Pacific–North America plate motion and opening of the Upper Delfín basin, northern Gulf of California, Mexico

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ABSTRACT

Correlation of conjugate rifted margins of the Upper Delfín basin constrains the timing and amount of transtensional opening along the Pacific–North America plate boundary in the northern Gulf of California. Lithologic, geochemical, paleomagnetic, and geochronologic data from a set of four ignimbrites, consisting of eight distinctive cooling units, are shown to correlate from northeastern Baja California to Isla Tiburón and adjacent areas of western Sonora. These matching ignimbrites are the ca. 12.6 Ma tuff of San Felipe, the 6.3 ± 0.2 Ma tuffs of Mesa Cuadrada (Tmr3 and Tmr4), the tuffs of Dead Battery Canyon (Tmr5), and the 6.1 ± 0.5 Ma tuffs of Arroyo El Canelo. Offset distributions and facies patterns of these ignimbrites support 255 ± 10 km of opening between conjugate rifted margins of the Upper Delfín basin. Addition of deformation from the continental margins of this basin indicates at least 276 ± 13 km of Pacific–North America plate motion between coastal Sonora and the main gulf escarpment in Baja California since ca. 6 Ma; a further 20 ± 10 km of northwestward displacement of Isla Tiburón relative to coastal Sonora occurred sometime after 12.6 Ma. These reconstructions agree with earlier estimates of slip across the Gulf of California and on the San Andreas fault system of southern California, but require that the Pacific–North America plate boundary became localized in the gulf at ca. 6 Ma. The restored continental margins of the Upper Delfín basin show that only a 20–25 km width of upper continental crust has thinned beneath this part of the northern Gulf of California.

INTRODUCTION

The Gulf of California of southwestern North America (Fig. 1) presents an exceptional opportunity to examine the formation of a young ocean basin within an evolving continental orogen. Opening of the Gulf of California is the result of transform motion and extension between the Pacific plate and the North America plate (Atwater, 1970). The tectonic setting of the Gulf of California and southwestern North America (Fig. 1) is well understood from the perspective of continental geology (Burchfiel et al., 1992; Stewart, 1998; Stock and Hodges, 1989; Gastil et al., 1991) and from marine plate-tectonic studies (Stock and Molnar, 1988; Lonsdale, 1989; Atwater and Stock, 1998). Opening of the Gulf of California followed the termination of subduction west of Baja California Sur at 12.5 Ma (Mammerickx and Klitgord, 1982; Spencer and Normark, 1979). Magnetic lineations at the mouth of the Gulf of California record >85% of Pacific–North America plate motion since 3.5 Ma and >95% of the plate motion since 1 Ma (DeMets, 1995; DeMets and Dixon, 1999; Dixon et al., 2000).

Continental geologic records define the tectonic history of the Gulf of California prior to 3.5 Ma. Offset Paleozoic metasedimentary rocks, Mesozoic batholithic rocks, and Tertiary conglomerates indicate that ~300 km of dextral displacement has occurred in the Gulf of California (Silver and Chappell, 1988; Gastil et al., 1991, 1973) (Fig. 1). Geologic relationships in southern California indicate that most or all of this displacement occurred after 12 Ma (Ehlig et al., 1975; Crowell, 1981). Correlation of synrift pyroclastic deposits from the Puertecitos volcanic province of Baja California to Isla Tiburón and coastal Sonora supports 255 ± 10 km of opening of the Upper Delfín basin of the northern Gulf of California during latest Miocene time. With adequate geologic control, fundamental tectonic problems such as the roles of strain rate, preexisting weaknesses, and strain partitioning in localizing continental rifting may be addressed from the geology of the Gulf of California. Critical geologic parameters from the Gulf of California are the rate of transfer of Baja California to the Pacific plate and the amount of crustal attenuation that accompanied this transfer. Until recently, no record has been documented that directly measured total offset, offset rate, and crustal attenuation in the Gulf of California.

This paper expands on the initial findings reported by Oskin et al. (2001) to document a complete record of Pacific–North America plate motion in the northern Gulf of California and its surrounding rifted continental margin. Four principal pyroclastic flow deposits, consisting of a total of eight separate cooling units, are correlated from Baja California to Isla Tiburón and coastal Sonora. Oskin et al. (2001) described initial results from matching two of these pyroclastic flow deposits: the ca. 12.6 Ma tuff of San Felipe, consisting of a single cooling unit (Stock et al., 1999), and the 6.3 ± 0.2 Ma tuffs of Mesa Cuadrada.
OSKIN and STOCK

Figure 1. Tectonic map of southwestern North America. Shaded areas represent Basin and Range province (light gray) and Gulf extensional province (dark gray). Present-day plate boundaries shown as dark lines. Inactive plate boundaries shown as gray lines. Distinctive conglomerate outcrops denoted by circled letters: P—Poway conglomerate of Abbott and Smith (1989); F—Conglomerate with distinctive Permian fusulinid-bearing limestone clasts of Gastil et al. (1973). AB—Agua Blanca fault; E—Elsinore fault; ETR—eastern Transverse Ranges; SG—San Gabriel fault; SJ—San Jacinto fault; ST—Salton Trough; WTR—western Transverse Ranges.

(new name), consisting of two primary cooling units named Tmr3 and Tmr4 (Stock, 1989; Lewis, 1996; Nagy et al., 1999). The study presented here elaborates on these correlations and establishes additional matches of one cooling unit of the ca. 6.3 Ma, ca. 6 Ma, and ca. 3 Ma (Stock et al., 1999; Stock, 2000). Detailed mapping in the northern Puertecitos volcanic province indicates sources for these deposits near the present-day western shore of the Gulf of California (Stock et al., 1991; Martín-Barajas et al., 1995; Lewis, 1994; Nagy, 1997). These widespread ignimbrites in Baja California with eastern sources comprise ideal candidates for cross-gulf correlation (Stock et al., 1999; Nagy et al., 1999). A likely target for correlation is the coastal area of central Sonora, located ~300 km southeast of the Puertecitos area. Reconnaissance mapping of coastal Sonora indicates a similar, extensive middle to late Miocene volcanic cover adjacent to the eastern shoreline of the Gulf of California (Gastil and Krummenacher, 1974, 1977).

Remapping of a distinctive Tertiary conglomerate—first correlated across the Gulf of California by Gastil et al. (1973)—supports that this unit is a robust geologic tie point. Inspection of the basement to cover transition over a large area of both northeastern Baja California and coastal Sonora confirms that outcrops of the distinctive conglomerate are limited to the two previously mapped areas (Gastil and Krummenacher, 1974; Bryant, 1986; Oskin and Stock, 2003b; distinctive conglomerate in Fig. 2). Outcrop patterns in the Sierra Seri of coastal Sonora suggest a single southwest-directed channel. Outcrops in Baja California appear to have been isolated as a terrace deposit by 12.6 Ma. Correlation of these outcrops suggests ~300 km of displacement across the Gulf of California (Gastil et al., 1973). The uncertainty of this displacement is difficult to estimate because only...
The Tuff of San Felipe

The tuff of San Felipe (Figs. 3 and 4) may be recognized in the field from its distinctive welding zonation, phenocrysts, and rhyolite lava inclusions (Table 1). Geochemical analyses consistently show distinctive anorthoclase and zoned pyroxe phenocrysts (Table 1) and high Nb, Ce, Rh, and La (Table 2). Primary thermal remanent magnetization of the tuff of San Felipe preserves an unusual low-inclination reversed-polarity direction (Stock et al., 1999; Oskin et al., 2001). Most sample localities of the tuff of San Felipe in Baja California and Sonora yielded consistent paleomagnetic results with evidence for clockwise vertical-axis rotation of as much as 50° between sample localities (Lewis and Stock, 1998a; Nagy, 2000; Table DR1).

Isotopic ages of the tuff of San Felipe and other bracketing units in Baja California are consistent with an age of ca. 12.6 Ma for this tuff, although individual, well-dated samples range from 13.0 ± 0.2 Ma to 10.6 ± 0.1 Ma (Stock et al., 1999). Ages spanning this range but with high uncertainty (9.7 ± 1.3 Ma to 13.9 ± 2.2 Ma) have been measured from the tuff of San Felipe in coastal Sonora and Isla Tiburón (Oskin, 2002). Argon loss may have contributed to anomalously younger ages. Older ages are associated with thick, higher-grade tuff outcrops with a higher percentage of rhyolitic inclusions. Macroscopic evidence for plastic deformation and petrographic evidence for disaggregation of these inclusions suggest that they may be contaminating the age data, as first proposed by Lewis (1994). Additional study is under way to separately date these inclusions and to clarify the isotopic age of the tuff of San Felipe.

The tuff of San Felipe provides a robust match across the northern Gulf of California. At 160 km³, it forms the largest-volume pyroclastic flow deposit in coastal Sonora (Oskin, 2002). The tuff of San Felipe preserves an unusual low-inclination reversed-polarity direction (Stock et al., 1999). Ages spanning this range but with high uncertainty (9.7 ± 1.3 Ma to 13.9 ± 2.2 Ma) have been measured from the tuff of San Felipe in coastal Sonora and Isla Tiburón (Oskin, 2002). Argon loss may have contributed to anomalously younger ages. Older ages are associated with thick, higher-grade tuff outcrops with a higher percentage of rhyolitic inclusions. Macroscopic evidence for plastic deformation and petrographic evidence for disaggregation of these inclusions suggest that they may be contaminating the age data, as first proposed by Lewis (1994). Additional study is under way to separately date these inclusions and to clarify the isotopic age of the tuff of San Felipe.

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The tuff of San Felipe provides a robust match across the northern Gulf of California. At 160 km³, it forms the largest-volume pyroclastic flow deposit in the study area and covers >4000 km² (Fig. 4 and Table 3). This ignimbrite is likely to have erupted from near the present-day mainland Sonora coastline at Punta Chueca (Fig. 4). The ca. 12.6 Ma age and stratigraphic position of the tuff of San Felipe make this ignimbrite ideal to measure the total dextral displacement across the Gulf of California since the onset of rifting after 12 to 11 Ma (Stock et al., 1999).

Distribution of the tuff of San Felipe west of coastal Sonora occurred through west-
Sierra Kunkaak is the only known pathway for the northern Puertecitos volcanic province. A trend of paleocanyons on Isla Tiburo and in western Isla Tiburón (Fig. 4). Additional pathways may exist in unmapped areas of the Sierra Kunkaak or beneath the channel between Isla Tiburón and the mainland. On the southern part of the conjugate margin in northeastern Baja California, the tuff of San Felipe also occupies trending paleocanyons on Isla Tiburón and in the northern Puertecitos volcanic province. A single 3-km-wide paleocanyon in the northern Sierra Kunkaak is the only known pathway for the tuff of San Felipe between coastal Sonora and western Isla Tiburón (Fig. 4). Additional pathways may exist in unmapped areas of the Sierra Kunkaak or beneath the channel between Isla Tiburón and the mainland. On the southern part of the conjugate margin in northeastern Baja California, the tuff of San Felipe also occupies
TABLE 2. TRACE ELEMENT ANALYSES AND COMPARISON OF CORRULATIVE TUFFS

| Trace element (ppm) | Tuff of San Felipe | Tmr3 | Tmr4 | Other PVP rhyolite
<table>
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<tr>
<td></td>
<td>Coastal Sonora1</td>
<td>Isla Tiburón3</td>
<td>Baja California4</td>
<td>S. San Fermín5</td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>51.8</td>
<td>52.6</td>
<td>48.1±51.9</td>
<td>53.6</td>
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<tr>
<td>U</td>
<td>5</td>
<td>5</td>
<td>4-5</td>
<td>4</td>
</tr>
<tr>
<td>Rb</td>
<td>176.3</td>
<td>195.4</td>
<td>166-188</td>
<td>155.6</td>
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<tr>
<td>Th</td>
<td>17</td>
<td>18</td>
<td>16-18</td>
<td>12</td>
</tr>
<tr>
<td>Pb</td>
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<td>24.6</td>
<td>25</td>
<td>22.5±24.4</td>
<td>20.5</td>
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<tr>
<td>Zr</td>
<td>315</td>
<td>321</td>
<td>384-402</td>
<td>328</td>
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<td>Sr</td>
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<td>Ce</td>
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<td>94</td>
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<td>Ba</td>
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<tr>
<td>La</td>
<td>54</td>
<td>56</td>
<td>54-56</td>
<td>43</td>
</tr>
</tbody>
</table>

Note: Trace element analyses (XRF [X-ray fluorescence]) were done at the University of Massachusetts, Amherst. See Rhodes (1988) for typical values of analytical precision from this facility. Analyses reprinted from Oskin et al. (2001) Data Repository.
1Sample number BK-99-09, 29.880'N, 112.001°W.
2Sample number BV-98-08, 29.979°N, 112.458°W.
3Range of values for samples of the Tuff of San Felipe from Baja California (Stock et al., 1999).
4Sample number SF-92-64, 30.594°N, 114.756°W.
5Sample number BV-98-08, 29.917°N, 112.447°W.
6Sample number SF-92-101, 30.566°N, 114.790°W.
7Sample number TIB-98-17, 29.879°N, 112.476°W.
8Range of values for other high-SiO2 rhyolite samples from the Puertecitos area reported by Martín-Barajas et al. (1995). PVP—Puertecitos volcanic province.

Paleocanyons cut into volcanioclastic strata (Fig. 4). In the northern Sierra San Fermín and the adjacent Sierra San Felipe, the tuff of San Felipe formed a sheet ponded over basement rock, arkosic sandstone, and locally derived fluvial deposits. The thickest and highest-grade deposits of the tuff of San Felipe occur in the northern Sierra San Fermín and adjacent parts of the Sierra San Felipe, northern Isla Tiburón, and mainland coastal Sonora (Fig. 4). The southern limit of the tuff of San Felipe may also correlate across the Gulf of California, but a cover of younger volcanic rocks limits exposures. The northern limit of the tuff of San Felipe on the Sonoran margin appears to have been controlled by paleotopography. Outcrops north of Isla Tiburón may be flooded by the Gulf of California or possibly were removed by erosion.

The Tuffs of Mesa Cuadrada

The tuffs of Mesa Cuadrada (Figs. 5 and 6) comprise two cooling units, Tmr3 and Tmr4, with intercalated Tmr3b nonwelded pyroclastic deposits. Tmr3 and Tmr4 form a distinctive pair of flow deposits with contrasting lithology and paleomagnetic remanence (Table 1). Geochemical analyses (Table 2) show that, similar to the tuff of San Felipe, cooling unit Tmr3 is also higher in Nb, Ce, Rb, and La than any other silicic rocks from the Puertecitos volcanic province measured by Martín-Barajas et al. (1995). The concentrations of these and other trace elements in Tmr3 are distinct from the tuff of San Felipe, as are the compositions of feldspar and pyroxene phenocrysts (Oskin et al., 2001). Isotopic ages of Tmr3 from the Isla Tiburón overlap isotopic ages of 6.3 ± 0.2 Ma for Tmr3 from Baja California (Stock, 1989; Lewis, 1996; Nagy et al., 1999; Oskin, 2002) (Table 1). A sample of Tmr3 from western Isla Tiburón (Fig. 6) was dated by Gastil et al. (1979) at 5.7 ± 0.6 Ma (sample no. 1012, K-Ar on feldspar).

On the basis of paleomagnetic measurements, Nagy (2000) distinguished two types of Tmr3 and suggested that neither Tmr3 (type 1) nor Tmr3b (type 2) of Santa Isabel Wash may be correlative to Tmr3 units mapped by Lewis and Stock (1998a). Reexamination of individual sample localities reveals that the range-wide averaging technique used by Nagy (2000) to test these correlations included more samples of Tmr4 from a zone of greater clockwise vertical-axis rotation in the southern Sierra San Fermín (Lewis, 1994). This approach biased the average declination for Tmr4 relative to the average declination of Tmr3 units from the Sierra San Fermín; the result was that the Tmr3 units of Lewis and Stock (1998a) appeared paleomagnetically distinct from the Tmr3 of Santa Isabel Wash. By using individual sample localities from the Sierra San Fermín instead of a range-wide average, we find that the inclination and declination of Tmr3 (type 2) and Tmr3b relative to Tmr4 are consistent throughout the Baja California margin and consistent with Tmr3 outcrops on Isla Tiburón (Oskin et al., 2001). Distinct remanent paleomagnetic directions from unit Tmr3 (type 1) of Santa Isabel Wash and unit Tmr3a of the Sierra San Fermín support the interpretation that these units are individual, local members of the tuffs of Mesa Cuadrada.

The distribution and facies of the tuffs of Mesa Cuadrada correlate closely between northeastern Baja California and Isla Tiburón. These ignimbrites comprise the largest of the ca. 6.3 to 6.1 Ma tuffs in both volume and areal extent, covering over 2100 km² with ~120 km³ of pyroclastic deposits (Table 3). The northern extent of outcrops is well exposed in the northern Sierra San Fermín and Sierra San Felipe of Baja California and the Sierra Alta of Isla Tiburón (Fig. 6). The southern extent of outcrops is well exposed in the Sierra Menor of Isla Tiburón but obscured by younger volcanism in the Puertecitos area of Baja California. Thick, higher-grade deposits of the tuffs of Mesa Cuadrada crop out adjacent to the eastern part of Arroyo Matomõ, in the southern Sierra San Fermín, and in the Santa Isabel Wash area in Baja California and the central Sierra Menor of Isla Tiburón (Fig. 6).

Facies changes within the tuffs of Mesa Cuadrada associated with younger rhyolitic volcanism suggest a vent for this ignimbrite located within a 20–30-km-diameter area centered at the eastern end of Arroyo Matomõ (Fig. 6). In Baja California, abrupt thickness changes in higher-grade Tmr4 occur southeast of Mesa Cuadrada, at Santa Isabel Wash, and in the southern Sierra San Fermín. These abrupt thickness changes may reflect underlying topographic relief caused by subsidence due to a prior eruption (e.g., Tmr3) and are inferred here to overlie caldera-collapse structures (Fig. 6). This same region encloses an area of extensive rhyolite lava flows and late Miocene and younger andesite volcanoes that probably filled in the collapsed area (Oskin and Stock, 2003b).

Tuffs of Dead Battery Canyon

The tuffs of Dead Battery Canyon (Figs. 7 and 8) in Baja California form two nearly identical cooling units, Tmr5 and Tmr6 (Table 1). Pumice and phenocryst content of outcrops on Isla Tiburón best supports correlation to cooling unit Tmr5. Cooling units Tmr5 and Tmr6 in Baja California both preserve normal-
polarity, moderate-inclination paleomagnetic remanence directions; those of Tmr6 are steeper and clockwise of unit Tmr5 (Lewis and Stock, 1998a). Paleomagnetic remanence of the one cooling unit present on Isla Tiburón is consistent with the overall paleomagnetic directions of Tmr5 and Tmr6 from Baja California, but it is not distinctive of either Tmr5 or Tmr6 given the uncertainties present in the data (Table DR1 [see footnote 1]).

The tuffs of Dead Battery Canyon may be an uppermost cooling unit of the tuffs of Mesa Cuadrada. This possibility was suggested by Lewis (1994), who observed that the tuffs of Dead Battery Canyon are lithologically similar to and conformably overlie Tmr4 in the Sierra San Fermín. Younger units, including a possible correlative to the tuffs of Arroyo El Canelo (Tmr8, Table 1) overlie the tuffs of Dead Battery Canyon with a slight angular unconformity (Lewis, 1994). This same relationship appears on Isla Tiburón at Punta Reina where the tuffs of Dead Battery Canyon conformally overlie the tuffs of Mesa Cuadrada but are overlain with slight angular unconformity by the El Oculto member of the tuffs of Arroyo El Canelo (Fig. 7). Although the tuffs of Dead Battery Canyon have not been dated, these relationships suggest an age close to the ca. 6.3 Ma Tmr3 cooling unit of the tuffs of Mesa Cuadrada.

The tuffs of Dead Battery Canyon cover a restricted area on both margins of the northern Gulf of California (Fig. 8). The maximum thickness of these tuffs occurs where two cooling units (Tmr5 and Tmr6) are present in Baja California. Thick deposits of the Tmr5 cooling unit are present in the Punta Reina area of Isla Tiburón. The tuffs of Dead Battery Canyon have the lowest volume of any unit that has been found to correlate across the northern Gulf of California. Known outcrops of the tuffs of Dead Battery Canyon cover 160 km² with ~4 km³ of pyroclastic deposits (Table 3). The northern limit of the tuffs of Dead Battery Canyon is well exposed in the central Sierra San Fermín of Baja California and the northern Sierra Menor of Isla Tiburón. These ignimbrites thin southward to zero thickness in the Sierra Menor and are buried by younger rhyolite lava flows in the southernmost Sierra San Fermín (Fig. 8). The tuffs of Dead Battery Canyon do not appear to extend south of Arroyo Matomí in Baja California.

The Tuffs of Arroyo El Canelo

The tuffs of Arroyo El Canelo are a completely zoned ignimbrite with at least four distinct cooling units of a complexly zoned ignimbrite (Figs. 7 and 9; Table 1). The stratigraphic definition of these tuffs is based upon the exposures in the Santa Isabel Wash region (Nagy et al., 1999). The units designated as members of the tuffs of Arroyo El Canelo in this study were given separate names by Nagy et al. (1999). These lithologically distinctive members are the tuff of Arroyo El Oculto, the tuff of Arroyo El Canelo (with one or more cooling breaks), the Big-horn Sheep Tuff, and the Flagpole Tuff (Table 1). Correlation of the tuffs of Arroyo El Canelo has not been confirmed by geochemical or paleomagnetic analyses. However, the complex zonation of the tuff of Arroyo El Canelo is consistent between the Sierra Santa Isabel of Baja California and western Isla Tiburón. Plagioclase phenocrysts from the El Canelo member from Santa Isabel Wash were isotopically dated as 6.1 ± 0.5 Ma by Nagy et al. (1999).

The four cooling units of the tuffs of Arroyo El Canelo cover >700 km² with ~45 km³ of pyroclastic deposits (Fig. 9 and Table 3). Outcrops of the tuffs of Arroyo El Canelo occur south of the tuffs of Dead Battery Canyon and partly overlap, but extend southeast of, the tuffs of Mesa Cuadrada. This pattern is seen on both margins of the Gulf of California (Figs. 6, 8, and 9). In Baja California, the tuffs of Arroyo El Canelo crop out primarily south of Arroyo Matomí, except for isolated exposures in the southern Sierra San Fermín. On Isla Tiburón, the tuffs of Arroyo El Canelo crop out south of Punta Reina and within the central and southern Sierra Menor. On both margins, the northern outcrop limit of the tuffs of Arroyo El Canelo lies south of the northern outcrop limit of the tuffs of Dead Battery Canyon. Also, the tuffs of Arroyo El Canelo crop out farther southeast than all other correlated ignimbrites.

Thicker, high-grade welded deposits of the tuffs of Arroyo El Canelo (e.g., tuff that is

Figure 3. Field photographs of the tuff of San Felipe. (A) Basal vitrophyre and densely welded tuff, Sierra Menor, Isla Tiburón. The tuff of San Felipe is 85 m thick at this locality. (B) Close-up of high-grade, densely welded tuff with light-colored pumice and dark rhyolite lithic fragments, Sierra San Felipe, Baja California. Lens cap is 5.5 cm in diameter.
densely welded throughout the section with post-emplacement rheomorphic flow lineations) form a more restricted distribution centered on outcrops of intra-caldera deposits in the eastern Arroyo Matomi area (Fig. 9). Paleotopography formed during eruption of the tuffs of Mesa Cuadrada (caldera wall?) in Figs. 6 and 9) acted as a buttress against which the tuffs of Arroyo El Canelo were deposited. On Isla Tiburón, thick deposits of the tuffs of Arroyo El Canelo crop out in two areas adjacent to the western coastline. Thick high-grade deposits occur in the southwest Sierra Menor, south of a paleotopographic barrier that was the southern limit of the tuffs of Mesa Cuadrada (Fig. 6). The tuffs of Arroyo El Canelo may have ponded here on the south side of this barrier. Outcrops of the thick, moderately to densely welded tuff of Arroyo El Canelo occur adjacent to the coastline of Isla Tiburón from the central Sierra Menor northward to Punta Reina, where outcrops of this ignimbrite abruptly terminate (Fig. 9). These thick deposits are separated by normal faults and buttress unconformities from thinner sections to the east.

**DISCUSSION**

Pyroclastic flow deposits offset across the northern Gulf of California permit restoration of Pacific–North America displacement (Figs. 10, 11, and 12). This analysis builds on the initial study of Oskin et al. (2001), which proposed 255 ± 10 km of opening of the Upper Delfin basin in the northern Gulf of California since the 6.3 Ma time of emplacement of Tmr3 (e.g., Fig. 6). Alternative restorations of 245 and 265 km illustrate the robustness of this reconstruction (Figs. 10A and 10C). Distributed dextral displacement of ignimbrite distributions is shown to support 41 ± 13 km of additional plate-boundary motion between Baja California and mainland Sonora (Fig. 11). By comparison of these results to plate-motion circuit data, Oskin et al. (2001) showed that the Pacific–North America plate boundary became localized in the Gulf of California during latest Miocene time. A more complete compilation of these data presented here, which includes distributed deformation...
### TABLE 3. VOLUME ESTIMATES OF CORRELATIVE ASH-FLOW TUFFS

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<td>0 m</td>
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<td>60 m</td>
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<td><strong>Tuff of San Felipe</strong></td>
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<tr>
<td><strong>Tuffs of Arroyo El Canelo</strong></td>
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</table>

¹Area measurements do not account for extension of the outcrop area after deposition and may overestimate the volume of tuffs by up to a factor of two.

²The 0 m contour was multiplied at 1/2 contour interval (15 m). Each complete contour above 0 m was multiplied at 1 contour interval (30 m). Final contour interval was multiplied at 1/2 contour interval (15 m) + 1/3 remaining thickness.

³The area and the volume estimate presented here account only for outcrops west of the coastal zone. Thick outcrops of the Tuff of San Felipe in coastal Sonora indicate that there is likely to be additional tuff farther east.

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Figure 5. Field photographs of the tuffs of Mesa Cuadrada. (A) Close-up of the basal vitrophyre of the Tmr4 cooling unit, overlain by densely welded tuff affected by spherulitic alteration, Sierra Menor, Isla Tiburón. (B) Tmr3 and Tmr4 cooling units of the tuffs of Mesa Cuadrada unconformably overlying an eroded remnant of the tuff of San Felipe, Punta Reina, Isla Tiburón. Note that multiple cooling horizons have developed in thick Tmr3 at this locality. Sea cliff is ~200 m high. (C) Close-up of Tmr3 outcrop, showing crystal- and lithic-rich composition, Sierra San Fermín, Baja California. Lens cap is 5.5 cm in diameter.
account for rotation of 4.0° about the modified NUVEL-1A Pacific–North America Euler pole (lat 50.5°N, long 75.8°W, DeMets and Dixon, 1999), Sonora and Isla Tiburón are rotated 2.3° counterclockwise in map view relative to true north. The restoration path defined by the Tiburón Fracture Zone and Ballenas transform fault is slightly counterclockwise of a 314° vector of Pacific–North America plate motion at Puertecitos calculated with this same Euler pole. Distributed deformation of the Baja California margin (described in Lewis and Stock, 1998a) may account for this difference, as discussed later in the following section.

The amount and uncertainty of the 255 km restoration (Fig. 10) were determined by the limits of a reasonable fit between tie lines from the tuffs of the northern Puertecitos volcanic province. The best fit of these tie lines is depicted on the map-view restoration of 255 km of displacement (Fig. 10B). Fits with 245 km and 265 km of displacement parallel to the transform faults illustrate the limits of the restoration (Figs. 10A and 10C). The partitioning of dextral displacement between the Ballenas transform fault and the Tiburón Fracture Zone (Fig. 2) depends upon the restoration of Isla Angel de la Guarda to an uncertain position south of Isla Tiburón (Lonsdale, 1989; Stock, 2000). This uncertainty does not affect the summed displacement measured here.

The distribution of the ca. 6.3 to 6.1 Ma tuffs constrains the amount and uncertainty of dextral displacement across the northern Gulf of California since late Miocene time (Fig. 10). In particular, several stratigraphic transitions in the Arroyo Matomí and southern Sierra San Fermín region of Baja California correlate to the Punta Reina region of Isla Tiburón (Figs. 6, 8, and 9). Here, the tuffs of Dead Battery Canyon and the tuffs of Arroyo El Canelo abruptly pinch out above the tuffs of Mesa Cuadrada. South of this tie line, thick, high-grade welded, and intracaldera facies of the tuffs of Mesa Cuadrada and the tuffs of Arroyo El Canelo fill in the inferred eruptive center at Arroyo Matomí. The 255 km restoration shows that thick deposits of these units in the central and southern Sierra Menor originally were adjacent to the mouth of Arroyo Matomí. North of the southern Sierra San Fermín and Punta Reina, only the tuffs of Mesa Cuadrada are present. Both the thickness and welding grade of cooling unit Tmr3 decrease northward in the Sierra San Fermín of Baja California and the Sierra Alta of Isla Tiburón.
The distribution of the tuff of San Felipe also matches in the favored map-view restoration (Figs. 6 and 10). The tuff of San Felipe fills west-trending paleocanyons that crop out along the entire western coastline of Isla Tiburón. The Sierra San Fermín and the northern Puertecitos volcanic province contain similar paleocanyons filled by the tuff of San Felipe. The precision of the map-view restoration is not enough to match individual paleocanyons; however, high-grade welded deposits of the tuff of San Felipe in the northern Sierra San Fermín and the northern Sierra San Fermín of Baja California are restored into the northern Gulf of California. The Sierra San Fermín and the northern Sierra San Fermín of Isla Tiburón, which are not significantly rotated, when projected onto an edge-on view of the western boundary of the rotating domain of the Baja California margin (Fig. 11) appears to accommodate differential extension and rotation between the Puertecitos volcanic province and the Sierra San Fermín (Nagy, 2000) and does not carry significant dextral displacement.

Lewis and Stock (1998a) documented distributed dextral displacement within the San Felipem rotated domain of the Baja California margin (Fig. 11). Their paleomagnetic and structural study proposed 23 ± 9 km of dextral displacement (along an azimuth of 340°) manifesting by 30° ± 15° of localized clockwise rotation since eruption of the ca. 6.3 Ma tuffs of Mesa Cuadrada (cooling units Tmr3 and Tmr4). The western boundary of the rotated domain is pinned to the Valle de San Felipe and/or San Pedro Mártir faults. The eastern boundary of the rotating domain is proposed by Lewis and Stock (1998a) to lie just offshore of northeastern Baja California. This boundary is consistent with rocks on Isla Tiburón, which are not significantly rotated, and with faulting offshore of Baja California (Persaud et al., 2003). When projected onto an azimuth of 314°, parallel to plate motion, clockwise rotation of the Baja California mar-
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Figure 8. Distribution of the tuffs of Dead Battery Canyon in Baja California and Isla Tiburón. See Figure 4 for explanation of isopach map symbols. Paleotopography and limited tuff volume probably restricted distribution of the tuffs of Dead Battery Canyon. Enclosed area of zero thickness on Isla Tiburón indicates a paleo-topographic high. A paleocanyon located northeast of this high and a basin located southeast of this high each contains eastward-thinning outcrops of the tuffs of Dead Battery Canyon. Proposed caldera wall corresponds to abrupt thinning of these ignimbrites from >30 m to <5 m thickness in the southern Sierra San Fermín.

Origin amounts to 21 ± 9 km of displacement (Lewis and Stock, 1998a). A vector sum of 23 ± 9 km of dextral displacement at an azimuth of 340° with 255 ± 10 km of opening of the Upper Delfín basin at an azimuth of 312° yields a combined vector of 276 ± 13 km (errors summed as root mean squares) at an azimuth of 314°, parallel to the modified NU-VEL-1A direction of DeMets and Dixon (1999) for Puertecitos.

The La Cruz fault forms a zone of discrete dextral displacement mapped through southern Isla Tiburón (Fig. 11). Neither the timing of motion nor the amount of offset across the La Cruz fault are well constrained. The only deposits to correlate across the fault zone are post-6 Ma marine rocks and pyroclastic flow deposits (Oskin and Stock, 2003a). Deposits from the middle Miocene volcanic arc on either side of the La Cruz fault do not correlate, which may indicate a large amount of dextral and/or normal displacement. The La Cruz fault is interpreted here as an early strand of the Tiburón Fracture Zone that forms the southern margin of the Upper Delfín segment of the Gulf of California (Fig. 2). The block south of the La Cruz fault was probably transferred across the Tiburón Fracture Zone during the earliest stages of opening of the Upper Delfín basin (Fig. 11). Slip along this fault therefore should not be included as an additional component of the opening of the Upper Delfín basin.

A northwest-trending zone of dextral shear and rotation is inferred on the mainland Sonoran margin and northeastern Isla Tiburón (Fig. 11). Offset of high-grade welded tuff of San Felipe between Punta Chueca and the northern Sierra Kunkaak suggests 20 ± 10 km of dextral displacement and/or northwest-directed extension across this zone. Basalt flows exposed in both of these areas may also correlate. Another zone of dextral displacement, the northwest-striking Sacrificio fault, separates the area of distributed shear on the southwest from the Seri block on the northeast (Fig. 11). The total displacement across this structure is difficult to estimate, because no volcanic strata match across the fault. However, outcrops of a distinctive conglomerate in the Sierra Seri preclude displacement on this structure that would sum with other offsets to exceed the ~300 km estimated for the Gulf of California by Gastil et al. (1973). Because 276 ± 13 km and 20 ± 10 km of displacement (296 ± 17 km total) is already accounted for, strike-slip displacement on the Sacrificio fault is unlikely to exceed a few tens of kilometers.

Distributed dextral deformation may also be
inferred from paleomagnetic declination data from Isla Tiburón and mainland coastal Sonora (Fig. 11). Localities on Isla Tiburón show minor, 5°–15° clockwise vertical-axis rotation of outcrops of the tuff of San Felipe relative to reference localities in Baja California. Overall, however, sample localities on Isla Tiburón show significantly less clockwise vertical-axis rotation than sample localities in Baja California. Therefore, no additional dextral displacement has been added from rotation of localities on western Isla Tiburón. Localities on coastal Sonora show 25°–40° clockwise vertical-axis rotation of outcrops of the tuff of San Felipe. This rotation may have been caused by right-lateral shear in the coastal zone between the Sacrificio fault and Isla Tiburón. Dextral displacement accumulated by rotation of these localities is tentatively attributed to displacement of correlative outcrops between Punta Chueca and the northern Sierra Kunkaak by 20 ± 10 km.

In summary, the total distributed dextral displacement within the marginal continental areas of the Gulf of California rift adds 41 ± 13 km of offset to the 255 ± 10 km measured by map-view restoration of correlative ignimbrite strata (Fig. 11). Offset of the tuff of San Felipe from Punta Chueca to the northern Sierra Kunkaak indicates 20 ± 10 km of displacement. Vertical-axis rotations documented by paleomagnetic studies add 21 ± 9 km of dextral displacement from the Baja California margin (Lewis and Stock, 1998a). Additional dextral displacement contributed by the Sacrificio fault is unknown at present. However, outcrops of a distinctive conglomerate in the Sierra Seri that correlate to outcrops in the Santa Rosa basin in Baja California (Gastil et al., 1973) preclude a large dextral offset across the Sacrificio fault. On the basis of the stratigraphic and paleomagnetic arguments presented here, the total amount of opening of the Upper Delfín segment of the northern Gulf of California is 296 ± 17 km along an azimuth of 314°, of which 255 ± 10 km has been accommodated within the ocean basin. This value is the same as that indicated by offsets estimated from Tertiary conglomerate (Gastil et al., 1973) and from pre-Tertiary batholithic and metamorphic rocks (Silver and Chappell, 1988; Gastil et al., 1991).

**Timing of Dextral Displacement**

Isotopic ages for the tuff of San Felipe, tuffs of Mesa Cuadrada, and the tuffs of Arroyo El
Canelo constrain the timing of dextral displacement in the Gulf of California. Restoration of northeastern Baja California to Isla Tiburón indicates that 255 ± 10 km of opening occurred in the Upper Delfín basin after emplacement of the tuffs of Mesa Cuadrada at 6.3 ± 0.2 Ma and the tuffs of Arroyo El Canelo at 6.1 ± 0.5 Ma. Likewise, vertical-axis rotations measured in the continental margin of Baja California also postdate emplacement of the tuffs of Mesa Cuadrada (e.g., Tmr3 and Tmr4 of Lewis and Stock, 1998a). Together, these displacements add up to 276 ± 13 km since ca. 6.3 Ma. Northwestward displacement of 20 ± 10 km between Isla Tiburón and the Sacrificio fault accrued after emplacement of the tuff of San Felipe at ca. 12.6 Ma.

Northeastern Baja California and Isla Tiburón do not show any evidence for significant displacement on northwest-striking dextral faults between 12.6 Ma and 6.3 Ma, despite widespread evidence for extension during this time period (Stock and Hodges, 1990; Lee et al., 1996; Lewis and Stock, 1998b). East- to northeast-directed extension during this time accommodated a component of Pacific–North America plate motion (cf. Stock and Hodges, 1989). East-directed extension took place on Isla Tiburón (Oskin, 2002), across northeastern Baja California (Stock and Hodges, 1990; Lewis and Stock, 1998b), including minor distributed dextral displacement on the Matomí accommodation zone (Nagy, 2000). However, the low magnitude of extension across Baja California and Isla Tiburón (10% to 40% across a 100-km-wide zone) does not approach the 160 ± 80 km of east-directed extension predicted by the plate-circuit model of Stock and Hodges (1989).

Additional extension and right-lateral shear within mainland Mexico probably makes up the balance of strain necessary to complete the plate circuit (Gans, 1997; Henry and Aranda-Gomez, 1992).

In summary, timing information for dextral displacement between Baja California and mainland coastal Sonora supports substantial dextral displacement of at least 276 ± 13 km from 6.3–6.1 Ma to the present. An additional 20 ± 10 km of displacement occurred sometime between 12.6 Ma and the present in a region lacking dated rocks younger than 12.6 Ma. No evidence firmly supports substantial dextral displacement within or significant opening of the Upper Delfín basin segment of the Gulf of California rift prior to 6.3 Ma, except for a component accommodated by east-directed continental extension from 12.6 Ma to 6.3 Ma.

**Dextral Pacific–North America Plate Motion in the Northern Gulf of California**

Restoration of conjugate rifted margins of the Upper Delfín basin of the northern Gulf of California defines the history of dextral plate motion in the Gulf of California (Fig. 12). Finite rotations derived from a plate circuit (Atwater and Stock, 1998) define the full Pacific–North America plate motion of ~760 km along an average azimuth of 304° from 15.1 Ma (chron 5b, time scale of Cande and Kent (1995)) to the present. Prior to 12.5 Ma, the Magdalena microplate separated the Pacific plate from the North America plate offshore of southern Baja California (Mammerickx and Klitgord, 1982). Subduction was dextral-oblique during this time (Atwater, 1989), and some component of dextral plate-boundary motion may have been absorbed within the North American continent. However, deposition of the tuff of San Felipe as a preextensional marker indicates that plate-boundary motion probably did not occur within the northern Gulf of California area west of coastal Sonora prior to ca. 12.6 Ma. Since 12.5 Ma,
coast-parallel Pacific–North America plate displacement has been divided into a component of dextral displacement accommodated across the Gulf of California, primarily after 6 Ma, and a second component of dextral displacement accommodated outside of the Gulf of California, primarily prior to 6 Ma (Fig. 12). The age and offset of correlative ignimbrites across the northern Gulf of California and the paleomagnetic record of seafloor spreading in the Alarcón basin in the southern Gulf of California (Fig. 1) define these components. Continental extension in the Gulf extensional province accommodated a significant component of the total plate motion (Stock and Hodges, 1989) but contributed little to opening of the Upper Delfín basin prior to 6 Ma.

The paleomagnetic record of seafloor spreading in the Alarcón basin defines the slip history in the Gulf of California from 3.6 Ma to present (Fig. 12). DeMets (1995) documented that the rate of seafloor spreading here was 10%–15% less than the full Pacific–North America displacement rate prior to 1 Ma. This lower rate is shown as a deviation of the rate of motion across the Gulf of California from the Pacific–North America plate-circuit rate (Fig. 12). At 3.6 Ma, this discrepancy is significant relative to the error for these reconstructions. The rate of seafloor spreading in the Gulf of California in the past 1 m.y. is indistinguishable from the full Pacific–North America displacement rate.

Figure 11. Tectonic block diagram illustrating distributed deformation of the continental margins of the Upper and Lower Delfín basins. See Figure 2 for present configuration. The Gulf of California is shown closed by 255 km between Isla Tíburón and Baja California (see Fig. 10 for rationale). Closure of the Lower Delfín basin is by restoration of Isla Angel de la Guarda to an uncertain position southeast of Puertecitos (Lonsdale, 1989; Stock, 2000). The La Cruz block is shown restored southeast of Isla Tíburón, adjacent to Isla Angel de la Guarda. The original position of this block is poorly constrained. Paleomagnetic declination anomalies for the tuff of San Felipe, relative to the Mesa Cuadrada (MC) paleomagnetic reference site, shown, by circular plots. Table DR1 (see footnote 1) lists paleomagnetic remanence values and declination anomalies. Clockwise rotation of 30° ± 15°—measured from the tuff of San Felipe and the tuffs of Mesa Cuadrada (Lewis and Stock, 1998a)—defines the San Felipe rotated domain on the Baja California rifted margin and accommodates to 23 ± 9 km of dextral shear along a 340° azimuth. Displacement of tuff of San Felipe outcrops between Isla Tíburón and coastal Sonora resulted in 20 ± 10 km of dextral displacement and rotation of tuff of San Felipe outcrops. Additional right-lateral displacement on the Sacrificio fault is unknown. Paleomagnetic sample localities from Lewis and Stock (1998a), Stock et al. (1999), Nagy (2000), and Oskin et al. (2001).
Figure 12. Dextral displacement in the Gulf of California relative to Pacific–North America plate motion. Lines, labeled with chron numbers, on graph indicate displacement with time. Light gray fields indicate uncertainty. The preponderance of Pacific–North America plate motion since ca. 6 Ma occurred in the Gulf of California, as indicated by seafloor magnetic lineations at the Alarcon Rise (Lonsdale, 1989; DeMets, 1995) (Fig. 1) and by offset of the tuffs of Mesa Cuadrada and the tuffs of Arroyo El Canelo. Restoration of the tuff of San Felipe indicates that Pacific–North America plate motion from 12.5 Ma to ca. 6 Ma occurred outside of the Gulf of California. This slip discrepancy may be absorbed by dextral displacement west of the Baja California Peninsula (Spencer and Normark, 1979) and/or by additional displacement within the southern Basin and Range province (Gans, 1997).

America rate within the uncertainty of recent reconstructions (DeMets and Dixon, 1999), although neotectonic studies of western Baja California Sur indicate minor activity (Fletcher et al., 2000; Dixon et al., 2000).

Restoration of the correlative ignimbrites across the northern Gulf of California (Fig. 10) requires that the Pacific–North America plate boundary and most of its motion was localized in the Gulf of California during or soon after eruption of the tuffs of Mesa Cuadrada and tuffs of Arroyo El Canelo. Opening of the Upper Delfin basin since this time is at least 276 ± 13 km (Fig. 12). To accumulate this displacement measured from the offset ignimbrites requires extrapolation of the rate of seafloor spreading at the Alarcon basin back to 6.6 ± 0.6 Ma. This extrapolated age is indistinguishable from isotopic ages of the tuffs of Mesa Cuadrada (6.3 ± 0.2 Ma) and the tuffs of Arroyo El Canelo (6.1 ± 0.5 Ma). If the full Pacific–North America rate of motion (DeMets and Dixon, 1999) were accommodated in the Gulf of California, 276 ± 13 km of displacement could have accumulated in 5.5 ± 0.4 m.y. Separation of outcrops of the ca. 12.6 Ma tuff of San Felipe from Isla Tiburón to Baja California does not require any additional dextral offset here prior to 6.3 Ma. These results indicate that the Pacific–North America plate boundary became localized in the Gulf of California during a short time interval at ca. 6 ± 1 Ma. It is likely that the large-volume silicic eruptions that produced the tuffs of Mesa Cuadrada and the tuffs of Arroyo El Canelo mark this localization event (Oskin and Stock, 2003b). Additional dextral displacement measured within coastal Sonora and between coastal Sonora and Isla Tiburón may be attributed to pre- and/or post–6 Ma slip. However, the majority of Pacific–North America plate-boundary motion from 12.5 Ma to 6.3 Ma must have occurred outside of the Gulf of California (Oskin et al., 2001) (Fig. 12).

The slip history presented here (Fig. 12) provides a test of existing models for opening of the Gulf of California. Lonsdale (1989) proposed that 50 km of seafloor spreading between Baja California and North America occurred at the Maria Magdalena Rise from 6 or 5 Ma until the onset of spreading at the Alarcon Rise at 3.6 Ma. The 276 ± 13 km of offset measured across the northern Gulf of California requires ~120 km more displacement than is recorded in the Alarcon basin. Seafloor spreading at the Maria Magdalena Rise, with additional displacement on the continental margins of the mouth of the Gulf of California during this time interval, would satisfy the amount of opening measured across the northern Gulf of California. Umhoefer et al. (1994) proposed acceleration of the Baja California–North America displacement rate at 3.5 Ma. A detailed resolution of dextral displacement in the Gulf of California prior to 3.5 Ma is not possible with the current geologic data. However, the total amount of slip recorded in the northern Gulf of California since ca. 6 Ma cannot accommodate significant acceleration of the displacement rate in the Upper Delfin basin at 1 Ma and 3.5 Ma (Oskin et al., 2001). In either case, the majority of Pacific–North America plate motion, 276 ± 13 km, must have been accommodated in the Gulf of California since at least 6.1 ± 0.5 Ma to 5.5 ± 0.4 Ma.

Implications for Dextral Pacific–North America Plate Motion in Southern California

Models for the development of the Pacific–North America plate boundary in southern California support a variety of displacement histories for the Gulf of California (e.g., Dickinson, 1996). The slip history presented here for the northern Gulf of California (Fig. 12) provides a new constraint with which to evaluate these models independent of the tectonic complexity of southern California. Recent efforts to summarize the amount of deformation
in central California successfully reconcile Pacific–North America motion measured from continental-deformation and plate-circuit data (Dickinson and Wernicke, 1997; Atwater and Stock, 1998). Similarly, displacement and timing information from the Gulf of California reconciles the majority of plate-boundary motion in northwestern Mexico since ca. 6 Ma (Fig. 12). In southern California, these data require that most of the dextral shear transmitted through the Transverse Ranges to the Salton Trough (Fig. 1) occurred after ca. 6 Ma.

Most models of the San Andreas fault system in southern California are compatible with offsets and timing measured in the northern Gulf of California, despite a range of slip estimates for the southern San Andreas fault from 150 to 180 km (Matti et al., 1992) to 240 km (Ehlig et al., 1975). When summed with additional displacement for other structures away from the San Andreas fault trace, both slip estimates overlap or exceed the 276 ± 13 km of dextral displacement measured for the northern Gulf of California since ca. 6 Ma. The most significant of these additional displacements are 12 ± 2 km of slip from the Elsinore fault (Hull and Nicholson, 1992), 45–75 km of shear by rotation of the eastern Transverse Ranges (Richard, 1993; Dickinson, 1996), and possibly up to 22 km of slip on the Agua Blanca fault (Allen et al., 1960). Addition of slip from the Agua Blanca fault to the Gulf of California is problematic because this fault appears to terminate before reaching the Gulf extensional province (Allen et al., 1960; Lee et al., 1996). A slip of 26 ± 2 km on the San Jacinto fault (Sharp, 1967) is included with estimates for the San Andreas fault.

If only 150–180 km of slip has occurred on the southern San Andreas fault (Matti et al., 1992), the total dextral displacement measured in the northern Gulf of California requires a considerable amount of slip along the San Gabriel fault (Fig. 1). Adding 60 ± 5 km of slip measured for the western San Gabriel fault (Crowell, 1974) yields a total of 289 ± 18 to 300 ± 21 km dextral displacement from southern California that would have been transferred into the Gulf of California (Dickinson, 1996). These values overlap the 296 ± 17 km total-displacement estimate for the northern Gulf of California. An acceptable match is also obtained by adding only 22 ± 1 km slip measured for the north branch of the San Gabriel fault (Ehlig, 1981), yielding a total of 269 ± 13 to 280 ± 16 km dextral displacement transferred into the Gulf of California (Dickinson, 1996). These estimates both support the conclusion that dextral displacement in the Gulf of California from 12.5 Ma to 6.3 Ma probably does not exceed the 20 ± 10 km estimate for displacement and rotation of outcrops of the tuff of San Felipe east of Isla Tiburón.

Alternatively, higher estimates of displacement for the southern San Andreas fault (Ehlig et al., 1975; Powell, 1993) could require up to 390 ± 20 km of dextral displacement within northwest Mexico (Dickinson, 1996). To accommodate this slip would require ~100 km of dextral displacement east of the Gulf of California, most of which would have had to occur prior to ca. 6 Ma. Significant problems remain in reconciliation of this higher slip value in southern California (Richard, 1993). Existing data from northwest Mexico cannot rule out substantial dextral displacement east of the Gulf of California during Miocene time. Ultimately, up to 350 km of dextral displacement is required in northwest Mexico from 12.5 Ma to 6.3 Ma (slip discrepancy in Fig. 12). Most of this slip is usually assigned to dextral displacement on the Tosco-Abreojos fault zone west of Baja California and extension in the Gulf extensional province (Spencer and Normark, 1979; Stock and Hodges, 1989) (Fig. 1). However, observations from southern California and evidence for strike-slip faulting east of Isla Tiburón (Gastil and Krumenacher, 1977) and in southeastern Sonora (Gans, 1997) indicate that additional field work is necessary to address the distribution of dextral shear during middle to late Miocene time.

Implications for Crustal Structure of the Northern Gulf of California

Foundered upper continental crust probably forms only a small component of the crust of the Upper Delfín basin of the northern Gulf of California. The proximity of restored conjugate rifted margins of the Upper Delfín basin segment of the rift indicates that the missing width of continental surface area is unlikely to exceed 25 km (Figs. 10 and 11). This result implies that ~100% southeast-directed extension has occurred within the Upper Delfín basin. Most likely, opening of the Upper Gulf of California has been accomplished by a combination of (1) large-magnitude extension of the foundered edge of the continental margin, (2) strain partitioning through conjugate strike-slip faulting and/or northeast-directed extension or to fill in the gap left by opening of the basin, and (3) rupture of the continent and formation of new transitional oceanic crust. Because of the narrow width of missing continental surface area, (1) significant finite extension of the foundered continental margins of the Upper Delfín basin would probably result in exhumation of lower-crustal levels. Exhumation of middle to lower continental crust as a metamorphic core complex (cf. González-Fernández et al., 2000) and exhumation of serpentinitized continental-mantle lithosphere (Nicholas, 1985) have been proposed to have produced part of the basin floor in the northern Gulf of California. (2) Strain partitioning does not appear to be a sufficient mechanism to compensate for opening of the Upper Delfín basin because faulting of the appropriate magnitude has not been described from the ocean basin or its margins. Strain partitioning as proposed by Nagy and Stock (2000) requires substantially more subsided continental margin than is indicated, although variations on this model could involve exhumed or transitional crust. Significant conjugate strike-slip faulting may also be expected to disrupt throughgoing transform faults in the ocean basin, contrary to the existing interpretation of the Tiburón Fracture Zone (Fenby and Gastil, 1991) (Fig. 1). Present-day crustal structure and volcanism in the northern Gulf of California and Salton Trough indicate recent crustal formation in the absence of continental crust and thus support possibility 3 that crustal rupture occurred at some time during opening of the northern Gulf of California (Herzeg and Jacobs, 1994; Couch et al., 1991). Our results from matching conjugate rifted margins cannot determine if or when each of these processes may have contributed to opening of the Upper Delfín basin. However, our results do require that any mechanism to open the Upper Delfín basin must preserve most of the surface area of the upper continental crust on the basin’s rifted margins.

CONCLUSIONS

Four pyroclastic flow deposits, with a total of eight cooling units, are correlated from northeastern Baja California to Isla Tiburón and coastal Sonora. These pyroclastic flow deposits are the ca. 12.6 Ma tuff of San Felipe, the 6.3 ± 0.2 Ma tuffs of Mesa Cuadrada (units Tmr3 and Tmr4), the tuffs of Dead Battery Canyon (unit Tmr5), and the 6.1 ± 0.5 Ma tuffs of Arroyo El Canelo (including the El Oculto, El Canelo, Bighorn Sheep, and Flagpole units). Restoration of the ca. 6.3 to 6.1 Ma tuffs indicates 255 ± 10 km of dextral displacement, at an azimuth of 312°, between northeastern Baja California and western Isla Tiburón. This restoration also satisfies the distribution of the tuff of San Felipe, supporting the conclusion that almost all opening of the Gulf of California took place within the past.

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6 m.y. Offset pyroclastic flows and paleomag- netic declination anomalies support an addi- tional 41 ± 13 km of distributed deformation within northwest-reaching zones on both mar- gins of the Upper Delfón basin, for a total of 296 ± 17 km of opening measured across this segment of the northern Gulf of California. At least 276 ± 13 km of this opening took place after eruption of the ca. 6.3 to 6.1 Ma tuffs. These results indicate that the Pacific–North America plate boundary became localized in the Upper Delfón basin over a short time inter- val at ca. 6 ± 1 Ma and that prior to 6.3 Ma, the majority of dextral plate-boundary motion must have occurred outside of the northern Gulf of California. This slip history also requires that most of the activity of the southern San Andreas fault system in southern California occurred after 6 Ma. Restoration of conjugate rifted margins of the Upper Delfón basin accounts for all but a 20±25 km width of continental surface area. This result indi- cates that at least 1000% southeast-directed extension has occurred across this rift seg- ment. Basically, the upper continental crust probably ruptured near the present-day coastlines.

ACKNOWLEDGMENTS

Support was provided by National Science Foun- dation grants EAR-9614674 and EAR-0001248 and a grant from the University of California MEXUS program. We appreciate the support of Jaime Roldán-Quintana and Carlos González-León, of the Universidad Nacional Autónoma de México. Per- mission to enter Isla Tiburón was granted by the Secretaría de Medio Ambiente y Recursos Naturales and the Cucumá (Seri) Indian Tribe. Prescott Col- leges Research Station, Bahía Kino, generously pro- vided logistical support during field studies. We are especially grateful to our Cucumá guide, Ernesto Molina. Scott Dobner, Matt Bachman, Robert Hous- ton, Jason Wise, Naomi Marks, and Lesley Perg as- sisted with field studies. Discussions with Gary Axen, Arturo Martín-Barajas, Elizabeth Nagy, and Claudia Lewis, and reviews by Paul Umhoefer and John Fletcher contributed to the development of this paper. California Institute of Technology Publication #88699.

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