincides with the boundary between lower heat flow in our study area and higher heat flow to the south (Lachenbruch et al., 1985). The area north of the Chiricahua fault zone is more seismically active (Williams et al., 1990; Shearer et al., 2005) and generally higher in elevation (Fig. 3). These observations lead us to suggest that despite many geologic simi-
larities, an important distinction in geophysical signature developed north and south of the Chiricahua fault zone during late Cenozoic crustal evolution of the province.

Nearly 900 new gravity stations along and north of the Blue Cut fault zone were added to earlier coverage (Biehler and Rotstein, 1979; Biehler et al., 2004; Chapman and Rietman, 1974; Roberts et al., 2002; Bracken and Sim-
pson, 1982) for this study. In addition, data from various theses from the University of California, Riverside, were reprocessed to a common datum and formula. Together, these nearly 6800 gravity stations (Langenheim et al., 2007) were used to create an isostatic residual gravity map of the region (Fig. 5). The isostatic correction, using a sea-level thickness of 25 km, a crustal density of 2670 kg/m³, and a mantle-crust density contrast of 400 kg/m³, removes the long-wavelength effect of deep crustal and/or upper mantle masses that isostatically support regional topography, assuming an Airy-Heiskanen model of isostatic compensation (Jachens and Griscom, 1985). Station distribution is on average 1 station per 2 km², although the station density is as low as 1 station per 25 km² within parts of the wilderness areas of Joshua Tree National Park.

The isostatic residual gravity data primarily reflect density variations within the middle and upper crust (Fig. 5; Simpson et al., 1986). One of the most significant density contrasts in the upper crust is that between dense crystalline basement rocks and Cenozoic lower-density sedimentary rocks and deposits. Many of the prominent gravity lows reflect deep (>1 km) basins, such as Coachella and Chuckwalla Valleys, where seismic-refraction data (Biehler et al., 1964; Blackman, 1988) indicate thick, low-velocity Cenozoic sedimentary deposits. Not all gravity anomalies, however, reflect this density contrast. Significant variations in gravity values located over basement outcrops must reflect density variations within the basement. For example, gravity values measured in the Coxcomb Mountains are 15–20 mGal lower than those measured in the adjacent Eagle Mountains to the west. We use the method of Jachens and Moring (1990) to separate the isostatic gravity field into that component produced by variations in basement density (basement gravity field) and that caused by thick sedimentary deposits, which is then inverted for basin thickness. We then can examine basin geometry (Fig. 6A) as well as use the basement gravity (Fig. 6B) to evaluate in a general sense cumulative offsets along the faults.

Aeromagnetic data consist of several surveys (U.S. Geological Survey, 1981, 1983, 1990; Grauch, 1984; Sweeney, 2002; Fig. 7) flown at various altitudes, directions, and flightline spacings. Flightline spacing ranged from 400 m to 4800 m, with most of the region covered by flightlines spaced at 800 m or less. Flight elevations ranged from 120 m above the ground surface to 1143 m constant altitude. The aeromagnetic data were adjusted to a common datum 305 m above ground and then merged by smooth interpolation across survey boundaries to produce an aeromagnetic map of the study area (Fig. 7).

Aeromagnetic anomalies reflect the distribution of magnetic minerals, primarily magnetite, in rocks from the surface to middle to lower crustal depths. Here the anomalies generally reflect the basement rock types either exposed or in the sub-
surface. Other possible magnetic rock types (such as Tertiary basaltic rocks) are geographically restricted and generally thin (<150 m; Carter et al., 1987; Powell, 2002b) within the study area (Fig. 4). Sedimentary deposits are generally weakly magnetic and thus the magnetic data allow us to map basement features beneath the Cenozoic basin fill. To define edges of significant magnetic sources, we use the maximum horizontal and vertical gradient method (Cordell and Grauch, 1985; Blakely and Simpson, 1986) using the magnetic potential field (Fig. 8), which removes the dipole effect and mathematically transforms the magnetic field into an equivalent gravity field (also known as pseudogravity). The magnetic potential map enhances longer-wavelength anomalies and thus emphasizes voluminous magnetic sources. Gradient maxima occur directly over vertical or near-vertical contacts that separate rocks of contrasting magnetizations.

GEOPHYSICAL ANOMALIES

Here we examine sources of gravity and magnetic anomalies in terms of the basement age and rock type in the Eastern Transverse Ranges and surrounding areas and how these anomalies constrain cumulative offsets on the sinistral faults and other bounding faults. To aid this discussion, Table 1 summarizes density and magnetic susceptibility measurements for various basement blocks in the study area.

The highest gravity values in both the iso-
static and basement gravity fields (Figs. 5 and 6B) are located over the Orocopia Mountains. Density measurements confirm that these rocks, primarily Orocopia Schist, are denser than base-
ment rocks in other areas (Table 1), although the basement gravity high may be produced in part by lower crustal density variations and/or crustal thinning in the Salton Trough (Langenheim and Hauksson, 2001). Density measurements indicate that the least dense basement is located east of the sinistral domain, where exposures of the Cretaceous Cadiz Valley batholith are widespread. This region is also marked by lower iso-
static and basement gravity values. The Eastern Transverse Ranges and the areas north and west of this block are characterized by intermediate average densities; however, within all the base-
ment blocks, hornblende-bearing, mostly Jurassic basement rocks of the eastern plutonic belt tend to be denser than those of Cretaceous age, as reflected by higher gravity values over areas heavily intruded by Jurassic plutons (regions marked J in Fig. 6B) and markedly lower base-
ment gravity values over predominantly Cretae-
cous rocks of the central and eastern plutonic belts (regions marked K in Fig. 6B).

Magnetic properties vary widely within the basement blocks, except for the Orocopia Schist. Magnetic susceptibility measurements indicate that the Orocopia Schist should not produce significant magnetic anomalies, and this is evident by the smooth magnetic field with generally low values and low amplitudes (sch in Fig. 7) observed over the Orocopia Mountains. This relatively featureless magnetic anomaly
Figure 5. Isostatic gravity map shown with faults (red) and Joshua Tree National Park boundary (black). Contour interval is 3 mGal. Dark blue dots are density boundaries derived from the maximum horizontal gradient method. Gray shaded region in southeast corner denotes area affected by 15° clockwise rotation of Sheep Hole fault. A–A’ is location of model profile (Fig. 9).
Figure 6 (continued on next page). (A) Thickness of basin fill from inversion of gravity data. Black dashed lines are basin-bounding faults, locations of which are based on analysis of maximum horizontal gravity gradients. CLF—Cleghorn Lake fault; CPF—Cleghorn Pass fault; DWF—Dog Wash fault; EVMF—East Valley Mountain fault; WVMF—West Valley Mountain fault.
Figure 6 (continued). (B) Basement gravity map. J and K denote areas dominated by Jurassic and Cretaceous plutonic rocks, respectively; sch shows area of Oroopia Schist. ELB is Emerson Lake body. Shaded gray areas are poorly constrained.
Figure 7. Aeromagnetic map. Dark blue dots are magnetization boundaries derived from the maximum horizontal gradient method; smaller dots reflect smaller-amplitude gradients. Black dashed lines are basin-bounding faults from gravity analysis (see Fig. 6A). 3MI shows areas outlined by white lines covered by poorer resolution data. A–A' is location of model profile (Fig. 9). ELB—Emerson Lake body; Jv—hydrothermally altered Jurassic volcanic and hypabyssal rocks. a–a' through i–i' denote offset anomaly pairs and are listed in Table 2. Anomalies marked 1 and 2 constrain apparent horizontal displacement on the Sheep Hole fault to be small.
Figure 8. Magnetic potential (also known as pseudogravity) map. J and K denote areas dominated by Jurassic and Cretaceous plutonic rocks, respectively; sch shows area of Orocopia Schist; ELB is Emerson Lake body. Arrows point to offset magnetic potential gradients by the Eagle Mountains strand of the Blue Cut fault zone.
pattern contrasts with the ~50-km-wide band of magnetic anomalies northeast of the San Andreas fault zone in Joshua Tree National Park. Griscom and Jachens (1990) attributed the source of these anomalies to Precambrian igneous and metamorphic rocks and Mesozoic plutons that roughly coincide with the mapped distribution of the western and central plutonic belts (Powell, 1993). Jurassic intrusive rocks, predominant in the eastern plutonic belt, are generally more magnetic than the Cretaceous plutons, as indicated by high-amplitude magnetic anomalies in the Eagle and Pinto Mountains and the generally low magnetic values present over the Cadiz Valley batholith, east and north of the sinistral domain. The most prominent magnetic high in the study area is attributed to a mostly concealed mass of Jurassic hornblende diorite named the Emerson Lake body (ELB in Fig. 7; Langenheim and Jachens, 2002). An exception to the generally magnetic Jurassic rocks thus is most likely composed of weakly magnetic, lower density basement similar to that exposed in the Coxcomb Mountains (Fig. 9) and in the hydrothermally altered eastern Pinto Mountains. The model also suggests that the magnetic source rocks for the belt of magnetic anomalies extend to depths of at least 10–15 km, consistent with the base of seismicity. Because the Orocopia Schist is weakly magnetic, the magnetic data suggest that if such rocks are present northeast of the Clemens Well fault zone, they are at or below the base of seismicity.

<table>
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<tr>
<th>Basement block</th>
<th>Number of samples</th>
<th>Density range</th>
<th>Average density</th>
<th>Susceptibility range</th>
<th>Average susceptibility</th>
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<td>East of Sheep Hole fault</td>
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<td>2632±53</td>
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<td>3.27</td>
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<td>North of Pinto Mountain fault</td>
<td>151/113</td>
<td>2550–3270</td>
<td>2679±111</td>
<td>0.00–41.5</td>
<td>7.41</td>
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<td>141/116</td>
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<td>2758±118</td>
<td>0.00–1.3</td>
<td>10.68</td>
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<td>Orocopia Schist</td>
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<td>2700–3110</td>
<td>2836±157</td>
<td>0.00–30.2</td>
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<tr>
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<td>2715±82</td>
<td>0.00–49.0</td>
<td>7.92</td>
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*Densities in kg/m³ and susceptibilities in 10⁻³ SI units.
§Number of density/magnetic susceptibility measurements.
†± one standard deviation.

Figure 9. Model across the Eagle Mountain strand of the Blue Cut fault. D—density in kg/m³; S—magnetic susceptibility in SI units. Profile location is shown in Figures 5 and 7.
LATE CENOZOIC STRUCTURE

In combination, potential-field geophysical and geological data allow us to document and model the three-dimensional architecture associated with the sinistral faults and the bounding structures of the Eastern Transverse Ranges province. We define fault strands within the sinistral fault zones based on gravity and magnetic gradients. We are able to assess overall cumulative fault displacements of geological and geophysical features in the crystalline basement and to discern patterns of faulting and the geometry of basins associated with the faults.

Cumulative Fault Displacements

In order to better constrain offsets on the sinistral faults and the northwest-striking Sheep Hole fault, we compare disruptions in the regional pattern of gravity and magnetic anomalies to mapped disruptions in basement paleogeographic patterns at the Earth’s surface. Geologic studies include several that used geologic mapping to document magnitude and timing of fault movements (Hope, 1966, 1969; Dibblee, 1975, 1992; Bacheller, 1978; Powell, 1981, 1982, 1993; Howard, 2002). Offset paleogeographic features in the pre-Cenozoic rocks provide measures of total cumulative offset along the sinistral fault zones.

Basement gravity and magnetic anomalies also constrain the amount of cumulative strike-slip offset (horizontal separation) on the left-lateral strike-slip faults because these anomalies are sourced by physical property variations within the crystalline basement rocks. Basement gravity variations typically give only a rough idea of cumulative offset because these variations are poorly constrained across the basins and in some of the wilderness areas. Estimates of offset based on magnetic data are more reliable because these data are more evenly spaced throughout the study area and yield more sharply defined anomalies, except for the surveys with a flightline-spacing of 5 km (areas marked 3MI, i.e., 3 mi, in Fig. 7). This approach offers a means of evaluating and refining estimates based on geologic data and of identifying additional offset features where magnetically transparent Cenozoic sedimentary deposits conceal bedrock patterns that otherwise would provide geologic evidence for offset. Magnetic and gravity anomalies used to infer offset carry ambiguity where the anomalies cannot be tied directly to observed geologic features. In some cases, anomalies sourced at depth may be inaccurately correlated. By using multiple sets of displaced anomalies, we posit that we can identify false correlations.

The specific technique we use to identify offset magnetic anomalies is analogous to that used to identify offsets of exposed geologic features. We search along the trace of a candidate fault for elongate magnetic anomalies that are subperpendicular to the fault and whose magnetic sources appear to be truncated at the fault trace. We then search the opposite fault block for similar anomalies that are truncated against the opposite side of the fault and estimate the magnitude of offset by measuring the along-fault separation between corresponding distinctive features of the anomaly. This technique has been used to measure offsets along faults in the Mojave Desert north of the Pinto Mountain fault zone (Jachens et al., 2002), yielding reasonable results for right-lateral offset along faults north of the Pinto Mountain fault zone (Jachens et al., 2002), when compared to geologic data, with an estimated uncertainty of ~0.6 km. Given the resolution of aeromagnetic data in our study area, 0.6 km is a reasonable estimate of uncertainty except for areas covered by lower-resolution data (3MI in Fig. 7), where the uncertainty could be as great as several kilometers. In the Eastern Transverse Ranges, strike-slip offsets defined on the basis of magnetic and basement gravity data are in good agreement with those from geologic data for the major through-going sinistral faults (Table 2).

Pinto Mountain Fault Zone

The Pinto Mountain fault zone forms the northern boundary of the rotated block and comprises at least four left-stepping strands, named here, from west to east, the Yucca Valley, Joshua Tree, Twentynine Palms, and Pinto Mountain strands (Fig. 6A). Where the locations of the Joshua Tree and Twentynine Palms faults are well constrained by scarp, there is good agreement between fault locations mapped on the basis of surface geology and those mapped on the basis of the geophysical gradients. The Yucca Valley strand, mapped on the basis of geophysical gradients, was not previously mapped, and the existence and location of the Pinto Mountain fault zone east of its intersection with the northwest-trending Mesquite Lake fault are now well documented on the basis of our geophysical data.

Based on offsets of distinctive basement types, the Pinto Mountain fault zone has 16–20 km of left-lateral displacement (1–1’, 2–2’, 3–3’ in Fig. 4; Dibblee, 1975; Bacheller, 1978). A best-fit reconstruction of all basement units across the central reach of the Pinto Mountain fault zone yielded a slip measurement of 16 ± 2 km (Powell, 1993). The range of offsets indicated by geologic features is generally consistent with estimates from matching magnetic anomalies of 13–18 km (Fig. 7; Table 2). The offset estimate from b-b’ (Fig. 7) is less than the geologic estimate 3–3’ (Fig. 4) based on the contact of gneiss with quartz monzonite; the northern contact is not well exposed and could be 2 km.

TABLE 2. COMPARISON OF FAULT OFFSETS FROM GEOLOGIC DATA (AS SHOWN IN FIG. 4) AND GEOPHYSICAL INTERPRETATIONS (FIGS. 6A AND 7)

<table>
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<tr>
<th>Fault</th>
<th>Offset from geologic data (km)</th>
<th>Offset from geophysical data (km)</th>
<th>Magnetic anomalies</th>
<th>Basin length</th>
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<tbody>
<tr>
<td>Sinistral faults</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinto Mountain</td>
<td>16(^a)–20(^a)</td>
<td>18 a-a’; 13 b-b’; c-c’ 15</td>
<td>13–17</td>
<td></td>
</tr>
<tr>
<td>Blue Cut</td>
<td>3–9(^a)</td>
<td>3 d-d’; 6 e-e’; 8 f-f’; g-g’</td>
<td>6–10</td>
<td></td>
</tr>
<tr>
<td>Chiriaco</td>
<td>1(^a)</td>
<td>10 h-h’; 11 i-i’</td>
<td>8–11</td>
<td></td>
</tr>
<tr>
<td>Corn Springs Wash</td>
<td>2.5–3(^a)</td>
<td>2.5</td>
<td></td>
<td></td>
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<tr>
<td>Ivanhoe</td>
<td>1.6–3.2(^a)</td>
<td>2</td>
<td></td>
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<tr>
<td>Porcupine Wash</td>
<td>3(^a)</td>
<td>no offset west of 116(^b)W</td>
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<tr>
<td>Substation</td>
<td>3(^a)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoke Tree Wash</td>
<td>1–1.5(^a)</td>
<td>no offset west of 116(^b)W</td>
<td></td>
<td></td>
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<tr>
<td>Victory Pass</td>
<td>1–1.5(^a)</td>
<td>1</td>
<td></td>
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<tr>
<td>Dextral faults</td>
<td></td>
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<tr>
<td>Sheep Hole(^*)</td>
<td>0–1.2(^d), 1.2–4.5(^d)</td>
<td>&lt;1</td>
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<td></td>
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<tr>
<td>Mesquite Lake</td>
<td>&lt;1.5(^d)</td>
<td>&lt;1</td>
<td></td>
<td></td>
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<tr>
<td>Bullion</td>
<td>6.4–14.4(^b)</td>
<td>7.8</td>
<td>8–10</td>
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<tr>
<td>ECSZ(^\dagger)</td>
<td>&lt;1</td>
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</tbody>
</table>

\(^a\)Richard (1993) predicted 3.5–4.5 left slip based on his reconstruction.

\(^b\)Eastern California shear zone in Little San Bernardino Mountains.

\(^c\)Dibblee (1975).

\(^d\)Bacheller (1978).

\(^e\)Hope (1966).

\(^f\)Powell (1981).

\(^g\)Howard (2002).

\(^h\)Howard and Miller (1992).

\(^i\)Jagiello et al. (1992).

\(^j\)Dokka and Travis (1990).

\(^k\)Jachens et al. (2002).

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farther east, making the two offset estimates more consistent. It is important to note, though, that whereas the offset of anomaly a-a' is along the same reach as the offset geologic features, anomalies b-b' and c-c' are offset along more eastern segments of the fault zone, and suggest eastward-diminishing overall displacement from 18 ± 1 km to ~14 ± 2 km.

Gravity and magnetic gradients indicate that the Pinto Mountain fault zone extends east of its intersection with the northwest-striking Mesquite Lake fault, contrary to Dibblee (1992), who argued against such an eastward continuation because of the apparent southward continuity of the Mesquite Lake fault. Although most recent rupture along the Pinto Mountain fault zone is clearly older than Holocene east of the Mesquite Lake fault (Bacheller, 1978), the continued linear escarpment along the northern front of the Pintos is suggestive of a major fault. Reconstruction of matching offset magnetic anomalies along this eastern reach (c-c', Fig. 7) also indicates offset along this proposed eastern extension of the Pinto Mountain fault zone that is comparable to offset along the previously mapped part of the fault zone west of the Mesquite Lake fault. This eastern extension also is consistent with mapping by Howard (2002) that shows the fault zone extending nearly 15 km east of its intersection with the Mesquite Lake fault.

Blue Cut Fault Zone

The Blue Cut fault zone is composed of four left-stepping strands, named here, from west to east, the Blue Cut, Hexie Mountains, west Pinto basin, and Eagle Mountains strands (Fig. 6A). Strands of the Blue Cut fault zone are exposed only in the vicinity of the Blue Cut in the Little San Bernardino Mountains and near El Dorado Canyon in the Hexie Mountains (Fig. 3), and the Eagle Mountains strand is tightly constrained by mapped units along the north front of the Eagle Mountains. Where well located by geologic mapping, there is excellent correspondence with the locations indicated by the gravity and magnetic data. Where there is little or no surface expression of fault strands, the geophysical data provide much more accurate fault locations, such as in the western Pinto basin. At the east end of the Blue Cut fault zone, gravity data clearly show that the Eagle Mountains strand extends east of Pinto Wells to 1 km east of the inferred extension of the Sheep Hole fault (Fig. 5).

The first studies that measured offsets along the Blue Cut fault zone matched contacts between Mesozoic granitic rocks and Proterozoic gneiss and within the gneiss to show offsets of 3 km across the western reach of the Blue Cut fault strand (4-4' in Fig. 4) and 5–6 km across what we call the Hexie Mountains fault strand (5-5' and 6-6' in Fig. 4; Hope, 1966, 1969). Across the west Pinto basin–Eagle Mountains fault strands, Hope measured 7–9 km by matching a displaced section of quartzite and pelitic rocks intruded by Jurassic quartz monzonite and monzodiorite. Subsequent geologic mapping identified a more detailed array of geologic units and contacts, including not only the metamorphosed sedimentary section and Jurassic pluton, but also the Proterozoic granite gneiss of Joshua Tree, layered paragneiss and orthogneiss, and Jurassic hornblende gabbro and diorite (Powell, 1981, 2002a, 2002b). Reconstructing the paleogeologic pattern of this whole array appears to indicate an offset of 5–6 km across that reach of the fault (7-7', Fig. 4; Powell, 1981, 1982, 1993), somewhat less than the offset Hope measured by matching just the metasedimentary part of the array. These findings led to a best-fit reconstruction of all basement units across the Pinto basin reach of the Blue Cut fault zone, assuming no variation of offset, by restoring a displacement of 5 km (Powell, 1993), which is a minimum with a reasonable uncertainty of as much as 2 km.

The geophysical data show an increasing magnitude of displacement in basement anomalies from west to east along several strands of the Blue Cut fault zone. In our study, measurements obtained from matching magnetic anomalies in the Eagle Mountains with anomalies revealed beneath the Pinto basin indicate offsets of 8 ± 1 km and 9 ± 1 km (f-f', g-g', Fig. 7) across the west Pinto basin and Eagle Mountains fault strands, respectively. These findings are closer to Hope’s measurement than to mine (Powell’s). Given the greater robustness of the paleogeologic pattern including both geologic features 7-7' and 8-8' (Fig. 3), one of us (Powell) argues that the uncertainties in reconstructing the magnetic anomaly patterns are >1 km and that the geophysical and geologic data are all compatible with a slip measurement of ~7 km. Displaced magnetic anomalies in the Pleasant Valley area indicate an offset of 6 km on the Blue Cut fault strand, consistent both with Hope’s and my (Powell’s) earlier findings. An offset anomaly (d-d', Fig. 7) along the western reach of the Blue Cut fault strand indicates a fault displacement of 3 km, consistent with Hope’s measured offset there.

The kinematics of fault displacement along the Blue Cut fault zone is not completely understood. Hope (1966, p. 88) attributed the smaller amount of offset at the west end to contraction on splay faults that branch northward from the Blue Cut fault, whereas Richard (1993) suggested that the increase in offset eastward may be accommodated by extension south of the fault zone. Based on physiographic expression, geologic and structural mapping, or geophysical data, we find no evidence that supports eastward-increasing extension south of the Blue Cut fault zone, although it may be difficult to identify such a small amount of extension (3–5 km) over a 60-km-long region. Kinematic considerations require, however, that eastward from the array of geologic and geophysical offset markers in the northeastern Eagle Mountains and south-central Pinto Mountains, displacement on the Blue Cut fault zone diminishes to zero, presumably at its junction with the Sheep Hole fault. Gravity data indicate that the Blue Cut fault zone extends ~1 km east of the inferred location of the Sheep Hole fault, whereas geologic mapping does not show the Blue Cut fault zone extending east into the Coxcomb Mountains (Hope, 1966). It is also clear that at its west end displacement along the Blue Cut fault zone either joins the San Andreas fault zone or is accommodated by deformation within the structurally complex basement terrain of the Little San Bernardino Mountains, or a combination of the two.

Chiriaco Fault Zone

The Chiriaco fault zone consists of three left-stepping strands, from west to east, the Shavers Valley, Chiriaco, and Hayfield faults. The west end of the Chiriaco strand is exposed where it cuts through the crystalline basement in the Cottonwood Mountains, and buried fault-line scarp occur along the Shavers Valley fault strand in piedmont of the north-central Orocoita Mountains. Where surface expression of a fault trace is present, geologically and geophysically mapped fault locations are coincident, but where there is no surface evidence for the fault location the mapped faults tend not to be coincident.

Well-constrained measurements of offset on the Chiriaco fault zone are found along the Hayfield fault strand, which displaces a distinctive vertical propylitized dacite dike (11-11', Fig. 4), the steeply dipping western contact between a pluton of Mesozoic biotite monzogranite and the Proterozoic granite gneiss of Joshua Tree (10-10', Fig. 4), and a steeply dipping folded fault between that granite gneiss and the Proterozoic augen gneiss of Monument Mountain (9-9', Fig. 4), all offset ~11 km (Powell, 1981). Newly discovered exposures of Eocene strata along the base of the Cottonwood Mountains (Fig. 4) indicate 2–3 km offset across the west end of the Chiriaco fault strand, where offset is likely to decrease as it steps left onto the Shavers Valley fault strand. The mapped distribution of Eocene strata on either side of the Chiriaco fault zone is consistent with an offset of ~11 km across the Shavers Valley fault strand (8-8', Fig. 4). Measurements made by matching magnetic anomalies are also ~11 km (h-h', i-i', Fig. 7, Table 2).
Other Sinistral Fault Zones

For the lesser sinistral faults with displacements of 3 km or less, the resolution of the aeromagnetic data along most of the mapped extent of the Porcupine Wash and Smoke Tree Wash faults precludes offset estimates, except west of long 116°W, where a linear north-trending gradient shows no left-lateral offset, consistent with geologic mapping that shows that these faults do not extend that far west. Aeromagnetic data suggest ~1 km of sinistral offset on the Victory Pass fault, 3 km on the Substation fault, 2 km on the Ivanhoe fault, and 2.5 km on the Corn Springs Wash fault, all consistent with estimates based on realignment of basement contacts (Hope, 1966; Powell, 1981, 1982, 1993; Howard, 2002; Table 2). We do not find evidence for much sinistral offset (>1 km) on the inferred fault in the central part of the eastern Pinto basin or the fault splay along the northern margin of the west Pinto basin. These faults are mapped in part by their topographic expression and therefore may be normal or normal-oblique faults.

Dextral Faults

We also estimate cumulative offsets along dextral faults that bound the Eastern Transverse Ranges. On the western margin of the sinistral domain in the Little San Bernardino Mountains, mapping by Rymer (2000) indicates that the basement rocks are cut by several geologically young, north-northwest–striking faults with small cumulative (<1 km), dextral offsets. Some of these faults showed triggered slip during the 1992 Joshua Tree and Landers earthquakes (Rymer, 2000). The continuity of the prominent magnetic anomaly bounded on the south by the Mission Creek strand of the San Andreas fault zone suggests that these faults, which may form a link to the Eastern California shear zone to the north, have little cumulative offset. Lack of pronounced offset of the magnetic anomaly is consistent with mapped evidence for youthfulness and distributed deformation along these faults. It is significant that the continuity of the anomaly severely limits offset on any other fault sets observed or inferred in the Little San Bernardino Mountains (Hope, 1966; Powell and Matti, 2006) and might indicate frequent fault reorganization between these faults and the Mission Creek fault.

On the eastern margin of the sinistral domain, clasts in older alluvial deposits offset from their sources north of the Pinto Mountains indicate 1.2–2.5 km of displacement on the Sheep Hole fault (Howard and Miller, 1992; Jagiello et al., 1992). Jagiello et al. (1992) argued for a maximum dextral offset of 4.5 km along the Sheep Hole fault based on matching outcrops of quartz monzonite in the Pinto and Bullion Mountains. Offset apparently decreases southward because the presence of a relatively rare metamorphosed quartz monzodiorite to quartz diorite on both sides of the fault in the Clarks Pass area shows little separation across the fault (Howard and Miller, 1992) and because the fault apparently does not offset an aeromagnetic high along the southwestern front of the Sheep Hole Mountains (1 in Fig. 7; Simpson et al., 1984). Similarly, to the south along the inferred extension of the Sheep Hole fault, the continuity of magnetic anomalies in northern Chuckwalla Valley (2 in Fig. 7) suggests little (<1 km) dextral offset along this fault. Clast provenance of Miocene deposits in the Pinto Wells area is also consistent with little or no right offset (<4–5 km) along the Sheep Hole fault between the Pinto Wells area and the south end of the Coxcomb Mountains.

Basin and Fault Geometry

Inversion of gravity data using the modified method of Jachens and Moring (1990) reveals several sediment-filled basins along the major through-going sinistral faults (Fig. 6A). Our modeling suggests that many of these basins have a rhombic morphology that is suggestive of having formed at releasing steps in a strike-slip fault zone (Crowell, 1974). Below we discuss these basins, define the strands of the sinistral fault zones that bound them, and then describe basins that are along the margins of the sinistral domain.

Basins in Left Steps

The gravity inversion shows two basins along the Pinto Mountain fault zone west of the Mesquite Lake fault. Both basins are narrow (no more than 2 km wide), elongate, and filled with low-density sediment <1 km thick. Both occur between left-stepping strands of the Pinto Mountain fault zone (Fig. 6A). The western basin extends ~17 km west of the town of Yucca Valley and is bounded by the Yucca Valley strand to the south and the Joshua Tree strand to the north. The eastern basin, centered on the town of Twentynine Palms, is shallower (<500 m deep) and is only 13–15 km long, possibly because of (1) the interaction between the Pinto Mountain and Mesquite Lake faults that results in distributive strain and uplift (Bacheller, 1978), or because (2) displacement is diminishing eastward as a result of kinematic interaction between left slip on the Pinto Mountain fault zone and right slip on the north-northwest–striking faults of the Mojave Desert. The latter is supported by 13–15 km offset of magnetic anomalies (b-b’ and c-c’ in Fig. 7) along this reach of the fault zone.

Along the Blue Cut fault zone, two mapped, left-stepping strands of the Blue Cut fault, the Blue Cut and Hexie Mountains strands, bound a basin beneath Pleasant Valley (Fig. 6A). Gravity, aeromagnetic, and electrical data show these faults to be steeply dipping and basin sediments to be as much as 1–1.5 km thick (McPhee et al., 2008). The length of the basin (6 km) equals the amount of left-lateral offset from matching bedrock patterns and magnetic anomalies. Thus, we argue that this basin is an extensional strike-slip basin.

Gravity data show that two other strike-slip basins along the Blue Cut fault zone underlie the Pinto basin on either end of the gravity-defined west Pinto strand. The basin-bounding faults mapped by geophysical data, however, do not coincide everywhere with mapped faults and scarps. For example, the west Pinto strand is well expressed by magnetic and gravity gradients, but is as much as 2–3 km south of the fault mapped by its topographic expression at the southern margin of the Pinto Mountains. However, the geophysical gradients coincide with a belt of tilted Pliocene and/or Pleistocene sedimentary rocks that poke up through the younger alluvial deposits (Powell, 2002a). The southern basin-bounding strand locally coincides with mapped scarps (Powell, 2002a). The gravity-defined fault strands represent most of the sinistral offset, whereas mapped traces may be related secondary fault zones or spays.

The central basin within the Pinto topographic depression has similar dimensions to the west Pinto basin, but this basin is nearly bisected by subtle scarps (Powell, 2002b). The basin-bounding strands as defined by gravity gradients do not coincide with these mapped scarps. The Eagle Mountains strand on the north and the west Pinto strand on the south again form a left-stepping geometry. Sandbox models of strike-slip basins show that faulting in extensional stepovers evolve such that younger fault strands commonly bisect the strike-slip basin (Dooley and McClay, 1997).

Along the Chiriaco fault zone there are two basins, one beneath Shaver Valley and the other beneath Hayfield Playa. Our results for the geometry of the basin beneath Hayfield Playa are consistent with those of Blackman (1988), but our results are an improvement in that we use a three-dimensional inversion of gravity data that removes a regional field that explicitly accounts for density variations in the basement. Thus, our basin depth is almost 1 km greater than that of Blackman (1988). We concur with Blackman (1988) that the Hayfield basin is bounded by left-stepping strands of the Chiriaco fault and thus is a strike-slip basin. We also suggest that the Shaver Valley basin is a strike-slip basin exhibiting similar geometry. For both basins, the basin-bounding faults also coincide with
linear aeromagnetic gradients. Faults based on
topographic breaks in slope do not coincide in
some places with the buried basin-forming fault
strands identified by geophysical analysis.

Basins at the Eastern Ends of the Sinistral
Faults

Areally larger and deeper basins from our
analysis are located at the east ends of the three
through-going sinistral faults (Fig. 6A). Along
the Pinto Mountain fault zone, east of its inter-
section with the Mesquite Lake fault, the gravity
inversion reveals a complex basin configuration
centered on Dale Lake Valley. The southern
margin of the basin coincides with the Old Dale
fault, but then diverges southward to the west
to connect to the Pinto Mountain strand where
the basin narrows and is only ~1 km deep. The
northern basin margin is irregular, presumably
reflecting interaction with northwest-striking
dextral faults, such as the Cleghorn Pass and
Cleghorn Lake faults (CPF and CLF in Fig. 4).
The eastern margin roughly coincides with the
Sheep Hole fault; where gravity data cross the
eastern basin margin, the steepest gradient is
located ~1 km west of the mapped Sheep Hole
fault. The western basin margin does not coin-
cide with any mapped or inferred faults, but
gradually shallows to a basement ridge on the
upthrown side of the East Valley Mountain fault
(EVMF in Fig. 4). Diffuse seismicity in this area
(Fig. 3) suggests that the basin margins may still
be tectonically active. A small depression in the
basement surface is evident on the downthrown
(west) side of the East Valley Mountain fault
and north of the Dog Wash fault, considered by
Bacheller (1978) to be the more recently active
part of the Pinto Mountain fault zone east of the
Mesquite Lake fault. We suggest, on the basis of
gravity and magnetic gradients that the Dog
Wash fault steps to the right eastward onto the
Pinto Mountain fault and form the East Hills.

At the east end of the Blue Cut fault zone is
a roughly triangular basin that is as much as
2.5 km deep. The southern margin of the basin
corresponds to the steeply dipping Eagle Moun-
tain strand of the Blue Cut fault zone (Figs. 6A
and 9). The northeastern basin edge is concave
to the southwest, indicating that the southeast
extension of the Sheep Hole fault may not be as
linear as inferred.

Another deep (>2 km) triangular basin is at
the east end of the Chiriaco fault zone. The
eastern margin is roughly aligned with a linear
Sheep Hole fault as inferred from gravity data,
and we propose that the Chiriaco fault forms the
southern basin margin, which is ~8–9 km long.

At the east ends of the Porcupine Wash-
Substation and the Smoke Tree–Victory Pass
faults is an asymmetric basin more than 750 m
deep in northern Chuckwalla Valley. The eastern
margin of the basin coincides with the inferred
extension of the Sheep Hole fault (Rotstein et
al., 1976) and an east-striking buried basement
ridge that extends 4 km beyond basement out-
crops forms the southern margin of the basin,
which is aligned with the Substation fault.
Based on this correlation, Rotstein et al. (1976)
suggested that the Substation fault extends, bur-
ied, most of the way across the valley. Rotstein
et al. (1976), based on sparser station coverage,
could not justify extending the Victory Pass fault
beyond basement outcrops; based on the denser
station array of this study, the Victory Pass fault
coincides with the edge of a shallow east-west-
elongated basin. We thus argue that the Victory
Pass fault also extends another 4 km east beneath
the alluvial floor of Chuckwalla Valley where it
intersects northward-striking faults.

Other Basins

The gravity inversion highlights other basins
that are not associated with sinistral faulting,
such as a major basin north of the sinistral
domain north of Twentynine Palms. The basin
is elongated in a northwesterly direction and is
~1.5 km deep. Although Bacheller (1978) sug-
gested that the basin is bounded on the east by
the Mesquite Lake fault, the Mesquite Lake
fault may not be the main basin-bounding fault
unless it is a reverse fault, because its trace is
located in the bottom of the gravity low. Jachens
et al. (2002) suggested local, recent changes in
stress regime from extensional to compressional
~20 km northwest of our study area along the
projection of the Mesquite Lake fault, because
of evidence of steeply dipping basin depos-
its above the deepest part of a gravity-defined
strike-slip basin. The Mesquite Lake fault could
therefore be a reverse fault; however, evidence
for contraction in our study area awaits more
detailed study. Based on the maximum hori-
zontal gravity gradient, the main basin-bounding
fault is concealed and located ~2 km to the
northeast of the mapped trace of the Mesquite
Lake fault (Fig. 6A).

DISCUSSION

Basin Structure and Fault Kinematics

The basins along the major sinistral faults
likely formed in a transtensional faulting regime
in the Eastern Transverse Ranges, given the
present-day stress field. Focal mechanisms in
this area are predominantly strike-slip, normal,
or oblique-normal faulting (Williams et al., 1990),
with nearly horizontal T axes (minimum stress
direction) trending west-northwest and P axes
(maximum stress direction) ranging from near-
horizontal to near-vertical and trending north-
 northeast to northeast. The focal mechanisms
thus indicate a transtensional faulting regime
in the Eastern Transverse Ranges. Williams et
al. (1990) suggested that the main east-striking
faults may have been rotated into positions no
longer favorable for further slip, although focal
mechanism orientations include N80°E strikes.

Basins at the east ends of these faults do not
require a significant component of dextral slip
on the Sheep Hole fault, and can result from
the simple termination of sinistral offset at the
east boundary of the rotated domain (Fig. 10).
The combination of gravity and magnetic data
suggests that the inferred Sheep Hole fault is
characterized more by vertical (2 km) than by
horizontal (<1 km) offset. Thus, the inferred
Sheep Hole fault in the Pinto basin is a normal
or normal-oblique fault that accommodates
space created as the Eastern Transverse Ranges
rotate and as the block north of the Eagle Moun-
tain strand moves west with respect to the Eagle
Mountains to the south (see also Powell, 1993),
an expected outcome of rigid-block rotation (Luyendyk, 1991).

The absence of basins either in the highlands
of the crystalline blocks between the sinistral
fault zones or beneath surficial deposits on
lowland piedmonts outside of the left-stepping
strands of the sinistral fault zones may place an
upper constraint on the amount of concealed
extension within the Eastern Transverse Ranges
domain. The narrowness of the basins defined
by the gravity inversion, particularly along the
Blue Cut fault zone in the physiographically
much broader Pinto basin (Fig. 11), is striking.
We speculate that the fault zone may become
even narrower and simpler within the seis-
mogenic zone, a conclusion that is consistent
with the large magnitudes of cumulative offset
along these faults. The left steps in the sinistral
faults are nowhere larger than 5 km, a distance
that modeling indicates is a lower bound for
inhibiting rupture in transtensional steps (Har-
riss and Day, 1993). The left steps in the East-
ern Transverse Ranges fault zones are thus suf-
ciently small that they are unlikely to present
such a barrier during a major earthquake.

Strike-slip faults defined by geophysical data
do not coincide everywhere with faults defined
by topographic scarp, such as the northern
margin of the west Pinto basin and the southern
margin of the Dale Lake basin. The discrepancy
in location between basin-bounding strands and
the strands that can be mapped at the surface
suggests that offset may be partitioned in space
and/or time. The concealed basin-bounding
faults appear to have accommodated most of the
strike-slip offset as they coincide with magnetic
gradients that then truncate sets of offset
Figure 10. Vertical displacement predicted from sinistral displacement resulting from an earthquake rupturing through five strands of the Blue Cut fault zone (white rectangles) using Coulomb 3.0 (Toda et al., 2005; Lin and Stein, 2004). At the far eastern end of the fault zone, note subsidence on the northern side of the fault, consistent with the location of the East Pinto basin, and uplift on the southern side of the fault, coincident with the Eagle Mountains. At the western end of the fault zone, the opposite pattern is predicted, but no deep basin is present at the southwest end of the fault.

Figure 11. Comparison of the perspective view of the topography of the Eastern Transverse Ranges (A) with the perspective view of the pre-Cenozoic bedrock surface (B), illustrating how narrow the subsurface basins are relative to the physiographic depressions. Vertical exaggeration is 4 x. View is to the northwest.
magnetic anomalies and they define margins of the sediment-filled basins. These faults may be older than the topographically expressed faults. For example, along the Pinto Mountain fault zone, the Dog Wash fault is the most recently active strand, as indicated by Quaternary scarps (Bacheller, 1978, p. 137), but the Pinto Mountain fault, as mapped by Bacheller (1978) and defined geophysically, probably accommodated most of the left-lateral offset east of the Mesquite Lake fault.

The estimates of cumulative sinistral offset based on geophysical data are consistent with matching bedrock patterns across the main through-going sinistral faults in the Eastern Transverse Ranges. The magnetic anomaly patterns do not indicate any significant (>3 km) offsets on the subsidiary sinistral faults. Another constraint on offset of the major through-going faults is the length of strike-slip basins. Thermo-mechanical modeling suggests that the length of strike-slip basins equals the cumulative horizontal displacement if the crust is weak (Petrunin and Sobolev, 2006). The basin lengths for the Pinto Mountain, Blue Cut, and Chiriaco fault zones are also similar to estimates of cumulative offsets from matching magnetic anomaly and bedrock patterns (Table 2).

Apparent increases in displacement eastward on the Blue Cut fault zone and westward on the Pinto Mountain fault zone suggest a possible link through the Pinto Mountains, perhaps along the Ivahoe fault or along northwest-striking faults projecting southeastward from the Mesquite Lake fault (Fig. 3). Such a link would be contractional in nature and reverse faults mapped along the eastern margin of Twenty-nine Palms Mountain (Howard, 2002) may reflect such a link. More speculative is the link southward into the Pinto basin, but geomorphic analysis indicating increased uplift and incision of the Pinto Peak block (Figs. 3 and 5A; Young, 1968) may reflect how offset is transferred into the Pinto basin. Similarly, displacement may be bled off of the Chiriaco fault zone onto the Corn Springs Wash fault (CSWF in Fig. 4), as suggested by a decrease in basin length along the Chiriaco fault zone east of its intersection with the Corn Springs Wash fault from 11 km to 8–9 km. Alternatively, slip gradients along these faults may result from rotation, depending on which end of the fault is pinned (Luyendyk et al., 1980); given the rotation and initial angle between sinistral and dextral domains for the Eastern Transverse Ranges, the calculated slip gradient is <1 km.

Seismicity in the area unbroken by the Porcupine Wash–Substation and Smoke Tree Wash–Victory Pass faults (Fig. 3), coupled with geophysical evidence to extend the Victory Pass and Substation faults farther east (Fig. 6A), suggests that these faults, although not entirely through-going at the surface, probably are through-going at depth and thus contribute to transrotation. These data, together with evidence for links between the Pinto Mountain and Blue Cut fault zones, indicate that the tectonic blocks cannot be modeled solely as rigid, and require more complex models than those applied by Carter et al. (1987) and subsequent workers. Our analysis of the geophysical and geologic data indicates an optimal average value of ~34–35 km of sinistral offset on the main through-going sinistral faults in our study area and as much as 4.5 km on the aligned subsidiary faults. The geophysical data do not indicate any additional faults with more than 1 km of sinistral offset.

Tectonic Rotation

Studies that model the sinistral fault domain in the Eastern Transverse Ranges must address not only geologic constraints on fault displacements, but also paleomagnetic declination data that indicate a clockwise rotation of 41° ± 8° since the late Miocene (Carter et al., 1987), recalculated herein as 44° ± 7° exclusive of the Mojave Desert Palen Mountains site. Four such studies illustrate a range of approaches in dealing with the implications of those data. Carter et al. (1987), in presenting their paleomagnetic findings, noted that known geologic displacements indicated a rotation of ~35° and concluded that the geologic and paleomagnetic data were in rough agreement at the 95% confidence level. One of us (Powell, 1993) examined the sinistral faulting domain in the context of a balanced reconstruction in which displacements on all late Cenozoic strike-slip faults in southern California were restored, avoiding overlaps and minimizing gaps between blocks of crystalline basement. Powell found that rotation of the fault blocks in the Eastern Transverse Ranges is required to achieve a balanced reconstruction. The indicated rotation for the Pinto Mountains block between the Pinto Mountain and Blue Cut fault zones is 15°. That rotation is increased to 20° for the Eagle Mountains and Orocopia Mountains blocks, allowing differential block rotation, and in effect removing extension by partially closing the Pinto basin in the reconstruction (Powell, 1993). Compared with rotation determined by palinspastic reconstruction, the paleomagnetically determined rotation is a factor of two larger. The Powell (1993) geometric rigid-block model to test the self-consistency of the reconstruction yielded rotations of 15°–20° for the sinistral faults, Powell restored minimal displacements from range of estimates for each, and did not include slip from subsidiary faults.

Richard (1993) developed a tectonic model for southeasternmost California that also showed that simple rigid block models using a rotation of 40° overestimate the sinistral displacements across the entire Eastern Transverse Ranges block. Richard (1993), in order to honor the paleomagnetic data, modified the boundary conditions to allow the Sheep Hole fault to rotate 15° clockwise south of its intersection with the Blue Cut fault zone. He assumed that the Sheep Hole fault originally was straight with an azimuth of N46°W (measured north of the Pinto Mountain fault zone). Geophysical data do not readily support the rotation of the eastern boundary. First, gravity data indicate that the overall fault zone does not change strike and that, at least in the Pinto basin, the Sheep Hole fault is not linear, but curved and suggestive of normal faulting. Second, rotation of the eastern boundary should result in extension in the domain east of the Sheep Hole fault. The amount of extension should increase southward from the pivot point in the southeastern corner of the Pinto basin, with as much as 6 km at lat 33°45′ (see shaded region in Fig. 5). Instead, a basement ridge is located between the Palen Valley and Chuckwalla Valley basins in the area that should be extended, according to Richard (1993, his Fig. 12). The basin beneath Palen Valley could be a potential location for this extension except that the basin should become wider to the south. Instead the basin is arguably wider at its north end. Perhaps the repercussions of rotating the Sheep Hole fault are distributed over a large area and thus are difficult to recognize in either the geology or in the existing geophysical data. We prefer the interpretation that the Sheep Hole fault is a loci of fixed points along which the Eastern Transverse Ranges fault panels swung without changing the orientation of the San Andreas edge of the domain (i.e., Dickinson, 1996).

Dickinson (1996) modeled left slip on the Eastern Transverse Ranges faults as the result of 44° of clockwise rotation (an average that does not include the Palen Mountains site [PM, Fig. 4], which is outside the rotated domain). He calculated sinistral slip using three models. His preferred model (case I; Fig. 12) pinned the midlines of the rotating panels and allowed the shear zone and panel widths to vary. The second model (case II) did not allow the panel width to vary, and the ends of the rotating panels were decoupled from the shear zone margins. His third model (case III), which he did not favor, assumed a constant shear-zone width with the rotating panels fully coupled at their ends to the shear-zone margins. For each of these three models, cumulative predicted offsets for the Eastern Transverse Ranges total 59 ± 1 km, given 44° of clockwise rotation, a width of 62 km for the rotating domain, a mean
sinistral fault strike of 87°, and a mean shear zone strike (San Andreas trend) of N46°W. His preferred rotation model, however, predicts that the width of the rotating domain measured perpendicular to the sinistral faults decreases from 85 to 62 km, indicating a transpressional regime, with more than 25% net north-south shortening. Such shortening has not been documented for the Eastern Transverse Ranges, although Hope (1966) attributed west-striking normal faults in the Pinto basin to be the response to earlier north-south compression that arched up the Eastern Transverse Ranges. The age of this inferred compression is not known, but most likely predates eruption of basalt, sinistral and normal faulting, and thus also any rotation.

The rotation models all have shortcomings, which we attribute to components of non-rigid behavior of the blocks between the through-going faults. None of these models accurately predicts the amount of offset for all of the individual faults because all these models assume rigid-block behavior and that the amount of offset on the fault is proportional to the fault spacing (and amount of rotation). Spacing between the main through-going faults is roughly the same, ~20–25 km, but offset on the Pinto Mountain fault is considerably more than that on the other through-going faults (Table 2). The greater displacement on the Pinto Mountain fault may be related to deformation in the Mojave block or to the deflection of the San Andreas fault in San Gorgonio Pass.

Another shortcoming shared by the rigid block rotation models is that gaps predicted to open along the margins of the rotating domain (Fig. 2) are not always observed. Some of these predicted gaps coincide with deep basins, such as those at the east ends of the sinistral faults. Gaps predicted at the western ends of the sinistral faults do not, however, coincide with deep basins. If deep basins were formed during transrotation along the western margin of the domain, they may have been subsequently highly modified by the San Andreas fault, as suggested by the red arrow pointing to the predicted angle of rotation given the rotation domain (see Powell, 1993). Geologic data to the south of our study area show that displacement on the through-going Salton Creek fault diminishes eastward and is likely taken up by subsidiary sinistral faults, such as the Ship Creek and Corn Springs Wash faults, in the eastern part of the domain (see Powell, 1993).

Whereas Powell (1993) and Richard (1993) utilized minimum displacements on the through-going major faults and disregarded the contribution of subordinate faults, Dickinson (1996) assumed that displacement on all subsidiary faults is completely independent of that on the main through-going faults. Our analysis (Table 3) suggests that these subsidiary faults are linked to variations in displacement along the through-going faults. As such, they cannot be treated as independent through-going faults, nor can they be disregarded. Thus, Dickinson’s (1996) fault offset estimates are likely too high and those of Powell (1993) and Richard (1993) are likely too low.

Other data also indicate that the blocks between the faults are not rigid. Available detailed mapping (Powell, 2001a, 2001b, 2002a, 2002b) shows a web of subsidiary northwest-striking, west-striking, and north-striking faults between the main through-going faults. Although the offsets on these faults are demonstrably small, their cumulative effect may contribute to resolving the discrepancy between total displacement and amount of rotation indicated by the paleomagnetic data.
The remaining alternative, that the Pinto Wells fault that results in no net rotation at Pinto Wells. The amount of dextral offset along the Sheep Hole Cut fault zone extends east of the Pinto Wells to three factors: (1) it is outside the rotation. Gravity data confirm that the Blue basalt is younger than the rotation, suffers from ambiguity in that ages for the Pinto Wells center range from 4.5 to 7.8 Ma and that preliminary analysis of GPS data indicates ongoing sinistral displacement on the Blue Cut fault zone (Bennett et al., 2006). Clearly this site would benefit from detailed geologic mapping and additional geochronologic and paleomagnetic studies.

CONCLUSIONS

Geophysical data provide markers of displacement on the sinistral faults in the Eastern Transverse Ranges that document variable displacement along the faults. These data are consistent with and augment displacements measured using offset geological features. Sinistral offsets derived from integrating best fits for the geophysical and geologic data indicate 16–18 km along the west-central Pinto Mountain fault, diminishing eastward to 13–16 km; 7–9 km on the eastern Blue Cut fault, diminishing westward to 3 km; and 11 km along most of the length of the Chiricahua fault to 8 km near the east end of the fault. Offsets on subsidiary faults sum to ~7 km in the study area. Of the subsidiary faults, the Smoke Tree Wash–Victory Pass and Porcupine Wash–Substation faults discontinuously transect the Eastern Transverse Ranges sinistral domain, having a combined displacement of 4–4.5 km. We group these fault pairs kinematically with the above through-going major faults as boundaries between rotational fault blocks. The remaining subsidiary faults are located in the eastern half of the sinistral domain and represent a principal mechanism of non-rigid fault-block behavior compensating for variations in magnitude of displacement along the through-going faults.

Patterns of alternating westward increasing and decreasing slip along the main through-going faults and the location and slip on the minor subsidiary faults are consistent with our interpretation of the minor faults as one mechanism of non-rigid fault-block behavior in the Eastern Transverse Ranges. Any discrepancy between our data and the 95% confidence window of the paleomagnetic data can be eliminated if blocks are allowed to further deform, a condition that is consistent with faults mapped within the blocks and by the absence of basins at the west ends of the sinistral faults, where rocks are intensely deformed in the Little San Bernardino Mountains.

Geophysical data indicate that sinistral faults in the Eastern Transverse Ranges form zones characterized by left-stepping segments and pull-apart basins in the stepovers. The basin geometry is consistent with a transtensional stress regime since inception of faulting, most likely associated with opening of the Salton Trough and the birth of the modern San Andreas system in this region ca. 5–6 Ma. The lengths of the pull-apart basins match offset estimates on the faults based on matching bedrock patterns and magnetic anomalies, with a cumulative sinistral offset of 34–40 km across the fault blocks between the Pinto Mountains and Chiriaco fault zones, calculated by adding displacements on the minor faults to compensate for slip deficiencies along the major faults. Regardless of the rigid-block rotation model used, this amount of cumulative offset is consistent with a clockwise rotation of 27°–39°, generally less than indicated by paleomagnetic measurements on late Miocene basalts, but sharing a small overlap with the 95% confidence range of 37°–51° for the paleomagnetic declination data.

The deepest basins along the sinistral fault zones are located at the eastern ends of the faults, near their intersections with the northwestern-striking Sheep Hole fault, as predicted by rigid-block models. Gravity and magnetic data suggest that the Sheep Hole fault is primarily characterized by vertical, rather than horizontal, displacement. The basins at the eastern ends of the sinistral faults do not necessarily reflect interaction between sinistral and dextral faults, but rather accommodate space created at the ends of the sinistral faults due to block rotations.

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