Extensional deformation and paleomagnetism at the western margin of the Gulf extensional province, Puertecitos Volcanic Province, northeastern Baja California, Mexico

Elizabeth A. Nagy* Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA

ABSTRACT

During the late Miocene east-northeast–directed extension in the Gulf of California extensional province, the western rift margin in northeastern Baja California, Mexico, was segmented at the northwest-striking Matomi accommodation zone. The accommodation zone passed through the northern Puertecitos Volcanic Province and separated pre–6 Ma extension to the north from the unextended region to the south. Pre–6 Ma northeast-sidetown displacement is documented across the accommodation zone, which may have undergone dextral oblique-slip motion. The rift margin migrated westward during the latest Miocene or Pliocene, bypassing accommodation-zone structures and incorporating the Puertecitos Volcanic Province into the region of Gulf extensional province deformation. East-northeast– to east-directed extensional deformation is at least post–6 Ma in the northern Puertecitos Volcanic Province and deformation currently continues. Pliocene changes in the Gulf of California spreading center system may have triggered incorporation of the Puertecitos Volcanic Province into the Gulf extensional province as recently as 2–3 Ma. Paleomagnetic analyses of 6.3–6.6 Ma pyroclastic flow deposits show no consistent evidence for rotational deformation, although minor (~10°–15°) clockwise rotation is possible given anomalous declination directions. Comparisons with paleosecular variation models and the late Miocene paleopole for stable North America imply no statistically significant rotation relative to geomagnetic north, although minor (~10°) clockwise rotation is permissible given uncertainties. Geologic relationships show that pre–6 Ma accommodation-zone structures identified in this study did not mark the southern boundary of later rotational deformation documented to the north. The boundary of Pliocene to Holocene rotations may be a broad, diffuse zone of extensional shear encompassing the northeastern Puertecitos Volcanic Province, which accommodated small rotations.

Keywords: accommodation zones, Baja California, extension tectonics, paleomagnetism, plate divergence, volcanics.

INTRODUCTION

Late Cenozoic extension associated with Pacific–North America plate interactions is distributed over a broad region in much of western North America (e.g., Zoback et al., 1981; Henry, 1989). In Mexico, the Gulf extensional province encompasses the region of high-angle normal faults bordering the Gulf of California (Fig. 1, inset) and has been the location of a divergent portion of the plate boundary since at least ca. 3.5 Ma (anomaly 2A) when seafloor spreading began in the mouth of the Gulf of California at a full plate rate of ~45–50 mm/yr (e.g., DeMets, 1995). Details are still emerging regarding the earlier history of Gulf extensional province deformation and its relationship to the evolving plate boundary and associated southern Basin and Range extension.

During the late Miocene, Pacific–North America plate motion was probably partitioned between “proto-Gulf” normal faults accommodating east-northeast–directed extension (Stock and Hodges, 1989) and dextral, offshore transform faults, such as the Tosco-Abreojos and San Benito faults (Fig. 1, inset; Spencer and Normark, 1979). Gans (1997) offered an alternative interpretation in which northwest-striking transform faults within the Gulf of California, rather than west of the peninsula, accommodated plate motion. The latter scenario requires ~500 km of northwest-southeast–directed right-lateral displacement within the Gulf extensional province as constrained by late Cenozoic offsets across the San Andreas fault system to the north (e.g., Atwater, 1989), whereas the strain-partitioning model places half of this displacement along the offshore transform faults. Geologic relationships in Baja California suggest a middle to late Miocene age (ca. 12–15 Ma) for the initiation of extension along the western rift margin of the Gulf extensional province (e.g., Gastil et al., 1975; Stock and Hodges, 1990; Lee et al., 1996). East–to-northeast-directed extension continued through Pliocene time in much of northeastern Baja California (see Nagy and Stock, 2000, for a detailed extension history of northeastern Baja).

Field studies that identify the timing, amount, and direction of extension in the Gulf of California region are necessary to clarify the contribution of such extension to overall plate boundary deformation. In this study I summarize the deformation history within the northern Puertecitos Volcanic Province located on the western Gulf extensional province rift margin in northeastern Baja California (Fig. 1). Detailed field mapping (Nagy, 1997) within volcanic deposits spanning pre–17 to 6 Ma (Nagy et al., 1999) provide the basis for structural interpretations. Paleomagnetic analysis of 6.3–6.6 Ma pyroclastic flow deposits investigates the possibility of relative rotations between fault-bounded structural blocks and provides a comparison with regions a few kilometers to the north, where Pliocene to Holocene vertical-axis block rotations are documented (Strangway et al., 1971; Lewis and Stock, 1998a; Stock et al., 1999).

GEOLOGIC SETTING

The sharp western margin of the Gulf extensional province is exposed along the eastern side of the Baja California peninsula (Main Gulf Es-
Figure 1. Geologic map (simplified from Gastil et al., 1975) of a portion of northeastern Baja California, Mexico, showing principal localities and faults discussed in text. Ball and bar are on downthrown side of normal faults; arrows indicate sense of slip on strike-slip faults; faults are dotted where concealed. The Matomí accommodation zone (A–A", after Stock, 1999; and A"–A", after Nagy, 1997, and this study) separated a region of pre–6 Ma east-northeast–directed extension to the north from an unextended region to the south. Abbreviations: MC—Mesa Cuadrada; UEFZ—Ultima Esperanza fault zone. Inset: GEP—Gulf extensional province; G—Gonzaga Bay; P—Puertecitos.

carpent in Fig. 1, inset) and separates the Cretaceous Peninsular Ranges batholith to the west from downdropped fault blocks to the east of batholithic rocks overlain by Cenozoic subduction- and rift-related deposits. In much of northeastern Baja California the rift margin is represented by the 100-km-long, east-dipping, San Pedro Mártir fault (Fig. 1). Although as much as 5 km of normal separation occurs on the fault (Gastil et al., 1975), displacement decreases southward to ~800 m in southern Valle Chico (Stock and Hodges, 1990) at the northern margin of the Puertecitos Volcanic Province (Fig. 1), a late Miocene–Pliocene ignimbrite field. The San Pedro Mártir fault has not been recognized south of Valle Chico; the western edge of the Gulf extensional province is thus poorly defined within the Puertecitos Volcanic Province. Northeast- to east-directed extension began 12–6 Ma along major east-dipping normal faults such as the San Pedro Mártir and Sierra San Felipe faults (e.g., Gastil et al., 1975; Stock and Hodges, 1990; Lewis and Stock, 1998b). Pre–6 Ma deformation south of Arroyo Matomí (Fig. 1) is documented for the first time in this study (see also Nagy, 1997).

Post–6 Ma east-northeast– to east-directed extension continued along structures north of Arroyo Matomí as well as on approximately north-striking normal faults in the Puertecitos Volcanic Province (Dokka and Merriam, 1982; Lewis and Stock, 1998b; Nagy et al., 1999). Faulted 3 Ma volcanic rocks in the easternmost Puertecitos Volcanic Province may have undergone less extensional deformation than the 6 Ma volcanics (e.g., Stock et al., 1991; Martín-Barajas et al., 1995). Northeast-striking, sinistral strike-slip faults also displace 3 Ma volcanic rocks in the Sierra San Fermín (Lewis and Stock, 1998b). Paleomagnetic studies show that the Sierra San Fermín and Santa Rosa basin have undergone ~30° of Pliocene to Holocene vertical-axis clockwise rotation relative to Mesa Cuadrada in the southern Sierra San Felipe (Fig. 1; Strangway et al., 1971; Lewis and Stock, 1998a; Stock et al., 1999). Recent scarp along the San Pedro Mártir fault and the dextral, strike-slip Valle de San Felipe fault indicate that these structures are active (Gastil et al., 1975; Grover et al., 1993).

The west- to northwest-striking Matomí accommodation zone was first hypothesized near Arroyo Matomí on the basis of changes in the style and amount of faulting to the north and south (Dokka and Merriam, 1982; Stock and Hodges, 1990), and its presence may have influenced Pliocene sedimentation rates in the region (Stock et al., 1996; Martín-Barajas et al., 1997). The Matomí accommodation zone may also mark the southern boundary of rotational deformation (Lewis and Stock, 1998a). Nevertheless, field evidence for an accommodation zone south of the Sierra San Fermín had not been identified prior to this study.

EXTENSIONAL DEFORMATION IN THE SANTA ISABEL WASH REGION

Lithology and Extensional Structures

Faulting and erosion expose as much as 700 m of volcanic deposits along the northern margin of the Puertecitos Volcanic Province in the Santa Isabel Wash study area in the Sierra Santa Isabel (Fig. 1). Geologic mapping (scale 1:20 000), lithologic and petrographic study, 40Ar/39Ar geochronology, and electron microprobe analyses of phenocryst compositions define 21 lithologic units that are combined into six Miocene volcanic groups and one pre-Miocene group (Fig. 2). Lithologic, stratigraphic, and geochronologic details given by Nagy (1997) and Nagy et al. (1999) are summarized here (oldest to youngest): pre-Miocene...
Extension in the Puertecitos Volcanic Province

Geologic Map of Santa Isabel Wash

Figure 2. Simplified geologic map of Santa Isabel Wash in the northern Puertecitos Volcanic Province. The $^{40}$Ar/$^{39}$Ar ages were determined by laser fusion of feldspar mineral separates (Nagy et al., 1999). Unit labels (after Nagy et al., 1999) indicate Tertiary (T), Miocene (m), basal (b), andesite (a), dacite (d), rhyolite (r), or volcaniclastic sediment (vs), followed by a unit name abbreviation. (See Nagy, 1997, for 1:20000 geologic map that differentiates the 21 lithologic units.) Fault symbols: dashed where approximately located, dotted where concealed (inferred), and illustrated with the letter s where lineaments in the Quaternary alluvium are interpreted to be fault scarp; symbols indicating fault motion are as described in Figure 1. Horizontal bedding is indicated by a circle and cross symbol. Two large arroyos are named Santa Isabel Wash and Arroyo Oculto. A–A’ and B–B’ mark the positions of two approximately northeast-facing topographic slopes across which 6.3–6.6 Ma tuffs (group 6) thicken considerably from southwest to northeast. The pre–6 Ma topographic slopes are interpreted to be fault controlled and mark the southwestern margin of the Matomí accommodation zone. Post–6 Ma faults at B–B’ appear to have reactivated these earlier structures.

Extensive deformation is classified as pre–6 and post–6 Ma based upon the relationship between faults and the 6.3–6.6 Ma series of tuffs. The majority of structures are northeast-striking, east- and west-dipping, high-angle normal faults. Planar fault surfaces and striations are rare; thus in some cases strike-slip or oblique-slip faulting may have produced apparent normal displacement. There are 14 faults that preserve measurable surfaces and 3 that preserve slickenlines (Fig. 3). The best indicators of tilt in the region are within the 6.3–6.6 Ma tuffs. Thick Tmr3 deposits generally filled preexisting topography and preserved a planar upper surface; overlying tuffs are roughly tabular in shape. In general these uppermost tuffs are horizontal to slightly west dipping (≤10°).

Pre–6 Ma Deformation

With one significant exception pre–6 Ma faults are rare in Santa Isabel Wash. East to east-northeast–striking, north-dipping normal faults, which do not offset the overlying 6.3–6.6 Ma tuffs, cut pre–15 Ma rocks (groups 2 and 3) and in one locality 12.5 and 9 Ma rocks (groups 4 and 5, respectively); thus deformation is post–9 Ma in some places but possibly as old as 15 Ma in others. About 100 m of north-side-down normal separation occurred across two east-striking faults (112 in Fig. 2); the amount of offset is otherwise poorly constrained.

Thickness and elevation variations of the 6.3–6.6 Ma tuffs imply the presence of a discontinuous, yet significant, pre–6 Ma northeast-facing topographic slope across the entire area. The approximate position of two subparallel, northwest–striking topographic breaks is shown in Figure 2 (A–A’ and B–B’) based upon the geometry of the onlapping tuffs. Specifically, individual tuffs occur at lower elevations and are an order of magnitude thicker northeast of the slopes relative to deposits on the volcanic plateau. For example, basal elevations of Tmr4 and Tmr6 are 350–390 m and 240–320 m lower, respectively, to the northeast of A–A’ relative to the southwest, and the tuffs change from 1–3 m thick southwest of A–A’ to at

(probably Paleozoic) metasedimentary rocks intruded by granitoids related to the Peninsular Ranges batholith (group 1); pre–17 Ma subduction-related volcaniclastic breccias, debris flows, lava flows, and pyroclastic flow deposits (group 2); ca. 15–17 Ma dacitic and mafic lava flows, which are also probably subduction-related (group 3); the syrnnit ca. 12.5 Ma Tuff of San Felipe (group 4); minor andesitic volcanism ca. 9 Ma (group 5); as much as 400 m of 6.3–6.6 Ma pyroclastic flow deposits or ash-flow tuffs (hereafter referred to simply as tuffs), and an intervening mafic lava flow, which filled irregular topography to produce the plateau-like, upper surface of the Puertecitos Volcanic Province (group 6); and as much as 500 m of rhyolite (ca. 6 Ma) and andesite (undated) lava flows (group 7). In addition to modern arroyo sedimentation in Santa Isabel Wash and Arroyo Oculto, older, high-standing alluvium occurs along the margins of the washes and surrounds isolated hills in the north. Modern playa deposits within closed basins are up to 2 km in diameter in the washes as well as on the volcanic plateau.
least 70–80 m thick in Arroyo Oculto. There is less pre–6 Ma displacement across B–B’ (~80–100 m). Downdip lineations within the Tuff of El Canelo (Tr_e) indicate flow to the north-northeast across A–A’, and steep northeast-dipping contacts of the rocks that core the plateau (groups 2 and 3) disappear below the surface at A–A’ and B–B’, further supporting a change in base level.

The deposition of 6.3–6.6 Ma tuffs along the topographic breaks obscures possible pre–6 Ma faults traces; thus erosion could explain the topographic variations. Alternatively, this zone may have undergone northeast-side-down displacement along northwest-striking normal faults prior to 6 Ma. Evidence for pre–6 Ma north-side-down faulting in other parts of Santa Isabel Wash confirms that the area underwent some pre–6 Ma deformation, and minor post–6 Ma displacement along northwest- to north-northeast–striking faults at A–A’ and B–B’ might represent reactivation of older structures. As elaborated in the Discussion section below, these pre–6 Ma paleotopographic features may be associated with the Matomí accommodation zone.

**Post–6 Ma Deformation**

Most normal faults in Santa Isabel Wash offset the 6.3–6.6 Ma tuffs. The closely spaced, approximately north-striking Cuervo Negro and Santa Isabel fault systems are the most continuous structures in the area, although the northernmost exposures are complicated by north-northwest–striking splays and cross-structures (C6 in Fig. 2). The faults accommodate ~500 m of east-side-down normal separation based upon the relative displacement of the ca. 12.5 and 6.3–6.6 Ma tuffs. Slickenlines preserved on the Santa Isabel fault plane (Figs. 3 and 4) indicate dip-slip motion with a sinistral component; thus extension may have been slightly oblique. Similar amounts of displacement of the two lithologic groups suggest that the faults did not accommodate extension between 12 and 6 Ma. However, the lowest group 6 tuff (Tmr6) is absent west of the Santa Isabel fault, and the overlying cooling unit (Tmr3; type I) is geographically restricted to regions immediately east of this fault (see paleomagnetic results below). A pre–6 Ma east-facing scarp forming a topographic boundary could explain these relationships, as could a fault-parallel topographic low east of the fault developed from hanging-wall rollover.

Other post–6 Ma north-northwest– to northwest-striking normal faults are considered secondary to the Cuervo Negro and Santa Isabel faults on the basis of discontinuous, arcuate outcrop patterns of fault traces, relatively small amounts of normal displacement, and the presence of extensional relay ramps between subpar-

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**Figure 3.** Orientations of 14 measured fault planes in Santa Isabel Wash (alluvium-bedrock contact is shown for simplicity; see Figure 2 for distribution of geologic units). Three fault planes that preserve slickenlines indicate sinistral oblique slip. Other structures in the area are high-angle normal faults; see Figure 2 for inferred sense of offsets. Present-day and older drainage patterns suggest that Santa Isabel Wash was structurally created by east- to northeast-side-down deformation along north- to northwest-striking normal faults that diverted northeast-directed flow to the southeast. Paleomagnetic sampling locations are also shown. Site J marks the location of samples collected from the ca. 12.5 Ma tuff of San Felipe (described in Stock et al., 1999).

**Figure 4.** The approximately north-striking, east-dipping Santa Isabel fault plane (view to the west). Slickenlines (subparallel to hand lens string), which trend N42°E and plunge 58°, record oblique (sinistral) dip-slip motion.
Recent Deformation

Ongoing extensional deformation is supported by the presence of small, structurally controlled pull-apart basins that localize sag pond sedimentation in the washes and on the plateau. Evidence that the Santa Isabel fault is still active includes sinistral stream offsets across fresh fault scarp. Two 2-km-long lineaments in the modern alluvium (M7 and O4 in Fig. 2) may be fault scarp, although the sense of motion along them is not apparent. Additional evidence for Quaternary deformation includes a change in flow direction of the Santa Isabel Wash drainage system, from northeast to southeast directed. The locations of the present wash, as well as abandoned drainages determined from sediment patterns in inactive washes, are indicated in Figure 3. North- to northwest-striking normal faults south of the wash may have accommodated east- to northeast-side-down displacement, thereby creating the northwest-southeast–trending topographic low (i.e., hanging-wall rollover) that forms the present-day wash between E5 and J9 in Figure 2.

Amount and Direction of Extension

The direction of pre–6 Ma extension is poorly constrained. Pre–6 Ma faults are east– to east-northeast–striking and accommodate north-side-down normal separation; however, fault-plane striae on one of these indicate a significant component of sinistral strike-slip motion (Fig. 3). Dip-slip motion along the inferred pre–6 Ma approximately northwest-striking structures at A′–A′ and B′–B′ implies northeast-directed extension. In any case, most of Santa Isabel Wash did not undergo significant pre–6 Ma deformation. Post–6 Ma east-northeast– to east-directed extension is inferred on the basis of slip indicators on the Santa Isabel fault plane and assuming normal dip slip across the north-northeast– to north-northeast-striking faults throughout the area. The secondary faults may also have undergone an oblique (sinistral) component of slip, as observed along the Santa Isabel fault. A maximum of 4% post–6 Ma east-northeast–directed extension was determined by restoring cross sections across the region shown in Figure 2 (Nagy, 1997). Although uncertainties in extension direction are large, especially for pre–6 Ma deformation, these results imply no appreciable change in extension direction from pre–6 to post–6 Ma. This is in agreement with the extensional history recorded elsewhere in northeastern Baja California (e.g., Gastil et al., 1975; Dokka and Merriam, 1982; Stock and Hodges, 1989; Lewis and Stock, 1998b).

PALEOMAGNETIC STUDY OF LATE MIOCENE VOLCANIC TUFFS

Field and Laboratory Methods

We sampled 4 of the 6.3–6.6 Ma tuffs for paleomagnetic analysis at 15 locations in Santa Isabel Wash (Fig. 3). Cooling breaks within some of the tuffs were used to further divide the 4 tuffs into 11 cooling units. All samples record normal polarities. The ⁴⁰Ar/³⁹Ar ages determined for Tmrₐₑ, Tmr₃, and Tmr₄ (from 6.2 ± 0.1 Ma to 6.7 ± 0.3 Ma (Nagy et al., 1999); thus the tuffs most likely erupted during subchron C3An.2n (6.269–6.567 Ma; Cande and Kent, 1995). Between 4 and 8 cores were drilled at each site for a total of 217 samples (see Nagy, 1997, for collection and preparation details). Samples were measured at the Caltech Paleomagnetics Laboratory in a cryogenic SQUID (superconducting quantum interference device) magnetometer in a magnetically shielded μ-metal room. Anhysteretic and isothermal remanent magnetization tests and magnetic susceptibility measurements were performed to discern the nature of the grains carrying the magnetic remanence in the rocks. Results indicate a predominance of ferrimagnetic minerals, such as single-domain or pseudosingle-domain magnetite, and smaller amounts of antiferromagnetic minerals, such as hematite. Superparamagnetic grains were detected in Tmr₄ₑ (t2) (see Nagy, 1997, for details).

Alternating field (AF) and thermal demagnetization techniques were compared in a pilot study of 46 samples. Half of the samples were subjected to progressive AF demagnetization, typically including 13 steps to 80 mT and in some cases to 260 mT. These samples were also demagnetized thermally after the AF procedure. The other half of the sample were thermally demagnetized in about 12 heating steps between 100 °C and 690 °C. AF and thermal demagnetization plots of three pairs of sister samples (i.e., cut from the same core) are shown for comparison in Figure 5. Both demagnetization procedures yield similar results; however, secondary overprints are in some cases incompletely removed with thermal techniques (e.g., Fig. 3, A and B), whereas a primary direction is resolved using AF demagnetization. In addition, AF demagnetized samples show a more regular and greater drop in magnetic intensity than do thermally demagnetized samples. Both low coercivity and high blocking temperature minerals are present and appear to record the same remanent direction (e.g., Fig. 5C). On the basis of these preliminary tests, the remaining samples were demagnetized using the AF procedure.

Analysis

Characteristic remanent magnetization (ChRM) vectors were calculated using principal component analysis (Kirschvink, 1980) to selected demagnetization steps for each sample. Low coercivity viscous magnetization was commonly removed by the 15 mT step. Single-component, primary ChRM directions were fit with lines in vector space; eight samples showing only partial removal of an overprint were fit with planes. Paleomagnetic results for the 11 cooling units are given in Table 1. A Fisher (1953) distribution function is used to calculate the uncertainties for the tilt-corrected site means. I discarded 13 analyses on the basis of poorly preserved ChRM directions or as extreme outliers from the rest of the samples at a (15° from site mean). ChRM directions cluster well at individual sites with ⁴σ < 10°. Three exceptions occur at site D (Tmr₉ₑ [θ₉ₑ = 17.6°], Tmr₄ [θ₄ = 12.7°], and Tmr₉ₑₑ (t3) [θ₉ₑₑ = 10.8°]), where the tuffs are less welded than at most other sites, although there is no clear correlation between the degree of welding and the amount of dispersion in ChRM directions. Small tilt corrections were applied based on contact dips between tuffs, and not on the basis of eutaxitic foliation planes, although the orientations of such planes were measured. Inclined eutaxitic foliation planes developed above the Curie temperature of the remanence-carrying minerals and do not represent paleohorizontal in this study (Nagy, 1997).

Results

The paleomagnetic data summarized in Table 1 suggest that the Santa Isabel Wash region may have undergone a small amount of clockwise vertical-axis rotational deformation. Unfortunately, this interpretation relies heavily on directions recorded at only two sites at the east and west limits of the region sampled. Furthermore, typical variations within a given cooling unit be-
AF and thermal demagnetization

A.

Sample from $T_{mrs_{iw}}$ (t4)

B.

Sample from $T_{mrao}$

C.

Sample from $T_{mrs_{iw}}$ (t5)

Figure 5. Pairs of sister samples from three cores (A, B, C) illustrate the results of alternating field (AF) and thermal demagnetization techniques by Zijderveld plots (closed/open symbols represent horizontal/vertical projections), lower hemisphere equal-area plots (isolated circle is present-day field at sampling location), and magnetic intensity plots normalized to the initial magnetic intensity. The histograms show the fraction of total intensity removed at a given demagnetization step. Samples were subjected to AF demagnetization followed by thermal demagnetization (top) or thermally demagnetized by incremental heating (bottom). NRM—natural remanent magnetization.
Tibble 1. Paleomagnetic data from the Puertecitos volcanic province, Baja California, Mexico.

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Tmr4 mean:

Site B*          | 187     | 5.5 | 5/5        | 6.5           | 42.4   | 1.5           | 42.1 | 236 | 5.4  |
| Site D           | 187     | 5.5 | 4/5        | 8.3           | 44.2   | 2.1           | 44.0 | 99  | 5.3  |
| Site K           | 186     | 4.0 | 5/5        | 31.3          | 66.3   | 22.8          | 66.3 | 149 | 5.5  |

Tmr3 mean:

Site K           | 186     | 4.0 | 6/6        | 26.6          | 44.2   | 12.7          | 44.0 | 53  | 10.9 |
| Site A           | 182     | 6.5 | 5/5        | 26.6          | 44.2   | 12.7          | 44.0 | 53  | 10.9 |
| Site D           | 187     | 5.5 | 5/5        | 26.9          | 44.8   | 12.7          | 44.0 | 53  | 10.9 |

Tmr1 mean:

Site A           | 182     | 6.5 | 5/5        | 26.9          | 44.8   | 12.7          | 44.0 | 53  | 10.9 |
| Site D           | 187     | 5.5 | 5/5        | 26.9          | 44.8   | 12.7          | 44.0 | 53  | 10.9 |

Tmr ao (one cooling unit):

Site B*          | 187     | 5.5 | 5/5        | 6.5           | 42.4   | 1.5           | 42.1 | 236 | 5.4  |
| Site D           | 187     | 5.5 | 4/5        | 8.3           | 44.2   | 2.1           | 44.0 | 99  | 5.3  |
| Site K           | 186     | 4.0 | 5/5        | 31.3          | 66.3   | 22.8          | 66.3 | 149 | 5.5  |

Tmr4 (two cooling units):

Site B*          | 187     | 5.5 | 5/5        | 6.5           | 42.4   | 1.5           | 42.1 | 236 | 5.4  |
| Site D           | 187     | 5.5 | 4/5        | 8.3           | 44.2   | 2.1           | 44.0 | 99  | 5.3  |

Between relatively unrotated sites suggest that the amount of rotation is at the threshold of resolution. Specifically, declinations recorded at site K (Fig 3) in Tmr_siw (t5) and Tmr3 (type I) are 10°–25° counterclockwise of most directions preserved in the same units at other sites. There is also a 15° difference in declination recorded in Tmr_siw (t3) between sites D and P (Fig 3). If the directions recorded at sites K and P are accurate, it implies that the entire area rotated 10°–20° clockwise relative to site K, and that site P underwent an additional 15° of clockwise rotation. An inferred fault east of site K, concealed beneath Santa Isabel Wash near E10 in Figure 2, could be a structure that separates site K from a region of rotation to the east. Site P is separated from the other sampling sites by a major north-striking, west-dipping normal fault (N8–N18 in Fig. 2), which could mark a boundary between regions of differential rotation.
North America paleopole (3–10 Ma) from Global Paleomagnetic database

North America paleopole (0–20 Ma) after Besse and Courtillot (1991)

Virtual Geomagnetic Pole from Santa Isabel Wash (corrected for post-5.5 Ma displacement relative to North America)

Virtual Geomagnetic Pole from Santa Isabel Wash (uncorrected)

Figure 7. Northern hemisphere (equal area) projection showing virtual geomagnetic pole directions (with 2σ uncertainty ellipses) from Santa Isabel Wash. The average direction of the 11 cooling units gives a virtual geomagnetic pole at lat 77.6N°, long 341.0E° (dp = 22.2°, dm = 9.9°). In order to account for divergence between Baja California (on the Pacific plate) and the North America plate since the latest Miocene, the virtual geomagnetic pole is rotated 4.7° (e.g., Stock and Hodges, 1989) about a pole at lat 48.7°N, long 281.8°E determined from the global plate motion model NUVEL-1 (DeMets et al., 1990; DeMets, 1995). The corrected virtual geomagnetic pole for Santa Isabel Wash is at lat 80.2N°, long 335.8E°. The virtual geomagnetic pole directions are statistically indistinguishable from a stable North America paleopole (lat 97.2N°, long 86.8E°, α95 = 3.8°) calculated from selected sites within the 1997 Global Paleomagnetic Database (McElhinny and Lock, 1995) for studies in 3–10 Ma rocks. Selection criteria included dp ≤ 15°, n (sites) > 3, and N (samples) > 35. Results from Santa Isabel Wash are also statistically indistinguishable from a stable North America paleopole (lat 87N°, long 57E°, α95 = 7°) calculated from 0–20 Ma by Besse and Courtillot (1991) in their study of apparent and true polar wander. A small (~10°) amount of clockwise rotation of Santa Isabel Wash relative to north would not be detectable given uncertainties.

Other examples of anomalous directions are not consistently recorded between different cooling units, which casts some doubt on the results from sites K and P. For example, the mean declination recorded at site M in Tmr_{w} (t5) is counterclockwise of the directions recorded within this cooling unit at most other sites and is very similar to results from site K in Tmr_{w} (t5). In contrast, results from site M are in good agreement with mean directions in overlying lower Tmr3 (type II) and Tmr3–4. Declinations recorded at site I also differ inconsistently relative to the mean directions in Tmr_{w} (t5), lower Tmr3 (type II), and Tmr_{w}. These examples suggest that in some cases anomalous directions are probably not tectonic in origin but rather due to sampling procedure errors or natural variations of the preserved magnetization directions. Incorrect structural corrections could account for anomalous results, although realistic uncertainties in bedding tilts do not significantly change the mean directions.

An argument for rotational deformation would be more convincing if more of the stratigraphic package had been sampled at sites K and P. With the possible exception of these two sites, post–6 Ma relative rotations between fault-bounded structural blocks are not apparent between the different sampling sites. Samples from sites K and P are thus removed from the following discussion in order to examine the directions recorded in the rest of the study area without the complication of possible rotations relative to these two sites. Mean directions for Tmr_{w} (t5) and Tmr3 (type I) without site K are listed in Table 1.

Virtual Geomagnetic Pole Direction from Santa Isabel Wash

An equal-area plot of the 11 cooling unit mean directions, without data from sites K and P, is shown in Figure 6. Secular variations of the Earth’s magnetic field are the most likely reason for the 11 different directions. A comparison between the mean directions and statistical studies of paleosecular variation (Quidelleur and Courtillot, 1996) shows that most mean directions are within expected limits of paleosecular variation around the Miocene geomagnetic pole. The 2σ confidence limits are shown in Figure 6 centered on D = 0° and the expected geocentric axial dipole value of I = 50° at the study latitude. Shallow inclinations recorded in some of the Tmr_{w} cooling units are from a single site (D) and may be due to rotation of magnetic grains during emplacement (e.g., Rosenbaum, 1986) rather than tectonic in origin.

Because most mean directions are within expected paleosecular variation limits, rotation of the entire region relative to geomagnetic north is not likely. To further test this interpretation, averaging the 11 directions may average the secular variation signal recorded in the different cooling units, thereby providing a virtual geomagnetic pole direction that can be compared to the stable North America paleopole. As illustrated in Figure 7, a virtual geomagnetic pole direction from Santa Isabel Wash, corrected for divergence between Baja California and the North America plate since the latest Miocene, overlaps within 95% confidence limits with the stable North America paleopole (Besse and Courtillot, 1991; McElhinny and Lock, 1995). The angular difference between the sampling site and the virtual geomagnetic pole directions from Santa Isabel Wash (50.3°) and the North America paleopoles calculated from McElhinny and Lock (1995) (60.1°) and Besse and Courtillot (1991) (58.0°) are 9.8° ±
TABLE 2. REGIONAL PALEOMAGNETIC RESULTS FROM NORTHEASTERN BAJA CALIFORNIA, MEXICO

<table>
<thead>
<tr>
<th>Age* (Ma)</th>
<th>Unit†</th>
<th>Santa Isabel Wash*</th>
<th>Mesa Cuadrada*</th>
<th>Sierra San Fermín*</th>
<th>Santa Rosa Basin**</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3–6.6</td>
<td>Tmr</td>
<td>Dec</td>
<td>Inc</td>
<td>α95</td>
<td>Dec</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3a</td>
<td>3.4</td>
<td>44.4</td>
<td>3.7</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3b</td>
<td>21.1</td>
<td>43.0</td>
<td>5.3</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Upper Tmr3 (type II)</td>
<td>355.6</td>
<td>36.4</td>
<td>3.4</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Middle Tmr3 (type II)</td>
<td>29.3</td>
<td>52.1</td>
<td>4.8</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Lower Tmr3 (type II)</td>
<td>25.9</td>
<td>56.0</td>
<td>2.7</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3 (type II)</td>
<td>314.1</td>
<td>65.3</td>
<td>3.9</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3a</td>
<td>9.5</td>
<td>53.9</td>
<td>8.9</td>
<td>39.2</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3b</td>
<td>52.4</td>
<td>52.2</td>
<td>12.9</td>
<td>77.8</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3 (type II††)</td>
<td>19.5</td>
<td>41.9</td>
<td>2.1</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3 (type II‡‡)</td>
<td>24.4</td>
<td>26.6</td>
<td>3.6</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3 (type II§§)</td>
<td>23.5</td>
<td>31.0</td>
<td>10.8</td>
<td>N.D.</td>
</tr>
<tr>
<td>6.3–6.6</td>
<td>Tmr3 (type II¶¶)</td>
<td>18.6</td>
<td>35.5</td>
<td>3.1</td>
<td>N.D.</td>
</tr>
<tr>
<td>~12.5</td>
<td>Tmr3</td>
<td>229.7</td>
<td>**</td>
<td>8.1</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Note: N.D.—no data.

*Based upon 40Ar/39Ar geochronology, stratigraphic position, and comparison with geomagnetic polarity time scale.

†Stratigraphic order of Tmr3a and Tmr3b in Mesa Cuadrada and Sierra San Fermín relative to the four Tmr3 cooling units in Santa Isabel Wash is unknown.

‡Lewis and Stock (1998a).

§§Site P removed from group mean.

DISCUSSION

Matomí Accommodation Zone

Dokka and Merriam (1982) first proposed a west-striking accommodation zone in the vicinity of Arroyo Matomí (Fig. 1) to explain the northward termination of late Miocene–Pliocene faults in the eastern Puertecitos Volcanic Province. Stock and Hodges (1990) further inferred that the accommodation zone separated pre–6 Ma east-northeast–directed extension north of Arroyo Matomí from the undeformed region to the south. In Axen’s (1995) regional analysis of segmentation and vergence reversal of the Main Gulf Escarpment, he assigned the entire Puertecitos Volcanic Province region to the role of a late Miocene west- to west-northwest–striking accommodation zone separating an east-directed normal fault system to the north from a west-directed system to the south. A Pliocene age for the accommodation zone has also been inferred. For example, Lewis and Stock (1998a) claimed that the Matomí accommodation zone marks the southern boundary of Pliocene to Holocene rotational deformation in the Sierra San Fermín, and the style of Pliocene rift margin sedimentation in the eastern Puertecitos Volcanic Province and the Sierra San Fermín is attributed to an accommodation-zone setting (Stock et al., 1996; Martín-Barajas et al., 1997). In summary, these studies imply the existence of a pre–6 Ma
segmentation along the Gulf extensional province rift margin that continued to mark the approximate location of a rift margin accommodation zone during the Pliocene.

Paradoxically, field evidence for pre- or post–6 Ma accommodation-zone structures is scarce. Most significantly, accommodation-zone structures have not been identified within 3 and 6 Ma volcanic rocks extensively faulted by north-northwest–striking normal faults in Arroyo Matomí (Stock et al., 1991), or within 3 and 6 Ma rocks between Arroyo Matomí and Arroyo Los Heme (Fig. 1; Stock et al., 1991; Martín-Barajas et al., 1995). Farther west, in the southeast corner of southern Valle Chico, Stock and Hodges (1990) described a west-northwest–striking extensional accommodation zone (Ultima Esperanza fault zone after Stock, 1993), which they associated with the Matomí accommodation zone. The Ultima Esperanza fault zone (Fig. 1) is composed of anastomosing strike-slip and dip-slip faults along which the sense of offset is not evident (Stock, 1993). Displacement along the fault zone occurred after deposition of the ca. 12.5 Ma tuff of San Felipe (unit Mr1 of Stock, 1993; geochronology updated by Stock et al., 1999), but is otherwise unconstrained. The fault zone cannot correspond to the southern boundary of Pliocene to Holocene rotations because Mesa Cuadrada, directly to the north, is not within the rotated region. The Ultima Esperanza fault zone terminates westward against a high-angle northwest–striking fault that might be the continuation of the Valle de San Felipe fault (Fig. 1; Stock and Hodges, 1990). A large alluvial plain north of Santa Isabel Wash conceals the area east of the Ultima Esperanza fault zone, where it may have been offset by a Pliocene northeast-striking sinistral strike-slip fault (Fig. 1; Stock, 1999).

The pre–6 Ma approximately northwest-striking normal faults inferred in the Santa Isabel Wash region (A′–A′′ and B′–B′′ in Fig. 2) are the first structures identified east of the Ultima Esperanza fault zone that might be associated with the Matomí accommodation zone. Because these fault zones are not aligned along strike, the region of accommodation-zone structures either broadened southeast of the Ultima Esperanza fault zone or formed an en echelon series of faults stepping southward into Santa Isabel Wash. Differential extension across the two segments in Santa Isabel Wash suggests a zone of deformation consisting of multiple subparallel structures rather than a single thoroughgoing fault.

The Matomí accommodation zone may have formed in a zone of weakness separating two offset portions of the north-northwest–striking rift margin during east-northeast–directed extension (Dokka and Merriam, 1982; Stock, 1999). One of these rift margin structures was the early San Pedro Mártir fault, and the other one was perhaps located near Gonzaga Bay (Fig. 1, inset; Stock, 1999). Stock and Hodges (1990) suggested that dextral strike-slip motion along the Matomí accommodation zone transferred slip from the southern end of the San Pedro Mártir fault onto Gulf of California structures to the southeast by dextral oblique-slip motion. Geologic relationships across inferred accommodation zone structures in Santa Isabel Wash, which document down-to-the-northeast normal separation, further support an oblique sense of motion. The Matomí accommodation zone may be structurally similar to oblique-slip transfer faults on the eastern margin of the Gulf of Suez (Red Sea rift system), which developed between originally offset, main-rift normal faults (McClay and Khalil, 1998). An irregularity in the early to middle Miocene arc may have been exploited at the time of rift margin development, causing the initial offset (Stock, 1999). The location and position of accommodation zones along other rift margins, such as in East Africa, similarly followed preexisting structural discontinuities or zones of weakness (e.g., Bosworth, 1992; Kilemba and Rosendahl, 1992; Scott et al., 1992). Most northwest-striking accommodation zone structures in Santa Isabel Wash were bypassed af-
ter 6 Ma when the rift margin migrated westward onto approximately north-striking extensional faults such as the Santa Isabel and Cuervo Negro faults (Fig. 2). Although some accommodation zone structures were reactivated, paleomagnetic results show that no relative rotation occurred across these faults since 6 Ma. For example, paleomagnetic sampling sites B, C, and D (Fig. 3) are northeast of the northwest-striking faults reactivated at B′–B″ (Fig. 2). Thus the southern structural boundary of Pliocene to Holocene rotations in the Sierra San Fermín, inferred by Lewis and Stock (1998a) to be the west-northwest–striking Matomí accommodation zone, cannot coincide with the pre–6 Ma accommodation zone structures inferred in this study. Pliocene accommodation zone structures may be concealed below the large alluvial plain north of Santa Isabel Wash, although where they project farther to the east is unknown. It is interesting that an unidentified Pliocene structural boundary must also occur within the Sierra San Felipe, separating the rotated Santa Rosa basin from Mesa Cuadrada. Overall paleomagnetic results from Santa Isabel Wash, and especially results from site P, hint that the eastern Puertecitos Volcanic Province may have in fact undergone a small amount (~10°–15°) of rotational deformation. Rather than being represented by a discrete fault zone, it is possible that the southern boundary of rotational deformation is a broad, diffuse zone involving extensional structures in the northeastern Puertecitos Volcanic Province, including Santa Isabel Wash, which accommodated small amounts of shear (rotational) deformation. This scenario is not supported, however, by results from the Arroyo Matomí sampling site in the study by Lewis and Stock (1998a), where declinations recorded in a 3 Ma tuff are 24°–30° counterclockwise of directions found at two sites in the Sierra San Fermín.

**History of Deformation in Santa Isabel Wash**

The Gulf extensional province rift margin has evolved structurally in the Santa Isabel Wash region since late Miocene time. Schematic block models (Fig. 8) illustrate deformation before and after 6 Ma. Prior to 6 Ma Santa Isabel Wash was separated from the extending region to the north by the northwest-striking Matomí accommodation zone. Roughly 300–350 m of pre–6 Ma northeast-side-down displacement occurred across the zone. A strike-slip component of motion along the zone is not evident in Santa Isabel Wash; however, dextral oblique slip may have occurred if the structures are related to those that transferred slip from the San Pedro Mártir fault onto Gulf of California structures to the southeast (Stock and Hodges, 1990), implying a more easterly (e.g., east-northeast–directed) extension direction. Dextral oblique-slip predominates along late Miocene, northwest-striking faults in the Sierra San Fermín (Lewis and Stock, 1998b); thus a similar sense of motion along this zone in Santa Isabel Wash does not contradict the late Miocene regional pattern of deformation. Other pre–6 Ma approximately east-striking faults accommodate relatively minor north-side-down displacement (not differentiated in Figure 8) and are perhaps related to accommodation-zone deformation.

Most extension in Santa Isabel Wash occurred after the deposition of 6.3–6.6 Ma tuffs. Faults generally strike north-northwest to north-northeast, although some faulting localized on pre–6 Ma northwest-striking accommodation-zone structures (B′–B″ in Fig. 2). The Santa Isabel and Cuervo Negro fault systems are major, east-dipping normal faults that accommodate ~500 m of post–6 Ma displacement. Conformable contacts between 12.5 and 6 Ma tuffs further imply that the area did not undergo significant pre–6 Ma deformation, in contrast to angularly unconformable contacts between the same units north of Arroyo Matomí (Gasíl et al., 1975; Dokka and Merriam, 1982; Stock, J., 1989, 1993; Lewis and Stock, 1998b). The Santa Isabel and Cuervo Negro faults may merge at depth to form a listric detachment surface such as interpreted for the San Pedro Mártir fault (Dokka and Merriam, 1982; Stock and Hodges, 1990). A shallow westward dip of 6.3–6.6 Ma tuffs in the hanging wall of the Santa Isabel fault is perhaps the result of reverse drag along the fault, also implying a listric geometry at depth. High-angle normal faults in the hanging walls of the Santa Isabel and Cuervo Negro faults are secondary structures that perhaps intersect the east-dipping fault planes at depth. Rotational deformation is not statistically supported by the paleomagnetic results for most of the area, although further sampling at the eastern and western limits of the area would help clarify some anomalous declination values. A minor amount (~10°) of clockwise rotation of the entire area relative to north is permissible given uncertainties.

Extensional deformation continues in Santa Isabel Wash, as evidenced by sag ponds, offset drainages, and fault scarp in the active alluvial surface, and may have controlled recent changes in the drainage pattern of Santa Isabel Wash. The Puertecitos Volcanic Province may continue to undergo extensional deformation with an increasing amount of dextral shear over time, and may eventually be fully incorporated into the region of rotational deformation. Northeast-striking faults within the Quaternary alluvium in Santa Isabel Wash could represent structures accommodating conjugate plate boundary slip such as described along post–3 Ma structures in the Sierra San Fermín and Arroyo Matomí regions (Lewis and Stock, 1998b).

The Santa Isabel and Cuervo Negro fault systems accommodate more than half of the offset observed along the San Pedro Mártir fault in southern Valle Chico (~800 m; Stock, 1989), suggesting that they represent principal structures accommodating Pliocene to Holocene rift margin deformation. The northward projection along strike of the Santa Isabel and Cuervo Negro faults is ~10 km east of the San Pedro Mártir fault and approximately along strike with the Valle de San Felipe fault (Fig. 1). The San Pedro Mártir normal fault and dextral Valle de San Felipe strike-slip fault were interpreted by Grover et al. (1993) to link the Gulf of California transform system to transpeninsular faults to the north by partitioning of normal and dextral slip. Reconnaissance investigations have not revealed major rift margin structures west of the Santa Isabel Wash region (Gasíl et al., 1975; Dokka and Merriam, 1982; J. Stock, 1997, personal commun.), although northwest–north-northwest–striking structures in the northwestern Puertecitos Volcanic Province (Fig. 1) probably link extensional deformation at the south end of the San Pedro Mártir fault to the Santa Isabel Wash region.

**Influence of Oceanic Plate Boundary Structures on Rift Margin Deformation**

There is an ambiguous relationship between late Miocene structures developed along the Gulf extensional province margin and those of the Pliocene–Quaternary oceanic spreading center system within the Gulf of California. The high angles between several accommodation zones and Gulf of California transform faults, as well as their relative ages and extension directions, suggest that there is little relationship between the earlier segmentation and the subsequent geometry of the Gulf of California spreading center system (Axen, 1995). Stock (1999), however, found correlations between several accommodation zones in northeastern Baja California and major transform offsets in the Gulf of California. The most convincing relationship is between the Tiburón transform fault (Fig. 9) and the Matomí accommodation zone, although structures associated with the accommodation zone have not been identified in the eastern Puertecitos Volcanic Province. If the pre–6 Ma approximately northwest-striking faults in Santa Isabel Wash are related to the accommodation zone, their orientation is not at a high angle to transform fault orientations, although they do differ in relative age and extension direction from Gulf of California structures.

The timing of formation of pull-apart basins between offset northwest-striking, dextral strike-slip faults in the central and northern Gulf of California is poorly constrained because of the ab-
sence of magnetic anomalies in most of the Gulf of California; however, development of the oceanic system probably began ca. 4–6 Ma (Lonsdale, 1989). Motion along the Tiburón transform fault and extension in the upper and lower Tiburón basins (Fig. 9) was replaced some time after 2 Ma by northwestward propagation of the Guaymas transform fault into the Ballenas transform fault and extension in the upper and lower Tiburón and Delfín basins (Lonsdale, 1989; Stock, 1999).

Deformation recorded in Santa Isabel Wash supports the idea that late Miocene–Pleocene structural adjustments along the rift margin are related to changes in the offshore spreading center system. In particular, post–6 Ma extension in the Puertecitos Volcanic Province may have begun when dextral strike-slip motion along the Guaymas transform replaced similar motion along the Tiburón transform. The Guaymas transform projects farther south into the rift margin than does the Tiburón transform (Fig. 9); thus Pleiocene extension began in the Puertecitos Volcanic Province when the Guaymas transform linked northwestward to rift margin structures such as the San Pedro Mártir fault. The Matomí accommodation zone was thus abandoned as rift margin deformation moved southwestward. It is interesting that this adjustment exposed the Puertecitos Volcanic Province to east-northeast–directed Gulf extensional province extension, producing N-striking structures such as the Santa Isabel and Cuervo Negro faults, rather than forming northeast-striking normal faults and/or northeast-striking dextral strike-slip faults to accommodate northeast-southeast–directed plate boundary motion.

As documented in this study, evidence for distributed deformation in northeastern Baja California includes ongoing east- to northeast-directed extension and Pliocene or younger vertical-axis clockwise rotations. These observations have led to a new model for the formation and evolution of the upper and lower Tiburón and Delfín basins, which is summarized here and detailed elsewhere (Nagy, 1997; Nagy and Stock, 2000). The model is based on the assumption that Pacific–North America plate boundary deformation in the northernmost Gulf of California is not accommodated along northwest-striking oceanic transform faults or northeast-striking spreading centers, such as in the central and southern Gulf of California, but rather occurs over a broad region undergoing diffuse deformation since the late Miocene. Dextral oblique slip along submerged structures in the Gulf of California north of about 30°N may occur on reactivated north- to north-northwest–striking normal faults developed during late Miocene extension. The absence of an oceanic plate boundary in the northern Gulf of California is supported by geophysical data, which indicate lower heat flow in the north relative to the central and southern Gulf of California, an absence of gravity lows such as those associated with extensional basins, and a greater depth to the Moho (20–35 km in the north vs. 10 km in the central and southern regions) (Heney and Bischoff, 1973; Gastil et al., 1975; Couch et al., 1991).

This region of diffuse, dextral plate boundary shear has been termed the Wagner transition zone (Fig. 9; Nagy, 1997; Nagy and Stock, 1998, 2000) and consists of a continuum of transtensional deformation north of lat 30°N that varies from east-northeast–directed extension along dip-slip faults in the west to dextral shear along the coast to dextral oblique slip along north- to north-northwest–striking faults in the Gulf of California. This structural scenario can account for Pacific–North America plate motion vector constraints at the latitude of the northern Gulf of California. The southeastern limit of the transition zone, which roughly coincides with the southern Puertecitos Volcanic Province on land and projects northeasterward into the Gulf of California, is a complex region where diffuse deformation within the Wagner transition zone is juxtaposed against discrete oceanic plate boundary structures in the central Gulf of California. Differential motion thus produced a northeast-striking zone of divergence that localized the positions of the upper and lower Tiburón and Delfín basins (Fig. 9). For example, in the early Pliocene the northwest-striking Tiburón transform fault accommodated northwest-southeast–directed motion and intersected
the region of ongoing east-northeast–directed extension in the Wagner transition zone. The upper Tiburón basin formed and the spreading axis translated along the Tiburón transform away from the Wagner transition zone. Because east-north-east–directed extension continued in the Wagner transition zone, a new zone of divergence was eventually created, and spreading in the upper Delfín basin developed 2–3 Ma. Development of the Tiburón and Delfín basins may correspond to the 6 and 3 Ma pulses of Puertecitos Volcanic Province volcanism (Stock, 1999). The creation of the lower Delfín basin and the northwestward propagation of the Guayas transform 2–3 Ma may have been facilitated by the zone of divergence in the southwestern corner of the Wagner transition zone.

North- to north-northeast–striking late Miocene structures control local topographic and bathymetric trends within the Wagner transition zone and differ from northwest-striking bathymetric features in the central Gulf of California. The intersection of these different zones of deformation are reflected in the ~35° jog in the coastline north and south of the Puertecitos Volcanic Province. Ongoing east-northeast–directed extension in the Wagner transition zone explains the greater width (east-northeast to west-southwest) of the northern Gulf of California relative to regions farther south. If a system of northwest-striking en echelon strike-slip faults developed within the Gulf of California region following the termination of subduction ca. 11 Ma (e.g., Gans, 1997), evidence for a continuation of this system into the northern Gulf of California is not corroborated by present-day structures and styles of deformation.

CONCLUSIONS

Two distinct periods and styles of deformation along the Gulf extensional province rift margin are recorded in the Santa Isabel Wash region of the northern Puertecitos Volcanic Province. Prior to the deposition of 6.3–6.6 Ma tufts, the northwest-striking Matomí accommodation zone segmented the rift margin and separated northeast–east-northeast–directed extension to the north from the undeformed Puertecitos Volcanic Province to the south. About 300–350 m of pre-6 Ma northeast-side-down displacement occurred across accommodation-zone structures in Santa Isabel Wash. Additional evidence for pre-6 Ma deformation in the region is rare and probably related to accommodation-zone deformation.

At some time after the deposition of the plateau-forming 6.3–6.6 Ma tufts, the Puertecitos Volcanic Province underwent <5% east-northeast– to east-directed extension. Rift margin deformation thus migrated southwestward from the Matomí accommodation zone onto new extensional structures such as the north-striking Santa Isabel and Cuervo Negro fault systems, which accommodate ~500 m of post-6 Ma east-side-down displacement. A similar amount of displacement of ca. 12.5 and 6.3–6.6 Ma tufts across these faults supports the notion that the Santa Isabel Wash region remained outside of the Gulf extensional province prior to 6 Ma. Other north-northwest–to north-northeast–striking post–6 Ma faults in Santa Isabel Wash are secondary faults in the hanging wall of these major structures and perhaps terminate against them at depth. Fresh fault scarps, active sag ponds, and stream offsets indicate that extensional deformation is actively continuing, and drainage patterns suggest that Santa Isabel Wash is a structurally controlled topographic low recently created by east- to northeast-side-down normal faults.

No measurable relative rotations occurred between most paleomagnetic sites within 6.3–6.6 Ma tufts, although two sites at the eastern and western limits of the sampled region with anomalous declination directions could be interpreted to indicate small amounts (10°–15°) of clockwise rotational deformation. Comparisons with models of paleosecular variation show that the mean directions of 11 cooling units generally are within permissible bounds (95% confidence) of secular variation of the geomagnetic pole. A virtual geomagnetic pole calculated by averaging the 11 mean directions is not statistically different from the stable paleopole for North America, although a small amount (~10°) of clockwise rotation is possible given uncertainties. Santa Isabel Wash thus remained predominantly south of the region that underwent Pliocene to Holocene block rotations. The southern boundary of rotational deformation recorded to the north may be a broad, diffuse zone of extensional shear within the northeastern Puertecitos Volcanic Province and the Santa Isabel Wash region that accommodates small vertical-axis rotations. Concealed structures may also exist below the alluvial plain north of Santa Isabel Wash.

The abandonment of portions of the Matomí accommodation zone, incorporation of the Puertecitos Volcanic Province into the Gulf extensional province, and the commencement of block rotations to the north may have occurred 2–3 Ma, when strike-slip motion along the Tiburón transform fault was replaced by similar motion along the Guayas transform fault. The rift margin thus migrated westward onto new structures as a consequence of changes in the geometry of the oceanic system. The evolution of both rift margin and oceanic structures may be due to differential movement at the boundary between a domain of diffuse deformation in north-eastern Baja California (and the northern Gulf of California) and the region accommodating plate boundary motion on discrete oceanic structures in the central Gulf of California.

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