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Oblique rifting ruptures continents: Example from the Gulf of California shear zone

Scott E.K. Bennett* and Michael E. Oskin
Department of Earth and Planetary Sciences, University of California–Davis, 1 Shields Avenue, Davis, California 95616, USA

ABSTRACT

We show that a belt of clockwise vertical-axis block rotation associated with dextral-oblique rifting in the Basin and Range province in Mexico hosted the localization of plate-boundary strain that led to formation of the Gulf of California ocean basin. Paleomagnetism of Miocene ignimbrites distributed widely across the rift reveals the magnitude, distribution, and timing of rotation. Using new high-precision paleomagnetic vectors ($\alpha_{95} \approx 1°$) from tectonically stable exposures of these ignimbrites in Baja California, we determine clockwise rotations up to 76° for intrarift sites. Low reference-site error permits isolation of intrarift block rotation during proto-Gulf time, prior to rift localization ca. 6 Ma. We estimate that 48% (locally 0%–75%) of the net rotation occurred between 12.5 Ma and 6.4 Ma. Sites of large (>20°) block rotation define an ~100-km-wide belt, associated with strike-slip faulting, herein named the Gulf of California shear zone, which was embedded within the wide rift Basin and Range province and kinematically linked to the San Andreas fault. After a protracted history of diffuse extension and transtension, rift localization was accomplished by focusing of Pacific–North America dextral shear into the Gulf of California, which increased strain rates and connected nascent pull-apart basins along the western margin of the province. Oblique rifting thus helped to localize and increase the rate of continental break up and strongly controlled the three-dimensional architecture of the resultant passive margins.

INTRODUCTION

Mechanisms of strain localization during continental rifting play a critical role in formation of ocean basins and the ultimate form of passive margins (Huismans and Beaumont, 2011). The Gulf of California rift formed by oblique separation across the Pacific–North America plate boundary, motion currently accommodated by a north-northwest–trending system of right-stepping, en echelon, strike-slip and oblique-slip faults that transfer strain between narrow pull-apart basins or spreading centers (Lonsdale, 1989). A majority of thinned continental crust on the rifted margins remains above sea level, exposing the recent record of rift formation (Fig. 1).

Localized extension in the Gulf of California was preceded by diffuse extension across the Basin and Range province in Mexico (Fig. 1, inset) that initiated in Oligocene time (Henry and Aranda Gomez, 1992) within the Sierra Madre Occidental, and expanded westward behind the subduction-related volcanic arc, now dissected by the Gulf of California. At the onset of proto-Gulf time (12.5 Ma), with the southward jump of the Rivera Triple Junction, the tectonic setting evolved from subduction and backarc extension to dextral transtension (Atwater and Stock, 1998). By the end of proto-Gulf time (6 Ma), at least 90% of plate motion had become localized along the western edge of this asymmetric province (Oskin et al., 2001; Miller and Lizarralde,

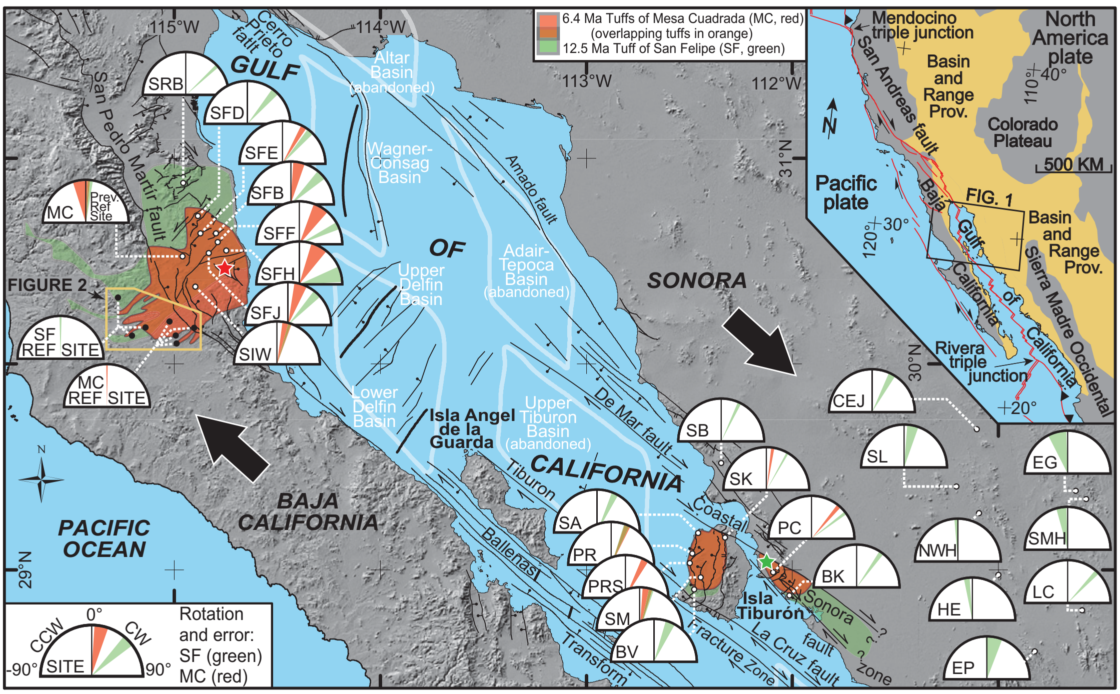

Figure 1. Extent of Miocene ignimbrites across northern Gulf of California. Pacific–North America relative plate motion (large black arrows) translated Baja California and outcrops of these ignimbrites to the northwest, relative to Sonora (North America). New paleomagnetic reference sites (black dots) are located in distal tuff outcrops of central Baja California, beyond western limit of rift-related faulting. Intrarift paleomagnetic sites (white dots) are rotated clockwise with respect to these reference sites due to dextral shear-driven block rotation. Of 11 paired sites, 7 show statistically significant larger magnitude rotation of older tuff. Site locations are provided in Table DR1 (see footnote 1). Colored stars show hypothesized ignimbrite vents from Oskin and Stock (2003b); thin black lines indicate rift-related strike-slip and normal faults; thick black lines indicate rift segment axes; white polygons outline sedimentary pull-apart basins created during formation of Gulf of California. CW—clockwise; CCW—counterclockwise. Inset: Present-day tectonic setting of western North America, showing diffuse Pacific–North America plate boundary and provinces of mid- to late Cenozoic extension (tan) (modified from Oskin and Stock, 2003b). Prov.—Province.

*Current address: U.S. Geological Survey, Geologic Hazards Science Center, 1711 Illinois Street, Golden, Colorado 80401, USA; E-mail: sekbennett@usgs.gov.

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2013), an event broadly synchronous with marine incursion and formation of a continuous Gulf of California seaway ca. 6.5–6.3 Ma (Oskin and Stock, 2003a). Focused dextral shear is well documented within the rifted margins of the northern Gulf of California (Lewis and Stock, 1998; Oskin and Stock, 2003b; Seiler et al., 2010; Bennett et al., 2013); however, the extent of this deformation and the amount that occurred prior to rift localization are unknown.

PALEOMAGNETISM OF REGIONAL IGNIMBRITES

To quantify dextral shear prior to rift localization, we compiled a transect of vertical-axis block rotations across the Pacific–North America plate boundary at lat 29°–31°N using paleomagnetism of extensive ignimbrite (welded ash-flow tuff) deposits. Two widespread ignimbrite markers that loosely bracket proto-Gulf time, the 12.5 Ma Tuff of San Felipe (SF) and the 6.4 Ma Tuffs of Mesa Cuadrada (MC), are offset by similar amounts across the northern Gulf of California (Oskin et al., 2001; Oskin and Stock, 2003b) (Fig. 1). Dextral shear may result in clockwise vertical-axis rotation, detectable by comparing paleomagnetic vectors preserved by the alignment of magnetic minerals, primarily magnetite (Nagy, 2000), in these tuffs. These vectors indicate the apparent orientation of the geomagnetic dipole field at the time the tuff cooled below the Curie temperature (500–650 °C). The eruption that produced SF blanketed >4000 km^2 (Oskin and Stock, 2003b). Paleomagnetic remanence vector directions from SF have unusually shallow inclinations (~5°), up to the southwest, associated with an apparent geomagnetic field excursion or reversal (Stock et al., 1999). MC is another widespread (>2100 km^2) ignimbrite with two distinct cooling units, Tmr3 and Tmr4 (Oskin and Stock, 2003b). MC carries a typical normal-polarity paleomagnetic remanence vector direction (Lewis and Stock, 1998).

Previous studies report paleomagnetic vectors for SF and MC from northeastern Baja California (Lewis and Stock, 1998; Stock et al., 1999; Nagy, 2000), Isla Tiburón (Oskin et al., 2001; Oskin and Stock, 2003b), coastal Sonora (Darin, 2011; Bennett et al., 2013), and central Sonora (Stock et al., 2006; Hernández-Méndez et al., 2008). These studies determine clockwise vertical-axis rotations relative to the Mesa Cuadrada reference site in Baja California (Fig. 1). Both SF and MC are gently tilted westward at Mesa Cuadrada, which is east of the rift-bounding San Pedro Martír fault. Due to the small number of collected cores ($n \leq 6$ per tuff), this reference site yields large uncertainty that propagates into all rotation calculations and prohibits detailed comparison of rotation between SF and MC.

To assess the proportion of rotation accumulated during proto-Gulf time, between eruption of SF and MC, we drilled new high-precision paleomagnetic reference sites for both tuffs in undeformed exposures in north-central Baja California, west of the San Pedro Martír fault (Fig. 2; see the GSA Data Repository[1]). Remanence directions determined here (declination, D_{SF} = 212.4°, inclination, I_{SF} = –3.0°; D_{MC} = 15.6°, I_{MC} = 56.2°) are consistent across tens of kilometers. Confidence cones (α_{95}) for multiple cores (SF = 1.3°, MC = 1.0°) are significantly smaller than those reported previously from Mesa Cuadrada (SF = 4.1°, MC = 8.9°) (Fig. 2 inset; Table DR1 in the Data Repository).

Comparisons of new paleomagnetic remanence directions from central Baja California with directions from 26 intrarift sites (2 new, 24 previously published) indicate clockwise rotations for SF and MC to 76° ± 11° and 40° ± 3°, respectively (Figs. 1 and 3; Table DR1). Mean magnitudes of the rotation errors (ΔR_{SF} = 4.9°, ΔR_{MC} = 6.3°) using these new paleomagnetic sites are lower than the rotation errors using the previous reference sites at Mesa Cuadrada (ΔR_{SF} = 6.0°, ΔR_{MC} = 13.2°), owing greatly to the larger number of cores (SF, n = 48; MC, n = 92) collected at the new reference sites. At sites where both the Tmr3 and Tmr4 cooling units of the MC were drilled, their rotations are similar. However, due to higher rotation errors for Tmr4 (Table DR1), we include only the results from Tmr3 in our analysis. At paired sites, where both SF and MC are present in the same fault block, clockwise rotation that occurred prior to 6.4 Ma is detectable by differential rotation between SF and MC. At 10 of 11 paired sites, SF is rotated clockwise by a greater amount than MC (Fig. 3). Of these 10 sites, 7 are precise enough to statistically isolate differential rotation. At paired sites, as much as 48° (weighted mean of 16°) of clockwise rotation occurred prior to 6.4 Ma. By weighting all paired site results by the differential rotation error, we estimate that 48% (locally 0%–75%) of the net rotation occurred prior to 6.4 Ma.

Overall, we find that clockwise vertical-axis rotation was widely distributed across the Basin and Range province in Mexico (Fig. 3). The lowest rotation values (error-weighted mean of 10°) are observed in central Sonora, where as many

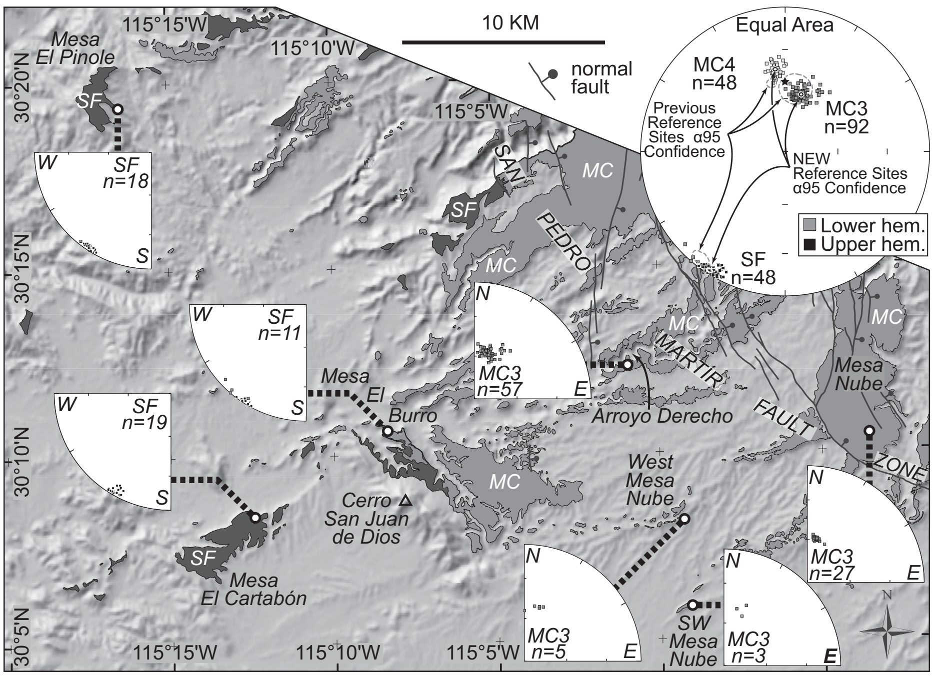

Figure 2. New paleomagnetic reference sites (white dots) are among distal, westernmost deposits of Tuffs of Mesa Cuadrada (MC) and Tuff of San Felipe (SF) in north-central Baja California. Primary natural remanent magnetization vectors for cores of SF and unit Tmr3 of MC collected in this study are plotted in stereonet quadrants tied to each drill site. Upper right stereonet shows all cores for SF tuff and both Tmr3 (MC3) and Tmr4 (MC4) cooling units of MC tuff collected in this study (hem.—hemisphere). Small white or black ellipses near center of data clusters indicate α_{95} confidence cones from new paleomagnetic drill sites; dashed gray ellipses are larger α_{95} confidence cones from previous reference sites at Mesa Cuadrada (cores not shown) (Lewis and Stock, 1998); black star shows modern-day geocentric axial dipole field location. No tilt corrections were performed. Examples of representative paleomagnetic demagnetization results are available in Figure DR2 (see footnote 1).

[1]GSA Data Repository item 2014074, paleomagnetic field and laboratory methods, panoramic field photographs of mesa-top outcrops near reference drill sites, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

sites show counterclockwise rotation as show clockwise rotation. In contrast, clockwise rotation is ubiquitous immediately surrounding the Gulf of California. Mean rotation of SF is ~36° in coastal Baja California and coastal Sonora, whereas the mean rotations for MC are only 15° and 22°, respectively. On western Isla Tiburón, concordant rotation of SF and MC (mean of ~21°) shows that prior to 6.4 Ma, before opening of the intervening Gulf of California ocean basin, this zone remained unrotated and embedded between zones of strong dextral shear in coastal Sonora and Baja California (Fig. 3).

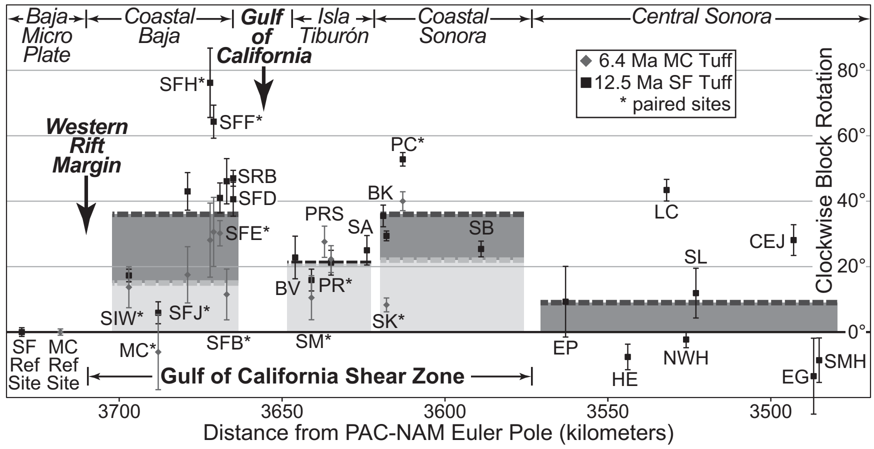

Figure 3. Paleomagnetic transect across northern Gulf of California. Plot shows updated clockwise vertical-axis block rotation at previous and new paleomagnetic drill sites of Tuff of San Felipe (SF) and Tuffs of Mesa Cuadrada (MC) using new paleomagnetic reference (Ref.) sites in central Baja California. Error-weighted mean rotation values for SF and MC from discrete tectonic zones are dashed black and gray bars, respectively. Zonal average block rotation that occurred 12.5–6.4 Ma, during proto-Gulf time, is shaded dark gray; post–6.4 Ma rotation is shaded light gray. See Table DR1 (see footnote 1) for paleomagnetic data and site locations. PAC—Pacific plate; NAM—North America plate.

DISCUSSION AND CONCLUSIONS

The results of this regional paleomagnetic study show that a narrow belt of focused dextral shear, herein named the Gulf of California shear zone (GCSZ), initiated during proto-Gulf time, was embedded within the western part of the Basin and Range province in Mexico, and probably linked northward with the San Andreas fault (Fig. 4). The Pacific–North America oblique-divergent plate boundary eventually localized within the core of this shear zone, where the Gulf of California subsequently formed (Fig. 1). After restoring the Baja California peninsula southeast to its ca. 6 Ma position (Fig. 4), the GCSZ is defined by an ~100-km-wide, north-northwest–trending transtensional belt of dextral strike-slip faulting and ubiquitous, large-magnitude clockwise vertical-axis block rotation. This rotation began between 12.5 and 6.4 Ma in coastal Baja California and coastal Sonora, and involved the intervening zone of western Isla Tiburón after 6.4 Ma. Block rotations in the GCSZ were broadly coincident, in both time and space, with rift localization (Oskin et al., 2001) and marine seaway incursion (Oskin and Stock, 2003a). Regions east of this shear zone, in central Sonora, accommodated heterogeneous and overall smaller block rotations. Two sites with large (>20°) clockwise rotation are probably associated with diffuse proto-Gulf dextral faulting here, as first proposed by Gans (1997).

Development of the GCSZ may have been caused by an ~15° clockwise shift in the azimuthal direction of Pacific–North America relative plate motion ca. 8 Ma (Atwater and Stock, 1998) that increased the obliquity of the rift and favored the development of strike-slip faults (Withjack and Jamison, 1986). We hypothesize that crustal thinning became focused within the GCSZ along en echelon pull-apart basins linked by these strike-slip faults and bounded to the west by the stable Baja California microplate. After 6 Ma, this facilitated the transition to narrow rifting and the subsequent ~250 km of northwest-southeast crustal extension on kinematically linked, large-offset normal faults (González-Fernández et al., 2005). The GCSZ is analogous to the modern-day Walker Lane

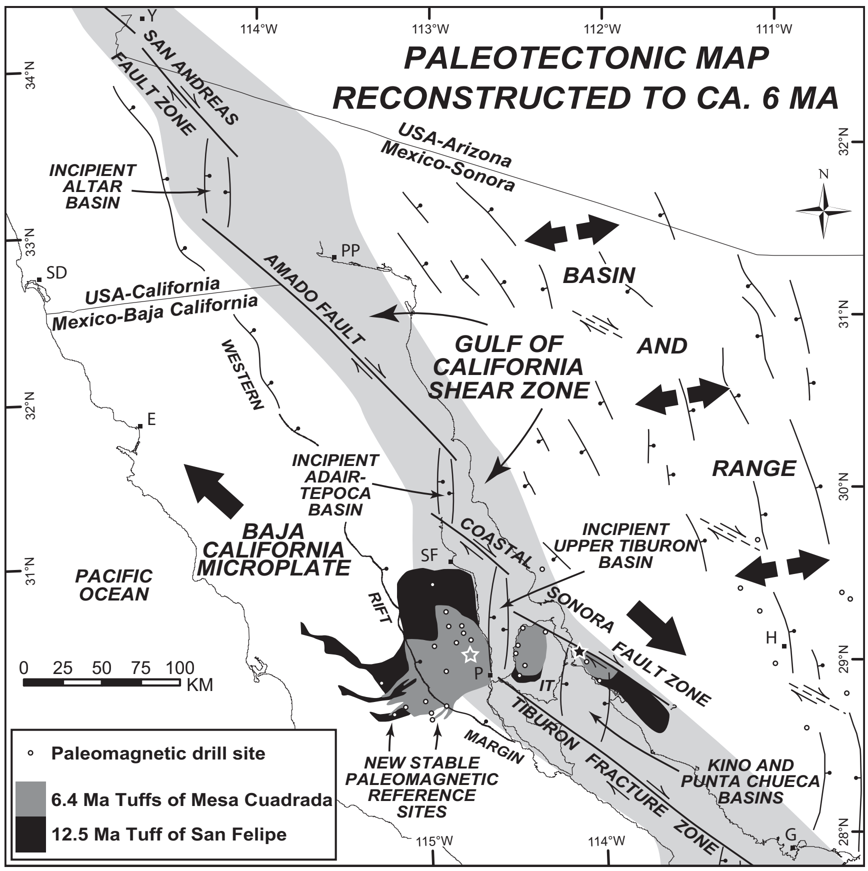

Figure 4. Palinspastic reconstruction of Pacific–North America tectonic plate boundary ca. 6 Ma. Paleomagnetic sites across northern Gulf of California (white dots) constrain ~100-km-wide Gulf of California shear zone (light gray) of incipient pull-apart basin formation, en echelon dextral strike-slip faulting, and related clockwise vertical-axis block rotation. Baja California peninsula is reconstructed to southeast (after Oskin and Stock, 2003b). Latitude and longitude grid on North America plate are modern-day coordinates; grid on Pacific plate (Baja) in modern-day coordinates, restored to their ca. 6 Ma position. Shaded stars are restored vent locations for the Tuffs of Mesa Cuadrada and Tuff of San Felipe. IT—Isla Tiburón, Y—Yuma, SD—San Diego, E—Ensenada, PP—Puerto Peñasco, SF—San Felipe, P—Puertecitos, G—Guaymas, H—Hermosillo.

transtensional belt of western Nevada and eastern California (western United States), where continental strike-slip and extensional faulting, block rotation, basin formation, and synrift volcanism occur along the western margin of the Basin and Range province, adjacent to the stable Sierra Nevada microplate (Faulds and Henry, 2008; Wesnousky, 2005).

Extension progressed for ~20 m.y. in the Basin and Range province in Mexico, but localized extension did not occur until an increase in rift obliquity and the development of strike-slip faults. Extensional pull-apart basins bounded by large-offset strike-slip faults focus crustal thinning more efficiently than orthogonal rifting (Brune et al., 2012; Van Wijk et al., 2011). In this way, an increase in obliquity may provide a mechanism to catalyze the rift localization process, accelerating the evolution from a wide to narrow rift (Buck, 1991). Resultant continental margins are likely to be structurally heterogeneous with strike-, dip-, and oblique-slip structures (e.g., Withjack and Jamison, 1986), and may be strongly asymmetric if they inherit a wide rift history formed by orthogonal or mildly oblique rifting. The record of deformation in the Gulf of California demonstrates that the degree of rift obliquity plays a fundamental role in the efficiency of localizing divergent plate boundary strain, a prerequisite for continental rupture and formation of new oceanic crust.

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