Reconciling disparate estimates of total offset on the southern San Andreas fault

Michael H. Darin and Rebecca J. Dorsey
Department of Geological Sciences, 1272 University of Oregon, Eugene, Oregon 97403-1272, USA

ABSTRACT

Late Cenozoic tectonic reconstructions of southern California (United States) have been hindered for decades by disagreement over the total displacement on the southern San Andreas fault; disparate estimates of dextral offset range from 160 km to 240 km. Prior estimates were based on purely translational models that neglect the effects of transrotational strain on the orientation and distribution of key geologic markers. We present a new reconstruction that integrates published lithologic, structural, and paleocurrent data with the effects of clockwise rotation in the eastern Transverse Ranges (ETR). This model yields 200 ± 14 km of cumulative offset on the southern San Andreas fault system in the Salton Trough. The disparity between our estimate and a lower estimate of 160 km for the Mojave segment can be explained by a combination of transtensional elongation along the southwest boundary of the ETR, transfer of strain to the eastern California shear zone, and diffuse crustal shortening in the Big Bend region. This reconstruction reconciles previously incompatible and long-debated models, and places an important new constraint on the tectonic evolution of the Pacific–North America plate boundary in southern California.

INTRODUCTION

The San Andreas fault (SAF) system in southern California (United States; Fig. 1) is an active, distributed intracontinental shear zone that accommodates Pacific–North America plate motion by a combination of dextral translation, transrotation, transtension, and transpression (e.g., Luyendyk, 1991; Powell, 1993; Dickinson, 1996). The onshore evolution of a throughgoing SAF system in southern California is generally considered to have begun with inception of the San Gabriel fault at ca. 10 Ma, followed by initiation of the SAF at ca. 5 Ma (Powell and Weldon, 1992, and references therein). During the past ~40 yr, tectonic reconstructions of the southern SAF system have produced irreconcilable estimates of 160 km (Frizzell et al., 1986; Matti and Morton, 1993), ~185 km (Dillon and Ehlig, 1993), and 240 km (Ehlig, 1981; Ehlert, 2003) for cumulative dextral offset, based on correlation of different geologic markers. Workers have discussed the need to resolve this impasse (e.g., Powell and Weldon, 1992; Powell, 1993; Richard, 1993; Dickinson, 1996), but no published model has successfully reconciled the conflicting estimates.

This paper presents a new tectonic reconstruction for the southern SAF since 10 Ma that satisfies existing geologic constraints. We use a simple geometric model for rigid block rotation to reconcile disparate estimates of offset on the Mojave and Coachella Valley segments of the SAF. We then integrate published lithologic and paleocurrent data with late Miocene transrotation in the eastern Transverse Ranges to derive a new estimate of net offset on the southern SAF.

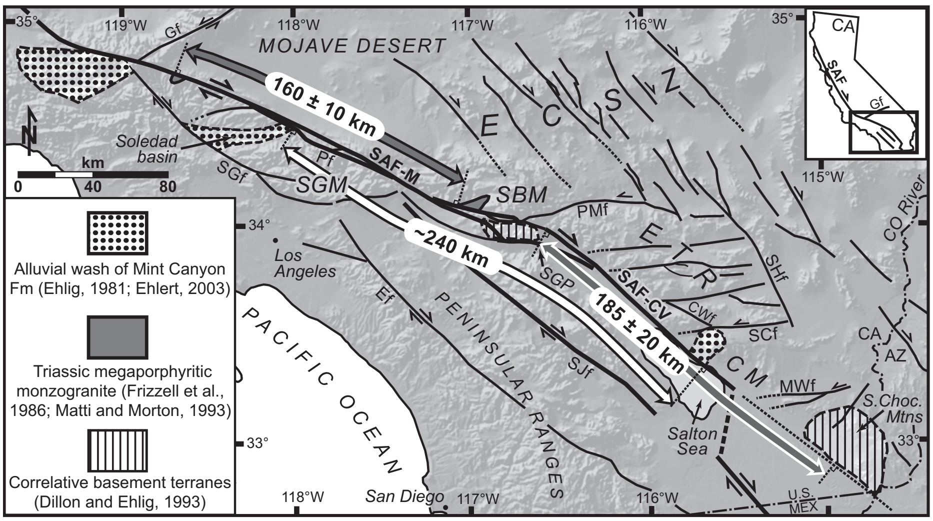

Figure 1. Simplified tectonic map of southern California (United States). Conflicting estimates of total offset on San Andreas fault range from 160 to 240 km based on different cross-fault correlations. CM—Chocolate Mountains; CWf—Clemens Well fault; ECSZ—eastern California shear zone; Ef—Elsinore fault; ETR—eastern Transverse Ranges; Gf—Garlock fault; MWf—Mammoth Wash fault; PMf—Pinto Mountain fault; Pf—Punchbowl fault; SAF-CV—Coachella Valley segment, San Andreas fault; SAF-M—Mojave segment, San Andreas fault; SBM—San Bernardino Mountains; SCf—Salton Creek fault; SGP—San Gorgonio Pass; SGf—San Gabriel fault; SGM—San Gabriel Mountains; SHf—Sheep Hole fault; SJf—San Jacinto fault; CO—Colorado; S. Choc. Mtns—South Chocolate Mountains.

INCOMPATIBLE PRIOR ESTIMATES OF SAF OFFSET

Various geologic markers have been used to generate disparate estimates of cumulative right slip on the southern SAF system, which includes the Mojave segment, Mission Creek–Coachella Valley segment, Punchbowl–Wilson Creek strand, San Bernardino–Mill Creek strand, and the San Jacinto fault (bold lines in Fig. 1; Matti and Morton, 1993). The widely cited estimate of 240 km of right-lateral displacement is based on fluvial conglomerates of the middle Miocene Mint Canyon Formation in the Soledad basin southwest of the SAF that are offset from their source area in the Chocolate Mountains northeast of the SAF (Ehlig et al., 1975; Ehlig, 1981; Ehlert, 2003). This correlation is based on a distinctive volcanic clast assemblage that includes rapakivi-textured quartz latite porphyry for which the only viable source is petrographically and geochemically similar rocks in the Chocolate Mountains (Fig. 1). A second less widely cited, though arguably more robust marker is a distinctive Triassic megaporphyritic monzogranite that is offset 160 ± 10 km between Liebre Mountain southwest of the SAF and similar outcrops northeast of the SAF in the San Bernardino Mountains near Mill Creek (Frizzell et al., 1986; Matti and Morton, 1993). The petrologic, geochemical, and geochronologic similarities of these rocks strongly support the interpretation that they were continuous parts of the same pluton prior to displacement on the SAF starting ca. 5–6 Ma (Frizzell et al., 1986). Neither of these estimates incorporates the effects of late Miocene transrotation that are critical to achieving an accurate solution (e.g., Richard, 1993; Axen, 2000).

GEOLOGY, September 2013; v. 41; no. 9; p. 975–978 | doi:10.1130/G34276.1 | Published online 22 July 2013

TRANSROTATION

Eastern Transverse Ranges

The eastern Transverse Ranges (ETR) comprise a domain of rotated crustal panels bounded by east-west–striking sinistral faults northeast of the Coachella Valley segment of the SAF (Fig. 1; Carter et al., 1987; Powell, 1993; Richard, 1993; Dickinson, 1996). Paleomagnetic data from the ETR record 44° ± 7° of clockwise rotation between 10 and 4.5 Ma (Carter et al., 1987; Dickinson, 1996; Richard, 1993). Rigid-block models based on geophysical data propose up to 39° clockwise rotation (Langenheim and Powell, 2009). There are no paleomagnetic data southeast of the Salton Creek fault in the ETR to constrain rotation there, leading some to interpret it as a zone of complex distributed strain and possible nonrigid behavior (Richard, 1993; Dickinson, 1996). We infer this zone to be part of the ETR transrotational domain based on a lack of throughgoing northwest-striking dextral faults and the presence of east-west sinistral faults in the Chocolate Mountains that are consistent with clockwise rotations in the ETR.

San Gabriel Domain

Consistent clockwise-deflected magnetic declinations in the San Gabriel Mountains reveal that rocks in the western Transverse Ranges have undergone net clockwise tectonic rotations of up to 100° since ca. 15 Ma (Hornafius et al., 1986; Luyendyk, 1991). However, sparse data from 10–11 Ma tuffs in the upper Mint Canyon Formation reveal 16° ± 30° of *counterclockwise* rotation in the San Gabriel domain since ca. 10 Ma, likely caused by translation of the San Gabriel block through the restraining bend of the SAF during Pliocene to Holocene time (Terres and Luyendyk, 1985).

Geometric Model

Figure 2 shows our geometric model for rigid-block rotation in the ETR. Localized extension is accommodated by a series of dilational steps near the edge of a domain of sinistral strike-slip faults bounded by master dextral faults. We propose that, as originally postulated by Powell (1993, p. 62), transform-parallel extension along the southwest boundary of the ETR during block rotation can explain much of the discrepancy between disparate estimates for total offset on the southern SAF.

We elect to use Dickinson's (1996) alternative "decoupled" transrotation model instead of his preferred "pinned" model to calculate the change in length of the ETR along the SAF, because the pinned model predicts 25% north-south shortening across crustal panels in the ETR that is not documented. Displacement of offset markers close to the SAF is not affected by changes in the width of the shear zone (*w*), which is allowed to vary in this model. The

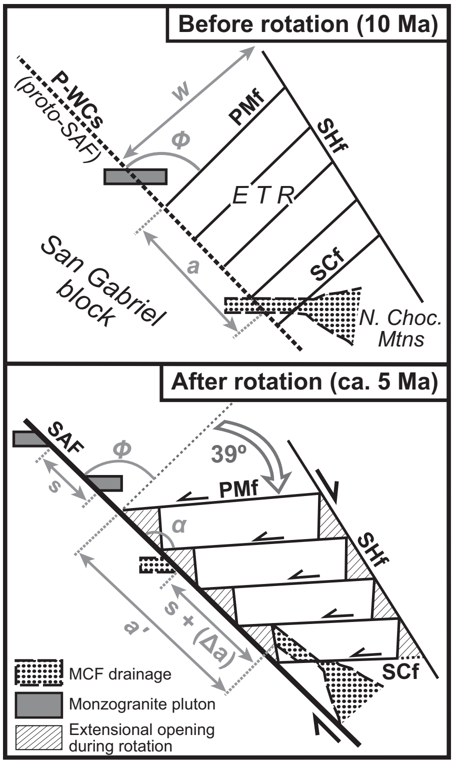

Figure 2. Geometric model for rigid block rotation in eastern Transverse Ranges. Cross-fault markers along southwest boundary of rotating domain are offset by a combination of right-lateral slip (s) on the Punchbowl–Wilson Creek strand (P-WCs) of the proto–San Andreas fault (SAF) and by extensional shingling in the transform-parallel direction due to 39° of clockwise block rotation ca. 10–5 Ma. This right separation (a′ – a, or Δa) causes cross-fault markers within rotating domain (stipple) to be offset more than markers located outside domain (dark gray). Model parameters: ϕ = 92°; α = 131°; s = 20 km; a′ = 88 km; a = 66 km; Δa = 22 km; w (width of the rotating domain measured perpendicular to the SAF) is free to vary in this model and is unspecified. MCF—Mint Canyon Formation; other abbreviations as in Figure 1.

dimensions of the rotating fault blocks are held constant during progressive transrotation, and the following trigonometric expression is maintained: $a = a'(\sin\alpha/\sin\phi)$, in which a and a′ are the initial and ending (modern) lengths of the rotating domain, respectively, measured parallel to the domain boundary (Fig. 2). We use a value of 88 km for a′, measured from the Pinto Mountain fault at the northwest corner of the ETR to our inferred paleo–dispersal path for the middle Miocene Mint Canyon Formation (MCF) just north of the Salton Creek fault. From the map relationships, we find that α = 131° and ϕ = 92° based on 39° of clockwise rotation. Thus the original length of the domain boundary, a, was ~66 km. This yields ~22 km of right separation along the SAF in the vicinity of the Salton Creek fault induced solely by transrotation. A range of 20–25 km reflects uncertainty in where the offset paleo–dispersal path crosses the SAF.

PALEOGEOGRAPHIC RECONSTRUCTION

Figure 3 shows our proposed reconstruction of the southern SAF system since 10 Ma. Paleocurrent indicators in the MCF record westward fluvial transport of sediment in the Soledad basin from a source in the northern Chocolate Mountains northeast of the SAF (Fig. 3C; Ehlig et al., 1975; Ehlert, 2003). This correlation provides the main basis for published reconstructions that call for 240 km of cumulative dextral offset on the southern SAF (Ehlig et al., 1975; Ehlig, 1981; Dillon and Ehlig, 1993; Ehlert, 2003). The 240 km estimate assumed an originally southwest-oriented transport system ca. 10 Ma (see Ehlert, 2003, his figure 14), in violation of the paleocurrent data.

Conglomerates in the lower MCF nonconformably overlie Pelona Schist in a structural trough that defines the Soledad basin (Ehlig, 1981; Ehlert, 2003). We infer that the eroding paleosource in the Chocolate Mountains was controlled by the same structural trough on the south flank of, and parallel to, a large structural culmination in the Orocopia Mountains prior to offset on the San Andreas or San Gabriel fault. Thus we assign an original east-west orientation to the Chocolate Mountains–Soledad drainage system in the 10 Ma reconstruction, consistent with paleocurrent data after restoring rotation of the San Gabriel block (Fig. 3A). Because exposures of both the MCF and its source rocks are located ~15–20 km from the SAF, this correction significantly reduces the amount of slip needed to restore the once-contiguous catchment-basin pair to their original pre-offset configuration.

Revised Tectonic Model and Estimate of Offset on the SAF

Using the data summarized herein, we realign the correlative Liebre Mountain and Mill Creek porphyry bodies and restore 39° of clockwise block rotation in the ETR and 16° of counterclockwise rotation of the San Gabriel block at 10 Ma (Fig. 3A). Between 10 and 5 Ma, the San Gabriel fault accommodated ~45 km of dextral displacement (Powell and Weldon, 1992; Matti and Morton, 1993). The Punchbowl–Wilson Creek strand of the proto-SAF may have been active during this time, although it has been suggested that at least half of the ~40 km of net dextral displacement occurred since Pliocene time, after deposition of the Punchbowl Formation (Powell and Weldon, 1992; Powell, 1993; Matti and Morton, 1993). We therefore arbitrarily assign 20 km of right slip to this earliest strand of the SAF ca. 10–5 Ma (s, Fig. 2; Fig. 3B). Coeval clockwise rotation of the ETR and attendant displacements on left-lateral faults dismembered and rotated the MCF paleodrainage such that its original extent can only be

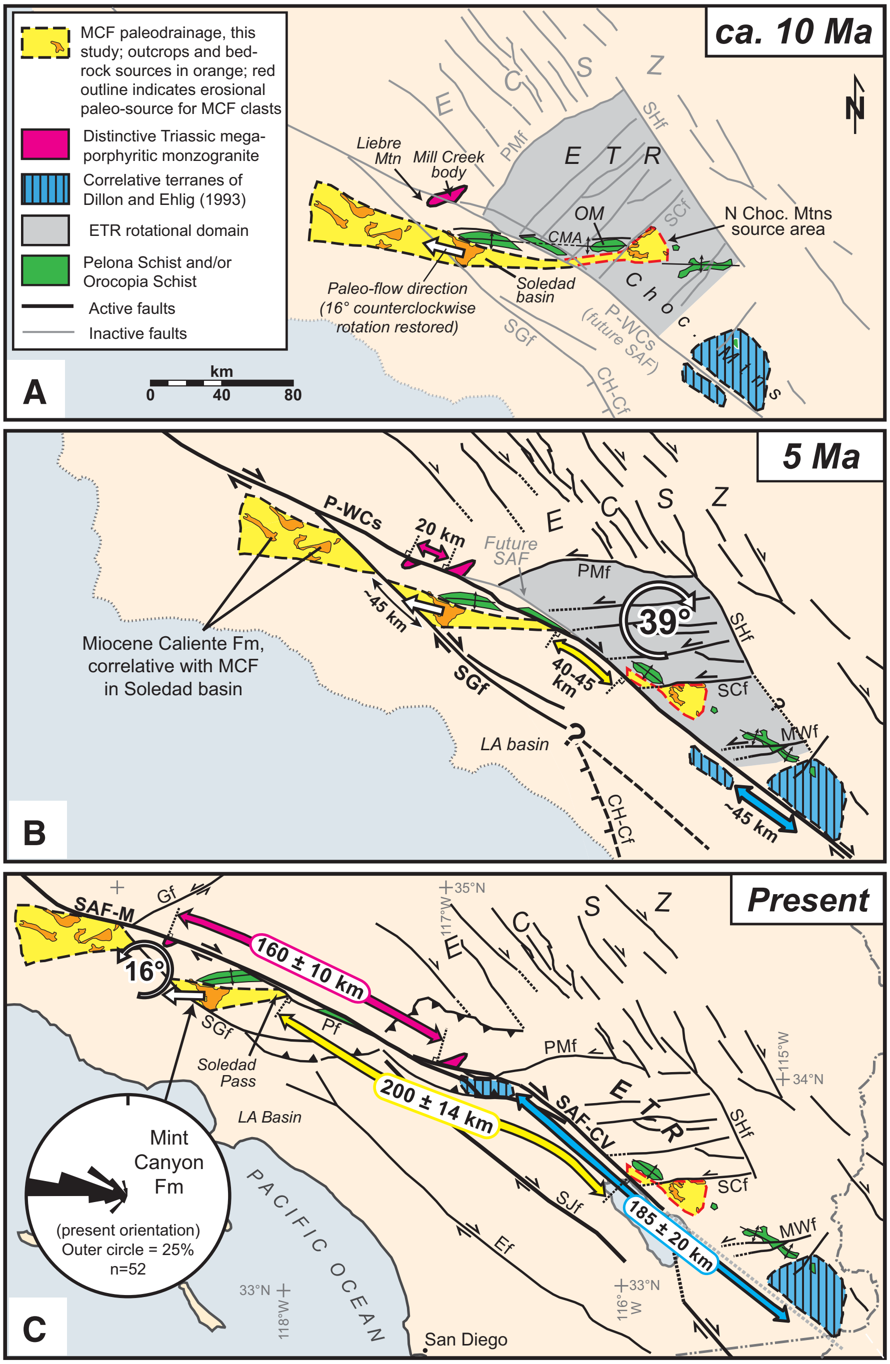

Figure 3. Tectonic reconstruction of southern San Andreas fault (SAF) since 10 Ma (North America reference frame). A: Prior to 10 Ma, Mint Canyon Formation (MCF) occupied approximately west-draining alluvial wash (yellow). Note continuity of original Chocolate Mountains anticlinorium (CMA) trend. B: Between 10 and 5 Ma, MCF drainage was offset by 45 and 20 km of right slip on San Gabriel fault (SGf) and Punchbowl–Wilson Creek strand (P-WCs), respectively. Synchronous clockwise rotation in ETR caused MCF paleo-source to be displaced an additional 20–25 km to the southeast ca. 10–5 Ma (see text). C: Present-day configuration of southern California after post–5 Ma offset on modern SAF. CH-Cf—Chino Hills–Cristianitos fault; OM—Orocopia Mountains; other abbreviations as in Figure 1.

inferred on the present-day map (Fig. 3B). Additional right slip on the SAF system since ca. 5 Ma displaced the Liebre Mountain and Mill Creek porphyry bodies a total of 160 ± 10 km (Fig. 3C). Using our reconstructed MCF piercing line, we estimate 200 ± 14 km of cumulative dextral offset on the southern SAF since 10 Ma, which is ~40 km less than prior estimates of at least 240 km based on the same correlative markers (compare to Fig. 1; Ehlig, 1981; Ehlert, 2003). Our new estimate is partitioned between ~25 km on the San Jacinto fault (Sharp, 1967) and 175 ± 14 km on the Coachella Valley segment of the SAF in the Salton Trough (this study); the latter is consistent with an independent estimate of 185 ± 20 km based on correlation of basement terranes between San Gorgonio Pass and the southern Chocolate Mountains (Figs. 1 and 3; Dillon and Ehlig, 1993).

Reconciliation with Other Models

Our new estimate of 200 ± 14 km of cumulative right slip on the southern SAF in the Salton Trough is ~40 km greater than the well-constrained estimate of 160 ± 10 km on the Mojave segment (Frizzell et al., 1986; Matti and Morton, 1993). This discrepancy can be seen by comparing the present-day distance between pairs of geologic markers on each side of the SAF (Fig. 3C). On the southwest side of the SAF, the Liebre Mountain pluton is ~65 ± 10 km northwest of the MCF paleodrainage near Soledad Pass. In contrast, the corresponding markers on the northeast side of the SAF (Mill Creek body, MCF source in the Chocolate Mountains) are ~105 ± 10 km apart. This contrast in along-fault distance between pairs of markers suggests that rocks on opposite sides of the SAF underwent different deformation paths. At least half of this discrepancy (20–25 km) is explained by transrotational elongation in the southwest ETR, northeast of the SAF (Fig. 2). The remaining discrepancy of ~20 km can be explained by slip transferred away from the Mojave segment and onto dextral faults that link to the eastern California shear zone north of the ETR (e.g., Dolan et al., 2007) and/or a component of distributed off-fault transpressional strain southwest of the Mojave segment.

DISCUSSION

While a detailed documentation of distributed regional strain is beyond the scope of this paper, the predictions made by our reconstruction model are broadly consistent with previous studies of the eastern California shear zone and ETR (e.g., Richard, 1993; Dickinson, 1996). One limitation of our model is uncertainty in the extent and configuration of the paleocatchment east of the SAF that delivered sediment to the MCF during middle Miocene time (Fig. 3); the paleodrainage cannot be precisely reconstructed due to a lack of MCF outcrops northeast of the SAF. Age relations in the Diligencia basin indicate that the Chocolate Mountains source area has been eroding since middle to late Miocene time (Law et al., 2001), which can explain why fluvial deposits of the MCF are not preserved. Despite this limitation, the MCF correlation is supported by distinctive clast lithologies that uniquely match bedrock sources in the northern Chocolate Mountains, making it a useful marker for estimating total offset on the SAF.

The assumption of purely rigid-body rotation in the ETR is difficult to validate. Gravity lows interpreted as transtensional basins along the Sheep Hole fault support our kinematic model (Fig. 2), but similar basins are not observed along the southwest boundary of the ETR (Richard, 1993; Langenheim and Powell, 2009). This may be due to post-rotation distributed shear, transpressional strain, and uplift close to the SAF, as seen in the Mecca and Indio Hills (e.g., Sylvester and Smith, 1976). Alternatively, the lack of basins in this belt could reflect nonrigid behavior along the southwest boundary of the ETR during transrotation. Similar transtensional elongation in the northeastern ETR should produce left separation across the Sheep Hole fault, but geologic and geophysical evidence indicate as much as 4.5 km of dextral offset on this fault (Richard, 1993; Langenheim and Powell, 2009). McQuarrie and Wernicke (2005) called for ~25 km of right slip on the Sheep Hole fault to satisfy their reconstruction of the eastern California shear zone. Thus it appears that dextral offset on the northwest-striking Sheep Hole fault is greater than sinistral separation related to clockwise rotation in the ETR.

CONCLUSIONS

Our reconstruction model yields 200 ± 14 km of total dextral displacement along the southern SAF in the Salton Trough and reconciles previously published incompatible models by incorporating the crucial effects of block rotation on the distribution of key geologic markers. This result has important implications for reconstruction of Pacific–North America plate motion in southern California and northern Mexico (e.g., Oskin and Stock, 2003; Fletcher et al., 2007). While such an analysis is beyond the scope of this paper, it is a necessary next step. When integrated with data from the eastern California shear zone, our reconstruction places a critical new constraint on the total relative plate motion accommodated by onshore faults in southern California and Arizona since 10 Ma.

ACKNOWLEDGMENTS

This study was funded by National Science Foundation grant EAR-0948170 to Dorsey. We thank Gary Axen, Scott Bennett, Ray Ingersoll, Mike Oskin, Paul Umhoefer, and Ray Weldon for insightful discussions. Critical constructive reviews by Whitney Behr, Jonathan Matti, Jon Nourse, and three anonymous reviewers helped to clarify and improve the final version of this paper.

REFERENCES CITED

Axen, G.J., 2000, Rigid microplates, deforming terrains, and the slip budgets of the southern San Andreas fault system and the Gulf of California: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. 157.

Carter, J.N., Luyendyk, B.P., and Terres, R.R., 1987, Neogene clockwise tectonic rotation of eastern Transverse Ranges, California, suggested by paleomagnetic vectors: Geological Society of America Bulletin, v. 98, p. 199–206, doi:10.1130/0016-7606(1987)98<199:NCTROT>2.0.CO;2.

Dickinson, W.R., 1996, Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system: Geological Society of America Special Paper 305, 46 p., doi:10.1130/0-8137-2305-1.1.

Dillon, J.T., and Ehlig, P.L., 1993, Displacement on the southern San Andreas fault, *in* Powell, R.E., et al., eds., The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution: Geological Society of America Memoir 178, p. 199–216.

Dolan, J.F., Bowman, D.D., and Sammis, C.G., 2007, Long-range and long-term fault interactions in southern California: Geology, v. 35, p. 855–858, doi:10.1130/G23789A.1.

Ehlert, K.W., 2003, Tectonic significance of the middle Miocene Mint Canyon and Caliente Formations, southern California, *in* Crowell, J.C., ed., Evolution of Ridge Basin, southern California: An interplay of sedimentation and tectonics: Geological Society of America Special Paper 367, p. 113–130, doi:10.1130/0-8137-2367-1.113.

Ehlig, P.L., 1981, Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges, *in* Ernst, W.G., ed., The geotectonic development of California (Rubey Volume I): Englewood Cliffs, New Jersey, Prentice-Hall, p. 253–283.

Ehlig, P.L., Ehlert, K.W., and Crowe, B.M., 1975, Offset of the Upper Miocene Caliente and Mint Canyon Formations along the San Gabriel and San Andreas faults, *in* Crowell, J.C., ed., San Andreas fault in southern California: California Division of Mines and Geology Special Report 118, p. 83–92.

Fletcher, J.M., Grove, M., Kimbrough, D., Lovera, O., and Gehrels, G.E., 2007, Ridge-trench interactions and the Neogene tectonic evolution of the Magdalena shelf and southern Gulf of California: Insights from detrital zircon U-Pb ages from the Magdalena fan and adjacent areas: Geological Society of America Bulletin, v. 119, p. 1313–1336, doi:10.1130/B26067.1.

Frizzell, V.A., Jr., Mattison, J.M., and Matti, J.C., 1986, Distinctive Triassic megaporphyritic monzogranite: Evidence for only 160 km offset along the San Andreas fault, southern California: Journal of Geophysical Research, v. 91, p. 14,080–14,088, doi:10.1029/JB091iB14p14080.

Hornafius, J.S., Luyendyk, B.P., Terres, R.R., and Kamerling, M.J., 1986, Timing and extent of Neogene tectonic rotation in the western Transverse Ranges, California: Geological Society of America Bulletin, v. 97, p. 1476–1487, doi:10.1130/0016-7606(1986)97<1476:TAEONT>2.0.CO;2.

Langenheim, V.E., and Powell, R.E., 2009, Basin geometry and cumulative offsets in the Eastern Transverse Ranges, southern California: Implications for transrotational deformation along the San Andreas fault system: Geosphere, v. 5, p. 1–22, doi:10.1130/GES00177.1.

Law, R.D., Eriksson, K., and Davisson, C., 2001, Formation, evolution, and inversion of the middle Tertiary Diligencia basin, Orocopia Mountains, southern California: Geological Society of America Bulletin, v. 113, p. 196–221, doi:10.1130/0016-7606(2001)113<0196:FEAIOT>2.0.CO;2.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California: Geological Society of America Bulletin, v. 103, p. 1528–1536, doi:10.1130/0016-7606(1991)103<1528:AMFNCR>2.3.CO;2.

Matti, J.C., and Morton, D.M., 1993, Paleogeographic evolution of the San Andreas fault in southern California: A reconstruction based on a new cross-fault correlation, *in* Powell, R.E., et al., eds., The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution: Geological Society of America Memoir 178, p. 107–159.

McQuarrie, N., and Wernicke, B.P., 2005, An animated tectonic reconstruction of southwestern North America since 36 Ma: Geosphere, v. 1, no. 3, p. 147–172, doi:10.1130/GES00016.1.

Oskin, M., and Stock, J., 2003, Pacific–North America plate motion and opening of the Upper Delfín basin, northern Gulf of California, Mexico: Geological Society of America Bulletin, v. 115, p. 1173–1190, doi:10.1130/B25154.1.

Powell, R.E., 1993, Balanced palinspastic reconstruction of pre-late Cenozoic paleogeology, southern California: Geologic and kinematic constraints on evolution of the San Andreas fault system, *in* Powell, R.E., et al., eds., The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution: Geological Society of America Memoir 178, p. 1–106.

Powell, R.E., and Weldon, R.J., II, 1992, Evolution of the San Andreas fault: Annual Review of Earth and Planetary Sciences, v. 20, p. 431–468, doi:10.1146/annurev.ea.20.050192.002243.

Richard, S.M., 1993, Palinspastic reconstruction of southeastern California and southwestern Arizona for the Middle Miocene: Tectonics, v. 12, p. 830–854, doi:10.1029/92TC02951.

Sharp, R.V., 1967, San Jacinto fault zone in the Peninsular Ranges of southern California: Geological Society of America Bulletin, v. 78, p. 705–729, doi:10.1130/0016-7606(1967)78[705:SJFZIT]2.0.CO;2.

Sylvester, A.G., and Smith, R.R., 1976, Tectonic transpression and basement-controlled deformation in San Andreas fault zone, Salton Trough, California: The American Association of Petroleum Geologists Bulletin, v. 60, p. 2081–2102.

Terres, R.R., and Luyendyk, B.P., 1985, Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vectors: Journal of Geophysical Research, v. 90, p. 12,467–12,484, doi:10.1029/JB090iB14p12467.

Manuscript received 29 November 2012
Revised manuscript received 21 April 2013
Manuscript accepted 26 April 2013

Printed in USA