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Notes
Rapid localization of Pacific–North America plate motion in the Gulf of California

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ABSTRACT
Correlation of late Miocene volcaniclastic strata across the northern Gulf of California shows that the Pacific–North America plate boundary localized east of the Baja California peninsula ca. 6 Ma. Dextral offset of the 12.6 Ma Tuff of San Felipe and a pair of overlying ca. 6.3 Ma pyroclastic flows indicate at least 255 ± 10 km of displacement along an azimuth of 310°. Isopach and facies trends of the Tuff of San Felipe support no more than a few tens of kilometers of additional dextral displacement between 12.6 and 6.3 Ma. These constraints indicate that nearly all of the dextral displacement between the Pacific and North American plates prior to 6.3 Ma was accommodated outside of the gulf region, and by 4.7 Ma, the plate boundary motion was localized in the Gulf of California. Although continental extension has accounted for a component of plate boundary motion in northwestern Mexico since cessation of subduction offshore of southern Baja California at 12.5 Ma, transfer of Baja California to the Pacific plate was delayed by at least 6–7 m.y.

Keywords: Gulf of California, Mexico, rifting, plate motion, ignimbrite, correlation.

INTRODUCTION
The Gulf of California is one of a few active examples of the transition from continental rifting to seafloor spreading. The opening of the gulf is directly related to dextral motion on the San Andreas fault (Larson et al., 1968; Fig. 1) following the cessation of subduction and microplate capture west of southern Baja California (Atwater, 1970; Mammerickx and Klitgord, 1982). However, only 300–350 km of the expected 500–600 km of post–12 Ma displacement between the Pacific and North American plates has been accommodated as transform slip within the gulf, the remainder being partitioned on faults west of Baja California (Spencer and Normark, 1979; Stock and Hodges, 1989). Transfer of Baja California to the Pacific plate by 3.5 Ma is evident from the formation of magnetically lineated oceanic crust at the Alarcon Rise in the mouth of the gulf (Lonsdale, 1989). The timing and location of plate boundary motion between 12.5 and 3.5 Ma, and any amount of pre–12.5 Ma strike slip, is not defined from within the gulf or its surrounding extensional province. From previous studies, it remains unclear whether the northwestward acceleration of Baja California was a gradual process beginning at 12.5 Ma or an abrupt event 6–7 m.y. later. Commonly, it is assumed that Baja California joined the Pacific plate at or near the full plate motion rate, sufficient to open the gulf at 5 to 6 Ma (Curray et al., 1982; Dickinson, 1996). The evidence for this timing is not conclusive. Dextral displacement on the southern San Andreas fault and extension and marine deposition in the gulf region began as early as 12 Ma (Stock and Hodges, 1989; Welldon et al., 1993; Lee et al., 1996; Helens and Carreño, 1999). Acceleration of Baja California at 3.5 Ma has been proposed (Lonsdale, 1989; Umhoefer et al., 1994) and the full Pacific–North America plate motion may not have occurred in the gulf until 1 Ma (DeMets, 1995).

We present a new set of cross-gulf geologic tie points that define the timing, magnitude, and rate of dextral shear in the gulf. Three distinctive pyroclastic flows correlate lithologically, geochemically, and paleomagnetically from the northern Puertecitos Volcanic Prov-

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ince of Baja California, across the gulf to Isla Tiburón and the adjacent coast of Sonora. These units are the 12.6 Ma Tuff of San Felipe (Stock et al., 1999), and a pair of ca. 6.3 Ma tuffs, Tmr3 and Tmr4, that overlie the Tuff of San Felipe (Stock, 1989; Lewis, 1996; Nagy et al., 1999).

**TUFFS OF THE PUERTECITOS VOLCANIC PROVINCE**

The Puertecitos Volcanic Province records the transition from the early Miocene andesitic arc to rift-related, bimodal volcanism (Martín-Barajas et al., 1995; Fig. 1). The synrift section here is dominated by a few extensive welded tuffs (Stock, 1989, 1993; Martín-Barajas et al., 1995; Lewis, 1996; Nagy et al., 1999). Thickening and facies trends of several of these tuffs indicate vent locations adjacent to the modern gulf coastline (Lewis, 1994; Stock et al., 1999), making these ideal targets for cross-gulf correlation.

Characteristic lithologic features of the Tuff of San Felipe are dense welding, 3%–15% phenocrysts (anorthoclase ≈ Fe-Ti oxides ≈ clinopyroxene), rare accidental lithics, and variably abundant distinctive, dark pods of rhyolite with 20% phenocrysts (alkali feldspar ≈ Fe-Ti oxides ≈ clinopyroxene ≈ fayalite). 40Ar/39Ar age determinations suggest that the Tuff of San Felipe is about 12.6 Ma in age (Stock et al., 1999).

The Tmr3 and Tmr4 ignimbrites form a distinctive package of similar extent with parallel changes in thickness and welding grade. Characteristic lithologic features of Tmr3 are partial welding, 5%–10% centimeter-sized, mostly volcanic lithics, and 10%–15% phenocrysts (alkali feldspar ≈ magnetite ≈ pyroxene ≈ zircon ≈ basaltic hornblende ≈ biotite ≈ fayalite). 40Ar/39Ar age determinations suggest that Tmr3 is about 6.3 m.y. old (Lewis, 1996; Nagy et al., 1999). Tmr4 is a densely welded vitric ash-flow tuff with rare phenocrysts and volcanic lithic inclusions. Tmr4 is undated, but stratigraphic evidence suggests that Tmr3 and Tmr4 together form a single eruptive sequence (Stock, 1989; Lewis, 1994). These units are grouped together for correlation (Fig. 1).

**CORRELATION**

The likely location of correlative deposits is the coastal region of Sonora and Isla Tiburón. Gastil and Krummenacher (1977) identified an extensive cover of volcaniclastic strata here, which they recognized as potentially correlative to the Puertecitos Volcanic Province. Northeastern Baja California and coastal Sonora also share a correlative Tertiary conglomerate (Gastil et al., 1973; Fig. 1) and Paleozoic stratigraphic trends (Gastil et al., 1991) supporting ~300 km of separation between these areas.

Our reconnaissance investigations identified ash-flow tuffs lithologically similar to the Tuff of San Felipe, Tmr3, and Tmr4 in coastal Sonora and Isla Tiburón (Fig. 1). To confirm correlation, several geochemical tests were applied. Feldspar and pyroxene phenocrysts from the Tuff of San Felipe, Tmr3, and from potential correlative ignimbrites in Sonora were analyzed in thin section by electron microprobe (Fig. 2). Both phenocryst composition and zonation are distinctive in these ignimbrites. The phenocrysts of samples from correlated deposits on Isla Tiburón and coastal Sonora are identical to those measured from the Tuff of San Felipe in Baja California (Fig. 2, Tables DR1–DR8). Whole-rock chemical analyses also support correlation (Table DR9; see footnote 1). 40Ar/39Ar age determinations of Sonoran samples are in progress to further validate these correlations.

Paleomagnetic remanence directions also verify the correlation of the tuffs (Fig. 3, Table DR10; see footnote 1). Remanent magnetic vectors were measured following the procedures outlined in Stock et al. (1999). The Tuff of San Felipe yields a distinctive, low-inclination reversed polarity vector of magnetization (Stock et al., 1999). Samples of similar tuff from Sonora also yielded low-inclination reversed polarity directions. Tmr3 and Tmr4 from Baja California yield a distinctive pair of moderate-inclination normal polarity vectors. Tmr4 has consistently lower inclination and is counterclockwise to Tmr3. Remanent magnetization of Tmr3 and Tmr4 from Isla Tiburón yield similar vector pairs, supporting correlation of these units.

Thickness and welding grade of the Tuff of San Felipe and the distribution of Tmr3 and Tmr4 are used to match opposite sides of the Gulf of California (Fig. 3). The Tuff of San Felipe in Baja California has a semicircular thickness pattern, centered on an area of higher grade, near-vent deposits in the eastern Sierra San Felipe (Stock et al., 1999). The isopachs of the correlative deposits in Sonora are complex. The thickest deposits and possible intracaldera facies are preserved near the Sonoran coastline. Outcrops on Isla Tiburón fill west-trending paleocanyons; higher grade deposits are present on the northern part of the island. The distribution of Tmr3 and Tmr4 is more uniform and restricted than the Tuff of San Felipe. Thick welded deposits occur in the Sierra Menor on Isla Tiburón and adjacent to the Jurassic–Cretaceous volcanic areas covered by younger rhyolitic lava and ignimbrites near the present-day coastline of Baja California (covered area of Fig. 3).

**DISCUSSION**

The identical lithologic, geochemical, and paleomagnetic characteristics of the outcrops in coastal Sonora and Isla Tiburón confirm that these deposits are displaced parts of tuffs known from Baja California. We restore 255 ± 10 km of right slip between Baja California and Sonora, along an azimuth of 310° defined by the Tiburón Fracture Zone and Ballenas transform (Figs. 1 and 3). This restoration brings into proximity the correlative ignimbrite outcrops, as well as older correlative conglomerates described by Gastil et al. (1973). The map-view restoration (Fig. 3) does not account for the effects of additional distributed dextral shear and east-west exten-
sion in the study area. The division of slip onto the Ballenas transform and the Tiburón Fracture Zone (Fig. 1) depends upon the restoration of Isla Angel de la Guarda to an un-

certain position south of Isla Tiburón (Lonsdale, 1989; Stock, 2000). This uncertainty does not affect the summed dextral displacement measured here.

Although a palinspastic reconstruction is beyond the scope of this paper, the map-view restoration defines the strike-slip history in the gulf. Extension in this area during the interval from 12.6 to 6.3 Ma (Stock, 1989; Stock et al., 1991; Lewis and Stock, 1998b; Nagy, 2000) was not accompanied by enough dextral shear to significantly displace the Tuff of San Felipe or the older correlative conglomerate of Gastil et al. (1973) more than a few tens of kilometers before deposition of Tmr3 and Tmr4. Comparison of the offset of 255 ± 10 km with estimates of plate motion from plate circuit analyses indicates that localization of strike slip into the gulf probably occurred during a short (1–2 m.y.) window during late Miocene–early Pliocene time (Table 1). This window is largest if the Pacific–North America rate is applied to the gulf. If the spreading rate in the Gulf was 10%–15% less than the Pacific–North America rate until 1 Ma (DeMets, 1995), then the time to acquire 255 ± 10 km of offset overlaps the age of Tmr3. Significant acceleration of Baja California both at 3.5 Ma and at 1 Ma are incompatible with the total amount of offset recorded since 6.3 Ma.

CONCLUSIONS

The locations of correlative deposits of the 12.6 Ma Tuff of San Felipe, and ca. 6.3 Ma Tmr3 and Tmr4 ignimbrites suggest at least 255 ± 10 km of transform displacement across the northern Gulf of California. These results agree well with models of the San Andreas fault system in southern California that partition significant strike slip into the gulf after 6 Ma (e.g., Crowell, 1981; Curray et al., 1982; Matti and Morton, 1993; Dickinson, 1996). Localization of plate boundary slip in the Gulf of California was a rapid transition from extension and minor dextral motion prior to 6.3 Ma, to the principal plate boundary by 4.7 Ma. Transfer of the Baja California peninsula to the Pacific plate was delayed 6±7 m.y. after microplate capture and initiation of transform faulting west of southern Baja California.

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**Figure 3. Map-view restoration of 255 ± 10 km of transform offset, at azimuth of 310°, across northern Gulf of California. Modern shorelines are shown for reference. Baja California is rotated 2.3° counterclockwise. Correlative, pre±15 Ma conglomerate outcrops (white, surrounded by white-dash boxes) are from Gastil and Krummenacher (1977) and Bryant (1986). Black is Tuff of San Felipe; gray is Tmr3 and Tmr4. See Figure 1 for sources of mapping for Baja California. Numbers are thicknesses in meters of Tuff of San Felipe. Small white boxes indicate sample localities. SFB, SFD, SFE, SFJ, and SFH are localities from Sierra San Fermín; SA—Sierra Alta; PRS—south of Punta Reina. Other abbreviations as in Figure 1. Inclination-declination plots are compilation of primary paleomagnetic remanence directions from Tuff of San Felipe, Tmr3, and Tmr4 from individual localities on both sides of gulf. Data in Baja California are from Lewis and Stock (1998a), Stock et al. (1999), and Nagy (2000). Shaded ellipses denote area of 95% confidence. Plots are lower hemisphere, equal area projection, with reversed inclination results projected from upper hemisphere. MC is considered unrotated reference locality. All other localities show clockwise vertical-axis rotation.**

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**TABLE 1. COMPARISON OF POTENTIAL DISPLACEMENT RATES ACROSS THE NORTHERN GULF OF CALIFORNIA**

<table>
<thead>
<tr>
<th>Rate (mm/yr)</th>
<th>Time interval (Ma)</th>
<th>Time to 255 km (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alarcon Rise (DeMets, 1995)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.9 ± 2.1</td>
<td>0–1.03</td>
<td></td>
</tr>
<tr>
<td>41.0 ± 1.9</td>
<td>1.03–3.16**</td>
<td>6.1 ± 0.3</td>
</tr>
<tr>
<td>Nuvel-1A (DeMets and Dixon, 1999)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49.5 ± 0.8</td>
<td>0–3.16**</td>
<td>5.1 ± 0.1</td>
</tr>
<tr>
<td>Plate circuit (Atwater and Stock, 1998)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>0–5.105</td>
<td>47</td>
</tr>
</tbody>
</table>

*Rates calculated for a point on the Tiburón Fracture Zone, 28.8°N 112.5°W (Fig. 1).

**Interval between magnetic anomalies used to calculate rate.

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