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Structural controls on the continent-ocean transition in the northern Gulf of California

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Abstract. In the Gulf of California the Pacific-North America plate boundary changes character from an oceanic-type spreading center and transform fault system (to the south) to a region of diffuse continental deformation (to the north). The presence of spreading centers commonly inferred in the northernmost gulf is not supported by bathymetric, heat flow, gravity, or seismic data which indicate significant differences north and south of latitude ~30°N. We suggest instead that north of ~30°N a continent-ocean transition begins which we name the Wagner Transition Zone (WTZ). Diffuse deformation characterizes the WTZ where slip occurs along reactivated north to NNW striking normal faults developed during late Miocene or Pliocene ENE directed extension. Transtensional deformation varies from ENE directed extension along dip-slip faults in the west to dextral shear along the coast to dextral-oblique slip along inferred north to NNW striking faults submerged in the northern gulf. By accounting for rotational and extensional plate motion deformation in northeastern Baja California, vector constraints require that submerged structures accommodate ~30 mm/yr of slip in a direction slightly clockwise of the relative plate motion direction. The juxtaposition of the discrete spreading center system in the central gulf with the diffuse WTZ appears to have been a stable configuration since 4-6 Ma, perhaps controlling the evolution of spreading center jumps between Upper and Lower Tiburón and Delfín basins due to the juxtaposition of kinematically partitioned structural domains. Different histories of prerift extension and subduction-related arc magmatism along the length of the gulf, partly related to the migration of the Rivera triple junction, may explain the location of the continent-ocean transition.

1. Introduction

The Gulf of California is an oblique extensional rift system within which occurs the oceanic to continental structural transition of the Pacific-North America plate boundary. Continental plate boundary structures associated with the San Andreas fault system in southern California and northern Mexico are linked through the Gulf of California (hereinafter referred to as the gulf) to the oceanic plate boundary system in the mouth of the gulf. Details concerning where and how the structural transition occurs are poorly known due to Quaternary sediments covering older geologic features in northern Mexico and the southwestern United States and to the submergence of crucial areas beneath gulf waters. Nevertheless, structural and bathymetric changes, unusual fault geometries, and diffuse extensional deformation in northeastern Baja California, Mexico, suggest that a key structural transition occurs in the northern gulf region. Although marine magnetic anomalies due to seafloor spreading are absent in most of the gulf [*Larson et al.*, 1972; *Ness et al.*, 1991], bathymetry, seismicity, geodetic, heat flow, seismic refraction, and gravity surveys [*Thatcher and Brune*, 1971; *Henyey and Bischoff*, 1973; *Gastil et al.*, 1975; *Goff et al.*, 1987; *Lonsdale*, 1989; *Ortlieb et al.*, 1989; *Couch et al.*, 1991; *Dauphin and Ness*, 1991; *Ness and Lyle*, 1991; *Schellhorn et al.*, 1991] distinguish NW striking transform faults and NE trending spreading centers as far north as the Midriff Islands (e.g., Isla Tiburón and Isla Angel de la Guarda; Figure 1a). We refrain from applying the term "oceanic" to the gulf spreading center and transform fault system because the absence of ridge morphology and definitive oceanic crust north of the Alarcon basin at about 23°N (Figure 1, inset) suggests that the system is still largely within thinned continental or transitional crust. We thus refer to this portion of the plate boundary as the "gulf spreading center system" with the inference that it is an early stage, oceanic-type plate boundary dominated by long transtensional transform faults and short incipient spreading centers. The latter do not show evidence for oceanic crust development but do experience active divergence at rates comparable to the relative Pacific-North America plate motion rate.

The presence of incipient spreading centers and transform faults in the northernmost gulf, as illustrated Figure 1a, is commonly inferred but, in fact, is not supported by geophysical data. Alternative orientations for such features (e.g., Figure 1b after *Fenby and Gastil* [1991]) are in better agreement with bathymetric data but fail geometrically to satisfy plate motion vector constraints unless divergence is highly oblique to the axis of the extending basin. A 10° difference in strike between the Cerro Prieto fault and the Ballenas transform fault prompted *Goff et al.* [1987] to suggest a fault-fault-fault triple junction model involving the Agua Blanca fault. Their model satisfactorily meets plate motion vector constraints but would, in its simplest interpretation, require a long NW striking extensional basin (e.g., encompassing the northern half of the gulf), which is not supported by geophysical data. Most importantly, diffuse extensional deformation documented in northeastern Baja California [e.g., *Barnard*, 1968; *McEldowney*, 1970; *Rossetter*, 1973; *Gastil et al.*, 1975; *Dokka and Merriam*, 1982; *Bryant*, 1986; *Neuhaus*, 1989; *Stock*, 1989; *Stock and Hodges*, 1990; *Martín-Barajas et al.*, 1995; *Lee et*

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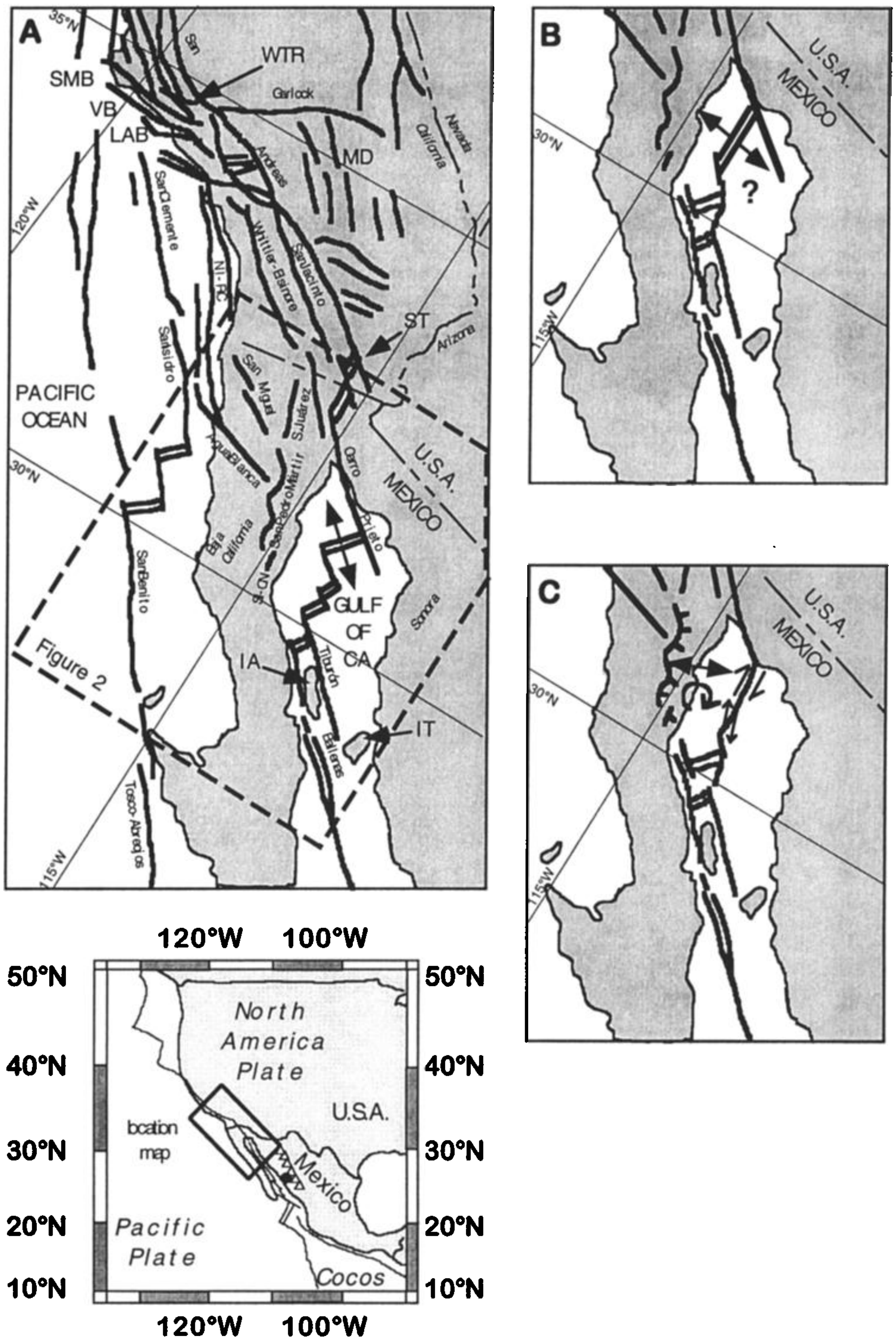


Figure 1. Major faults associated with the present-day Pacific-North America plate boundary (modified from *Atwater* [1989]) showing three tectonic interpretations for plate boundary structures in the northernmost Gulf of California. (a) The simplest interpretation is a continuation of NW striking transform faults and NE striking spreading centers as in the central and southern Gulf of California. This scenario is not supported by geophysical studies or bathymetry. (b) A spreading center oriented parallel to north striking bathymetric contours [after *Fenby and Gastil,* 1991] fails to meet plate motion vector constraints if spreading is orthogonal to the rift axis. (c) Plate motion may be accommodation on reactivated north to NNW striking faults formed during late Miocene or Pliocene ENE directed extension. Diffuse deformation is partitioned between ENE directed extension, dextral shear (vertical axis block rotations), and dextral-oblique strike-slip motion along submerged structures (solid arrows on dextral fault indicate slip direction required to meet plate motion vector constraints). Inset shows location of Figure 1a (box) and principal Pacific-North America-Cocos plate boundaries (thin line). Thin double line in mouth of Gulf of California is the East Pacific Rise and the NW striking fracture zone at its northern end is the Tamayo fracture zone. Open triangles in Mexico mark the approximate location of the unextended Sierra Madre Occidental, and the solid circle shows location of Sinaloa. Abbreviations are IA, Isla Angel de la Guarda; IT, Isla Tiburón; LAB, Los Angeles basin; MD, Mojave Desert; NI-RC, Newport-Inglewood-Rose Canyon faults; SI-CN, Santa Isabel and Cuervo Negro faults; SMB, Santa Maria basin; ST, Salton Trough; VB, Ventura basin; WTR, Western Transverse Ranges.

al., 1996; *Lewis and Stock*, 1998a,b; *Nagy*, 1997, 2000; *Axen and Fletcher*, 1998] needs to be incorporated into models of plate boundary deformation north of latitude ~30°N.

This paper summarizes existing data regarding the timing, nature, and direction of late Miocene to Recent extensional and rotational deformation in northeastern Baja California and geophysical studies from the northernmost gulf. Pacific-North America plate motion vectors and bathymetry north of Delfín basin (Figure 2) are discussed and reinterpreted. We suggest a structural scenario in the northernmost gulf in which north to NNW striking faults inherited from earlier extension are presently accommodating plate boundary deformation with dextral-oblique slip (Figure 1c). We define the Wagner Transition Zone (Figure 2), named for the major north striking basin in the northern gulf, as the beginning of the continent-ocean transition which merges northward with a broader region

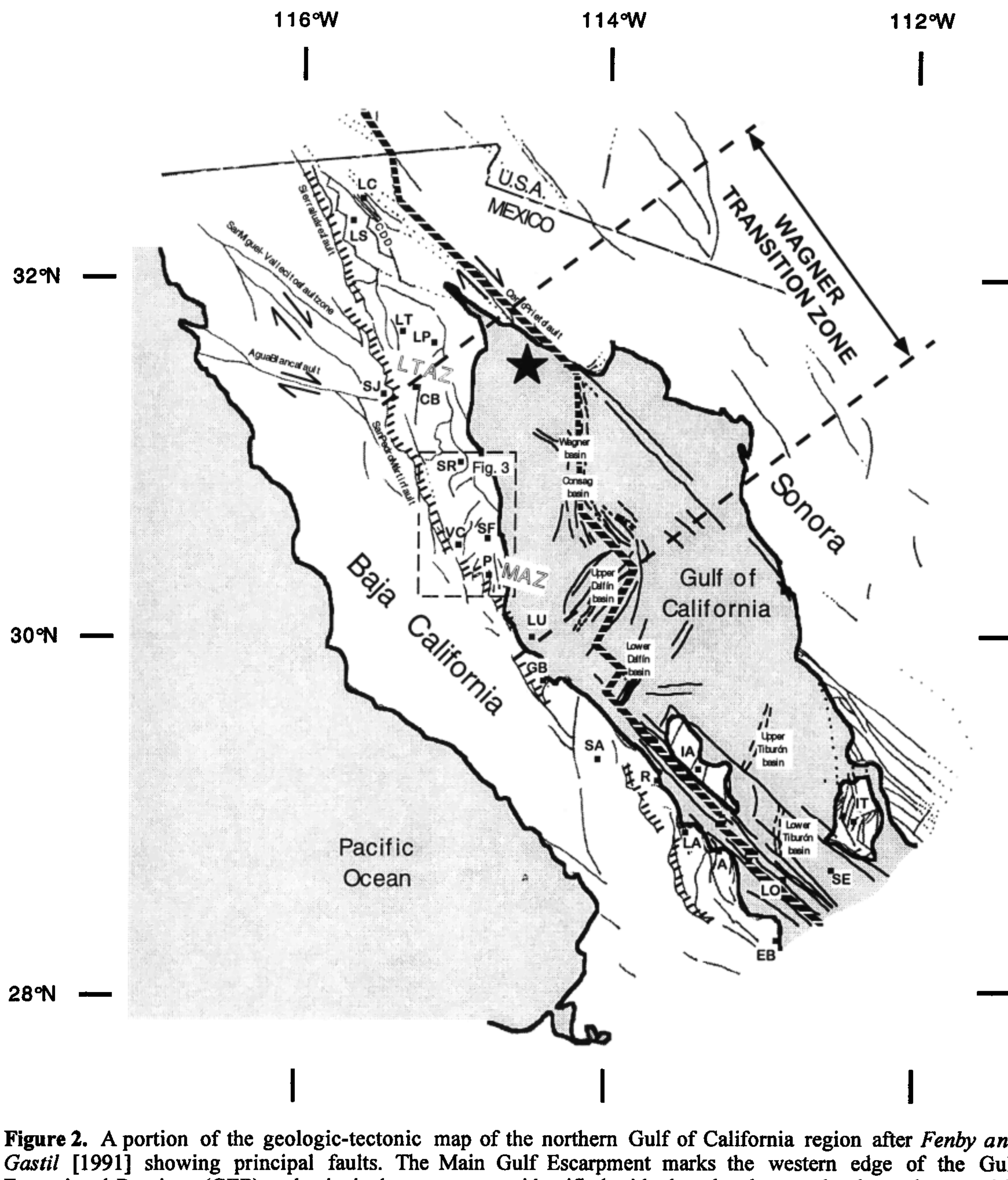


Figure 2. A portion of the geologic-tectonic map of the northern Gulf of California region after *Fenby and Gastil* [1991] showing principal faults. The Main Gulf Escarpment marks the western edge of the Gulf Extensional Province (GEP) and principal structures are identified with short hatches on the down thrown side of normal faults. Principal Pacific-North America plate boundary is marked with thick striped line. The evolution of the Wagner Transition Zone is detailed in Figure 5. Star marks the epicenter (latitude 31.25°N, longitude 114.31°W [*Goff et al.*, 1987]) of the 1969 earthquake. Geographic locations are A, Animas basin; CB, Cerro Borrego; CDD, Cañada David detachment; EB, El Barril; GB, Gonzaga Bay; IA, Isla Angel de la Guarda; IT, Isla Tiburón; LA, Bahia de los Angeles; LC, Sierra de los Cucapas; LO, San Lorenzo island groups; LP, Sierra las Pintas; LS, Laguna Salada; LT, Sierra las Tinajas; LTAZ, Sierra las Tinajas accommodation zone; LU, San Luis island groups; MAZ, Matomí accommodation zone; P, Puertecitos Volcanic Province; R, Bahia de Remedios; SA, Sierra la Asamblea; SE, Isla San Esteban; SF, Sierra San Fermín; SJ, southern Sierra Juárez; SR, Santa Rosa basin; VC, southern Valle Chico.

of continental deformation north of the Agua Blanca fault. While previous workers questioned a simple continuation of the spreading center system into the northernmost gulf [e.g., *Lomnitz et al.*, 1970; *Henyey and Bischoff*, 1973; *Goff et al.*, 1987], our structural model helps explain the evolution of spreading center and transform fault adjustments [e.g., *Lonsdale*, 1989; *Stock*, 2000] in the central gulf over the past 4-6 Myr. Specifically, the juxtaposition of two kinematically partitioned structural provinces provides a mechanism for the northwestward shift of spreading from Upper and Lower Tiburón basins (Figure 2) into Upper and Lower Delfín basins at ~2-3 Ma and offers an explanation for the geographic location of these basins. The model can also explain late Miocene-Pliocene adjustments in rift margin geometry in the Puertecitos Volcanic Province [*Stock*, 2000; *Nagy*, 2000].

2. Tectonic History of the Gulf of California and Nearby Regions

The gulf region experienced a complex history of Cenozoic deformation associated with three distinct phases of the evolving Pacific-North America plate boundary: (1) pre-late Miocene east directed subduction of Farallon plate fragments beneath North America, (2) late Miocene partitioning of deformation between ENE directed extension east of Baja California and dextral strike-slip faulting west of the peninsula, and (3) latest Miocene to Recent development of transform faults and spreading centers accommodating NW-SE directed relative plate motion.

1. Approach of the Pacific-Farallon divergent plate boundary to the Farallon-North America subduction zone resulted in Farallon plate breakup starting just after Chron 10 [*Atwater and Stock*, 1998] (28 Ma on timescale of *Cande and Kent* [1995]) and had a significant effect on North America deformation. Coupling between the Pacific and North America plates [e.g., *Nicholson et al.*, 1994; *Bohannon and Parsons*, 1995] resulted in the broad transmission of NW directed Pacific plate motion across the western United States to produce diffuse Basin and Range extensional deformation. As early as 30 Ma, but at least by 17 Ma, western Mexico experienced ENE directed southern Basin and Range extension, including a major episode at ~12-13 Ma [*Zoback et al.*, 1981; *Henry*, 1989; *Christiansen and Yeats*, 1992; *Nourse et al.*, 1994; *Henry and Aranda-Gómez*, 1992; *Gans*, 1997; *Henry and Aranda-Gómez*, 1997; *McDowell et al.*, 1997]. Following Pacific-North America plate contact, the Rivera triple junction migrated southwards along the western side of the Baja California peninsula, replacing subduction of the Farallon plate with a transcurrent plate boundary [*Atwater*, 1970]. This change occurred at ~20 Ma at the latitude of northernmost Baja California and reached midway down the peninsula by ~13 Ma [*Stock and Lee*, 1994] at which time (end of Chron 5A) subduction ceased simultaneously west of the southern half of the peninsula [*Atwater*, 1970; *Mammerickx and Klitgord*, 1982; *Atwater*, 1989; *Spencer and Normark*, 1989; *Stock and Lee*, 1994]. The Pacific-North America relative plate motion changed direction from N60°W (30 Ma to ~8 Ma) to N37°W (~8 Ma to the present), and the rate of relative displacement increased from ~33 to ~52 mm/yr around 12 Ma [*Atwater and Stock*, 1998].

2. Following the cessation of subduction, and until at least 5.5 Ma, Pacific-North America relative plate motion at the latitude of Baja California was partitioned between large, dextral, offshore transform faults located along and subparallel to the former trench, such as the Tosco-Abreojos and San Benito faults (Figure 1) [*Krause*, 1965; *Spencer and Normark*, 1979], and proto-gulf structures accommodating ENE directed Gulf Extensional Province (GEP) extension to the east of the present-day peninsula [*Stock and Hodges*, 1989]. At least 200 km of dextral strike-slip motion along the Tosco-Abreojos fault zone displaced features such as the Magdalena fan and the Franciscan subduction complex belt [*Lonsdale*, 1991; *Crouch and Suppe*, 1993]. It is conceivable that the offshore transforms accommodated a normal component of motion in addition to strike-slip displacement. The GEP is the region of high-angle normal faults bordering the Gulf of California in Mexico which is essentially continuous with the southern Basin and Range Province [*Zoback et al.*, 1981; *Henry*, 1989; *Henry and Aranda-Gómez*, 1992, 2000]. A 45° clockwise change in the least principal stress direction 13-10 Ma in the southern Basin and Range Province north of Mexico to NW to WNW directed extension [*Zoback et al.*, 1981] has not been identified within the GEP portion of the southern Basin and Range Province [e.g., *Karig and Jensky*, 1972; *Gastil et al.*, 1975]. A major period of southern Basin and Range extension at ~12 Ma [e.g., *Henry and Aranda-Gómez*, 1992, 2000] may have been related to an increase in the Pacific-North America plate motion rate from ~33 to ~52 mm/yr at ~12 Ma as determined by *Atwater and Stock* [1998]. Proto-gulf extension occurred within a broad region, including a western zone thermally weakened by the early Miocene subduction-related volcanic arc [*Hausback*, 1984; *Lonsdale*, 1989; *Stock and Hodges*, 1989], and produced the Main Gulf Escarpment in Baja California marking the western GEP rift margin (Figure 2) [*Gastil et al.*, 1971, 1975].

3. NW-SE directed extension began ~5.5 Ma in the mouth of the gulf with brittle and ductile stretching of the upper and lower continental crust, respectively [*Curray and Moore*, 1984]. By ~4 Ma, pull-apart basins formed at step overs between newly formed, NW striking dextral transform faults along most of the length of the gulf [*Lonsdale*, 1989]. Since ~3.5 Ma (Anomaly 2A), 45-50 mm/yr of Pacific-North America relative motion occurred along the new spreading center system north of the Tamayo fracture zone (Figure 1, inset) [*Larson et al.*, 1968; *Curray and Moore*, 1984; *Lonsdale*, 1989; *DeMets*, 1995]. *Lonsdale* [1989] postulated that a slight counterclockwise rotation of relative plate motion from 3.5 Ma until the present caused several changes within the gulf including (1) reorientation of transform fault azimuths and spreading center axes, (2) breakup of spreading centers into offset pairs, and (3) the abandonment of old spreading centers and the creation of new ones. Interestingly, post-6 Ma extension documented along the western GEP rift margin in most of eastern Baja California remained east to NE directed during Pliocene and Recent times, notably perpendicular to approximately NW-SE directed relative plate motion [*Karig and Jensky*, 1972; *Gastil et al.*, 1975; *Angelier et al.*, 1981; *Dokka and Merriam*, 1982; *Hausback*, 1984; *Stock and Hodges*, 1990; *Zanchi*, 1994; *Martín-Barajas and Stock*, 1993; *Umhoefer et al.*, 1994; *Umhoefer and Stone*, 1996; *Nagy*, 1997; *Lewis and Stock*, 1998a; *Nagy*, 2000]. A Pliocene clockwise rotation to east to SE directed extension along the western GEP margin in southern Baja California [*Angelier et al.*, 1981; *Zanchi*, 1994; *Umhoefer and Stone*, 1996] is attributed to the increasing influence of approximately NW-SE directed Pacific-North America relative plate motion.

3. Diffuse Deformation in Northeastern Baja California

The timing, direction, and nature of extensional deformation in northeastern Baja California are summarized here and are incorporated into Pacific-North America plate motion vector calculations in section 5. Regions are discussed from north to south and are identified in Figure 2. Extension is localized east of the Main Gulf Escarpment, although deformation also occurs along transpeninsular strike-slip faults such as the Agua Blanca and San Miguel faults.

East of the Main Gulf Escarpment in northernmost Baja California, represented by the Sierra Juárez fault, the Laguna Salada area records a significant amount of relatively recent E-W extension. East-side-down normal faulting along the Sierra Juárez fault produced the steep eastern range front of the Sierra Juárez, which is actually in the hanging wall of the west dipping Cañada David detachment, thus making the range front a faulted rollover structure antithetic to the detachment system [*Axen*, 1995]. The detachment system is exposed east of Laguna Salada, accommodated at least 14-18 km of E-W directed extension in late Miocene to Pliocene time, and may still be active [*Axen and Fletcher*, 1998; *Axen et al.*, 1999]. Many of the high-angle NW striking faults in the Laguna Salada region that cut the low-angle detachment faults exhibit pure normal displacement, although dextral-oblique normal slip also occurs on major NW striking faults in the Sierra de los Cucapas [e.g., *Gastil et al.*, 1975; *Axen and Fletcher*, 1998].

Extensional deformation recorded east of the southern Sierra Juárez is generally older and less well constrained than deformation to the north. NNW to NE striking normal faults postdate 7-9 Ma volcanic rocks in the Sierra las Pintas [*McEldowney*, 1970], and WNW striking faults are present in the northern part of the range [*Gastil et al.*, 1975]. NW striking, east dipping normal faults in the Sierra las Tinajas offset Tertiary volcanic rocks [*Gastil et al.*, 1971, 1975]. The Miocene Sierra las Tinajas accommodation zone, located approximately at the intersection of the Agua Blanca fault and the Main Gulf Escarpment, may separate the east directed fault system to the south from a west directed fault system to the north [*Axen*, 1995]. Approximately 14-16% E-W directed extension in the southern Sierra Juárez (east end of Agua Blanca fault) occurred between 16 and 11 Ma [*Lee et al.*, 1996]. Quaternary NW striking normal faults and east striking dextral strike-slip faults imply ongoing deformation in the southern Sierra Juárez [*Lee et al.*, 1996]. Undated basalt flows in Cerro Borrego have been steeply tilted to the west [*Gastil et al.*, 1975].

The Quaternary Agua Blanca and San Miguel-Vallecitos fault systems accommodate principally strike-slip deformation, transferring a portion of GEP deformation across northern Baja California to the California borderland. The east end of the Agua Blanca fault has not been traced across the Main Gulf Escarpment [e.g., *Lee et al.*, 1996]; thus it remains unclear how it actually connects to gulf extensional structures. About 4 km of Quaternary dextral displacement is evident across the WNW striking Agua Blanca fault zone, which offsets an undated granodiorite massif up to 5 times as much [*Allen et al.*, 1960]. Minor normal displacement also occurs across the fault zone [e.g., *Hatch and Rockwell*, 1986; *Suarez-Vidal et al.*, 1991] which projects offshore west of the peninsula into a transtensional region of dextral-oblique rifting [*Legg et al.*, 1991]. A slip rate of 4 ± 2 mm/yr from Global Positioning System (GPS) studies [*Bennett et al.*, 1996] agrees with a late Quaternary slip rate of 2-5 mm/yr determined from trench excavations [*Hatch and Rockwell*, 1986]. In contrast to the historically aseismic Agua Blanca fault, the NW striking San Miguel-Vallecitos fault system is seismically active, although the maximum dextral offset of Mesozoic geologic features is only 0.3-0.6 km [*Suarez-Vidal et al.*, 1991; *Hirabayashi et al.*, 1996]. Paleoseismic studies estimate a maximum slip rate of 0.2 mm/yr [*Hirabayashi et al.*, 1996], and GPS estimates are 3 ± 3 mm/yr [*Bennett et al.*, 1996].

Dated volcanic rocks tilted in the hanging wall of the active, NNW striking, east dipping San Pedro Mártir fault, which marks the Main Gulf Escarpment north of the Puertecitos Volcanic Province (PVP), have been used to bracket various phases of extension between ~12, ~6, and ~3 Ma. There is evidence for at least 5 km of displacement along the fault [*Gastil et al.*, 1975], which decreases southward to ~ 800 m in southern Valle Chico (Figure 3) [*Stock*, 1989]. Basin and Range-type topography produced by north to NNW striking normal faults characterizes the hanging wall. ENE directed extension began between 12 and 6 Ma east of the fault [*Stock*, 1989, 1993; *Lewis*, 1996; *Lewis and Stock*, 1998a; *Stock et al.*, 1999], and stratigraphic relationships suggest that significant uplift of the Sierra San Pedro Mártir began prior to ~9 Ma [*Gastil et al.*, 1979]. Estimated amounts of pre-6 Ma extension in the Sierra San Felipe and Sierra San Fermín (Figure 3) are 5-15% [e.g., *Stock*, 1993; *Lewis and Stock*, 1998a]. NE striking sinistral faults also characterize the region east of the Valle de San Felipe and are post-6 Ma in the southern Sierra San Fermín [e.g., *Gastil et al.*, 1975; *Lewis and Stock*, 1998a]. Post-6 Ma extension (7-10%) remained east to NE directed [*Stock and Hodges*, 1990; *Lewis and Stock*, 1998a]. *Lewis and Stock* [1998b] calculate significantly greater extension (20%) in the Sierra San Fermín manifested as dextral shear over the past 3-6 Myr. They use a model of oblique divergence to predict ~21 km of shear in the direction of plate motion (N45°W) and ~7 km of ENE directed extension over a ~50-km-wide region (E-W) between the Valle de San Felipe fault and the east side of the Sierra San Fermín. *Lewis and Stock* [1998a] determine an ENE directed axis of least principal stress in Plio/Quaternary time and an east directed axis in late Miocene time (prior to any corrections made for subsequent rotational deformation) for the region of dextral shear in the Sierra San Fermín. One exception to the ENE directed extension found east of the San Pedro Mártir fault is post-12 Ma ESE directed extension documented in the Santa Rosa basin [*Bryant*, 1986] (geochronology updated by *Stock et al.* [1999]); however, late Miocene or Pliocene vertical axis clockwise rotation of the basin may have produced the anomalous direction [*Stock et al.*, 1999].

The Puertecitos Volcanic Province (PVP) is a large, late Miocene-Pliocene ignimbrite field which is deformed by closely spaced, NNW to NNE striking normal faults accommodating <5% post-6 Ma (probably post-3 Ma) east to NE directed extension [*Gastil et al.*, 1975; *Dokka and Merriam*, 1982; *Stock et al.*, 1991; *Martín-Barajas et al.*, 1995; *Nagy*, 1997, 2000]. Prior to ~6 Ma the NW striking Matomí accommodation zone (Figure 3) segmented the GEP rift margin at the southern end of the San Pedro Mártir fault and projected through the northern PVP region [*Dokka and Merriam*, 1982; *Stock*, 1989; *Stock and Hodges*, 1990; *Stock*, 1993; *Axen*, 1995; *Nagy*, 1997; *Stock*, 1999; *Nagy*, 2000]. Most of the PVP region thus remained outside of, although just on the edge of, the GEP rift margin prior to 6 Ma. Some structures associated with the Matomí accommodation zone were abandoned before 6 Ma; the GEP rift margin eventually migrated westward to incorporate the PVP into the region of ENE directed extension [*Nagy*, 1997, 2000]. Post-6 Ma Matomí accommodation zone structures have not been identified in the PVP region, although their presence is required along the southern boundary of late Miocene-Pliocene vertical axis block rotations in the hanging wall of the San Pedro Mártir fault [*Lewis and Stock*, 1998b; *Nagy*, 2000]. In section 6 we detail how incorporation of the PVP into the GEP and the commencement of rotational deformation to the north may be related to late Pliocene adjustments in the offshore spreading center system.

South of the PVP, where the Main Gulf Escarpment is discontinuous and less well defined, deformation is related to extension as well as to the offshore spreading center system. The Gonzaga Bay region is divided into three north trending fault-bounded valleys [*Gastil et al.*, 1975] where *en echelon* NW striking, NE-side-down normal faults cut the escarpment fault [*Axen*, 1995]. Although there is no evidence for Miocene ex-

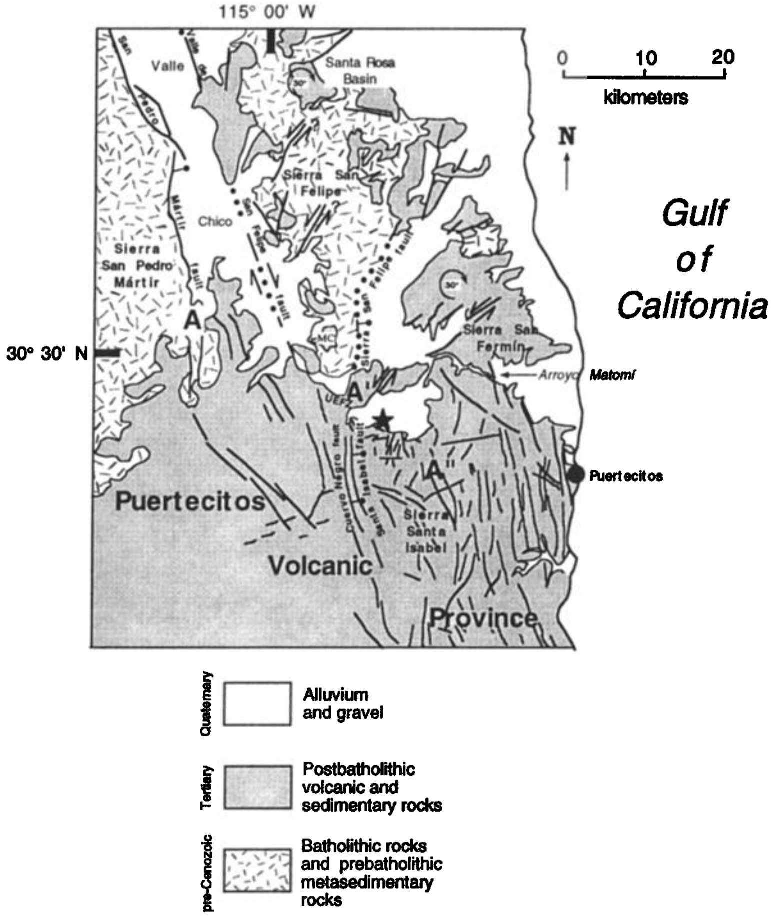


Figure 3. Geologic map [after *Gastil et al.*, 1975] of a portion of northeastern Baja California showing localities and faults discussed in text. Ball and bar are on downthrown side of normal faults; arrows indicate sense of slip on strike-slip faults (queried where uncertain); faults are dotted where concealed. The Sierra San Fermín and Santa Rosa basin in the northern Sierra San Felipe have undergone 30° of vertical axis clockwise rotation relative to Mesa Cuadrada (MC) in the southern Sierra San Felipe and Santa Isabel Wash (star) in the northern PVP as observed in 3 Ma, 6 Ma, and 12.6 Ma pyroclastic flow deposits [*Strangway et al.*, 1971; *Lewis*, 1994; *Nagy*, 1997; *Lewis and Stock*, 1998b; *Stock et al.*, 1999; *Nagy*, 2000]. The Matomí accommodation zone ((A-A', including the Ultima Esperanza fault zone (UEFZ)) after *Stock* [2000] and (A'-A") after *Nagy* [1997, 2000]) separated a region of pre-6 Ma extension to the north from an unextended region to the south. Given the amount of separation across the Main Gulf Escarpment in the nearby southern Valle Chico (~800 m [*Stock*, 1989]), the Santa Isabel and Cuervo Negro faults probably represent principal structures presently accommodating deformation in the PVP.

tensional deformation in the Remedios region, Plio-Quaternary structures consistent with a dextral wrench regime include NNW to NNE striking normal and sinistral faults, NE striking thrust faults, and east striking normal and dextral faults [*Parkin*, 1998; *Parkin and Axen*, 1998]. Between the Remedios and El Barril regions, the Bahia de los Angeles and Animas basins consist of north striking faults bounding Basin and Range-type topography, and the east dipping Main Gulf Escarpment swings abruptly to N80°W [*Gastil et al.*, 1975]. NNW to NNE striking normal faults within recent fluvial deposits in the Bahia de los Angeles region may be associated with emplacement of shallow, basaltic magma bodies [*Delgado-Argote and García-Abdeslem*, 1999].

Extensional deformation is also documented on the Midriff Island, although the timing is poorly constrained. Isla Tiburón experienced post-12 Ma extension along NNE to NNW striking faults [*Gastil and Krummenacher*, 1977]. Isla Angel de la Guarda consists of north to NW striking normal faults bounding tilted Miocene(?) volcanic rocks and overlain by flat-lying Pliocene(?) volcanic rocks [*Gastil et al.*, 1975]. Deformation on smaller islands includes normal faults noted on Isla San Esteban [*Desonie*, 1992] and within the San Luis and San Lorenzo island groups [*Rossetter*, 1973]. Two populations of crevasses and structural lineaments on Holocene Isla San Luis trend due north and N50°W [*Rossetter*, 1973; *Gastil et al.*, 1975, 1983].

In summary, many faults in northeastern Baja California strike NNW to NNE and accommodate primarily dip-slip deformation. Although NW striking dextral transform faults dominate the plate boundary to the north (i.e., San Andreas fault system), oblique- to pure dip-slip motion occurs on NW striking faults in Laguna Salada, the Sierra las Tinajas, and the northern PVP. Estimates of pre-6 Ma ENE directed extension (10-15%) are slightly greater than post-6 Ma estimates (5-10%) with the significant exception of the Sierra San Fermín, where 20% ENE directed extension is predicted by a model of oblique divergence [*Lewis and Stock*, 1998b]. The Main Gulf Escarpment is well-developed north of the PVP, partitioned onto multiple structures within the PVP, and discontinuously exposed to the south.

4. Geophysical Data

Geophysical data from the northernmost gulf, which generally preclude the presence of active spreading, include heat flow, gravity, and seismic surveys, and earthquake seismicity. More than a quarter of a century ago, *Henyey and Bischoff* [1973, pp. 328 and 323] presented seismic profiles and preliminary heat flow data from multiple transects across the northern gulf and concluded that the data "do not support a spreading center centered on Upper Wagner basin" and that "a simple picture of several small spreading centers connected by transform faults trending toward the Colorado River delta and the Imperial Valley does not appear to be justified." Their findings included small-scale Basin and Range-type relief between Lower Delfin and Wagner basins (Figure 2), lower observed heat flow in Wagner basin relative to Delfin basin, and abrupt changes in structural trends and bathymetry north of Lower and Upper Delfin basins. In particular, bathymetric contours in the central and southern gulf [e.g., *Dauphin and Ness*, 1991] generally parallel the NW striking transform faults south of latitude 30°N but have a northerly trend around ~31°N. Significantly, this change is paralleled by a bend in the Baja California coastline near 30°N. Subsequent heat flow studies [e.g., *Gastil et al.*, 1975; *Sanchez-Zamora et al.*, 1991] also indicate that values in the Wagner basin are lower than those measured in other regions of the gulf. For example, *Sanchez-Zamora et al.* [1991] compute an average heat flow of 114 mW/m^2 in the central part of the northern gulf. This is slightly greater than the average observed by *Henyey and Bischoff* [1973] (~100 mW/m^2), but both are less than the background heat flow within the nearby, actively extending Guaymas basin (180 ± 10 mW/m^2 [*Sanchez-Zamora et al.*, 1991]) and significantly less than measured values up to 9 W/m^2 [*Becker and Fisher*, 1991].

Seismic refraction profiles indicate that the depth to the Moho averages 9.4 km across the southern and central gulf, whereas in the northern gulf, although poorly defined, it is 20-25 km below the surface [*Gastil et al.*, 1975]. More recent geophysical cross sections based upon seismic refraction measurements, gravity, and magnetic data indicate that the minimum crustal thickness across the northern gulf is ~13 km, which is twice as thick as crust measured in the southern gulf but notably about half as thick as normal continental crust [*Couch et al.*, 1991]. Recent seismic reflection data show the Moho depth to be >15 km beneath the Upper Delfin Basin [*González-Fernández et al.*, 1999]. Greater rates of seismic slip (estimated from seismic moment data) observed in the northern versus southern gulf suggest a stronger coupling of the plate boundary in the north due to the different plate boundary natures [*Tajima and Tralli*, 1992]. Free-air gravity lows associated with basins/spreading centers in the southern gulf, most likely related to lithospheric thinning, are not present in the northern gulf [e.g., *Couch et al.*, 1991].

Seismic events large enough to produce focal mechanisms are rare in the northernmost gulf, and small earthquakes do not delineate coherent fault patterns. Fault plane solutions for a series of earthquakes in March 1969 (M_B = 5.3, 5.6) near Wagner basin (location in Figure 2) suggest oblique-slip normal faulting [*Lomnitz et al.*, 1970; *Thatcher and Brune*, 1971; *Goff et al.*, 1987]. *Thatcher and Brune* [1971] produced a focal mechanism for the largest event with dextral-oblique normal slip on a N5°E, 70°SE fault plane or, alternatively, sinistral-oblique normal slip on a N50°E, 60°NW fault plane. If NE striking sinistral strike-slip faults in northeastern Baja California continue offshore, the NE striking fault plane solution could, in fact, represent the plane of rupture. More recently, *Goff et al.* [1987] generated a slightly different focal mechanism (35/43/274 (strike/dip/slip, in degrees, after convention by *Aki and Richards* [1980]) for the M_B = 5.6 event by adopting a crustal structure determined by *Ebel et al.* [1978] from their study of the 1966 El Golfo earthquake (M_B = 6.3) along the Cerro Prieto fault.

A geodetic network measured by laser trilateration methods using electronic distance measurements (EDM) between eastern Baja California and western Sonora, which included stations on Isla Tiburón and Angel de la Guarda, reveals that dextral shear strain covers the entire gulf via motion along several faults [*Ortlieb et al.*, 1989]. The study confirms regional Plio-Quaternary E-W extension and N-S compression identified from focal mechanism analyses [*Goff et al.*, 1987]. Over a 4-year period an average NW directed relative velocity of 8 ± 3 cm/yr occurred across the entire zone in a dextral sense, although relative motion between Baja California and the Midriff Islands varied. For example, 17 ± 4 cm dextral displacement occurred between the peninsula and Isla de la Guarda over the 4-year period, whereas farther south, west of Isla San Esteban, relatively minor deformation remained within the range of estimated errors. *Ortlieb et al.* [1989] suggest that this region may be a locked zone within the plate boundary. In contrast, slip estimates determined from GPS studies along the Cerro Prieto fault (42 ± 1 mm/yr) and transpeninsular faults (~7 mm/yr of slip) account for essentially all relative plate boundary motion in northernmost Mexico [*Bennett et al.*, 1996].

5. Pacific-North America Plate Motion Vectors

Diffuse dextral shear documented in northeastern Baja California, manifested as east to NE directed extension and vertical axis rotations, may represent a component of Pacific-North America plate boundary deformation [e.g., *Lewis and Stock*, 1998a]. Submerged, poorly understood structures in the northernmost gulf (near Consag and Wagner basins) undoubtedly accommodate plate motion deformation as well. Basin and Range extensional deformation to the east ended at ~6 Ma in northern Sonora and southern Arizona, with minor Pliocene and Quaternary faulting continuing in northeastern Sonora and adjacent Chihuahua [*Christiansen and Yeats*, 1992]. We thus assume in the following discussion that all plate boundary deformation north of latitude 30°N and south of the eastern end of the Agua Blanca fault is accommodated by slip on structures in northeastern Baja California as well as those in the northernmost gulf. The direction and magnitude of deformation along all of these structures should sum to the total Pacific-North America plate motion vector.

A vector representing present-day Pacific-North America relative plate motion is shown in Figure 4 at a rate of ~52 mm/yr and oriented N37°W as determined from plate reconstruction models [*Atwater and Stock*, 1998]. This direction of Pacific-North America relative plate motion agrees with other global plate motion models [e.g., *Minster and Jordan*, 1978; *DeMets et al.*, 1990, 1994] but differs slightly from directions calculated by other methods such as from GPS studies (N40-45°W [e.g., *Bennett et al.*, 1996; *Shen et al.*, 1997]) or earthquake slip vector azimuths (N48°W to N57°W [*Goff et al.*, 1987]). The latter are in good agreement with major bathymetric trends of transform faults but distinctly counterclockwise of the plate reconstruction and GPS estimates, which might indicate that the Baja California microplate does not exactly

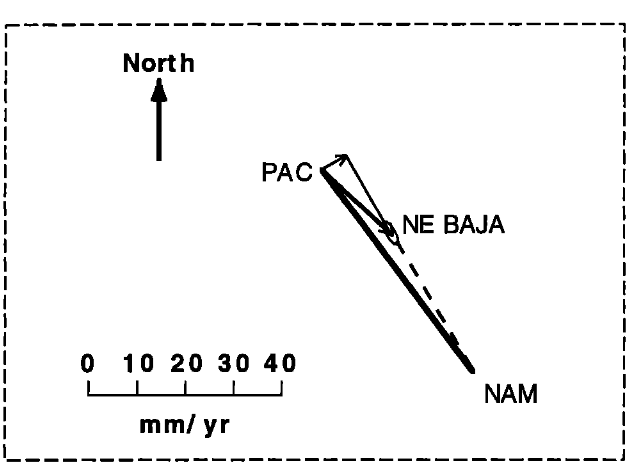


Figure 4. Vector diagram showing present-day Pacific-North America relative plate motion direction (~52 mm/yr oriented N37°W after *Atwater and Stock* [1998]) and slip motion vectors at the latitudes of 30-31°N that sum to the total plate motion. Thin lines with arrowheads represent ENE directed extension (6 mm/yr) and NNW directed shear (18 mm/yr) predicted by the oblique divergence model of *Lewis and Stock* [1998b] for northeastern Baja California. These two components sum to 19 mm/yr oriented N45°W (vector between PAC and NE BAJA). The ellipse represents 15% uncertainty derived from the paleomagnetic data upon which the model relies but does not include uncertainties related to the age of rotations. The remaining vector required to sum to the total plate motion is oriented N31°W at 32 mm/yr (dashed line). We suggest that this remaining motion is accommodated on one or more north to NNW striking dextral oblique-slip faults.

move with Pacific plate velocity [*Lonsdale*, 1989]. These discrepancies do not affect the principal conclusions in the following vector calculations.

The vector diagram in Figure 4 incorporates a component of motion representing extensional and rotational deformation in northeastern Baja California. Geologic studies (in section 3) suggest 5-10% extension since latest Miocene time but perhaps as much as 20% as predicted by a model for oblique divergence in the rotated regions south of the eastward projection of the Agua Blanca fault and east of the Valle de San Felipe fault [*Lewis and Stock*, 1998b]. The block rotations are at least post-6 Ma events and, possibly, post-3 Ma [*Strangway et al.*, 1971; *Lewis and Stock*, 1998b; *Nagy*, 2000]. If rotation rates were constant, the oblique divergence model of *Lewis and Stock* [1998b] predicts that eastern Baja California should have accommodated 2.3 mm/yr ENE directed extension and 7 mm/yr of shear in the direction of relative plate motion (N45°W in their analysis) over the past 3 Myr. If rotations occurred over the past 6 Myr, the predicted rates would be correspondingly halved. If the region of shear deformation extends offshore, for example, from the coast to the Wagner and Consag basins, these rates would be 2-3 times greater. The rates would also be greater if the block rotations began at a younger time (i.e., more recently than 3 Ma). We use a somewhat intermediate ENE directed extension rate of 6 mm/yr in the vector diagrams in Figure 4, although the following discussion is viable using smaller extension rates as well. The uncertainties in net clockwise rotations determined by *Lewis and Stock* [1998b] are significant (30° ± 16°); however, subsequent paleomagnetic studies within ~12.6 and 6.5 Ma ash flow tuffs also find ~30° (±5°) of clockwise rotation of Santa Rosa Basin and the Sierra San Fermín relative to the unrotated (or very slightly rotated) Santa Isabel Wash region in the northern PVP (Figure 3) [*Stock et al.*, 1999; *Nagy*, 2000]. We thus assume uncertainties of the order of ±15% for extension and shear deformation rates. Post-6 Ma extension between the Main Gulf Escarpment and the Valle de San Felipe fault (3.5% [*Stock and Hodges*, 1990]) and in the PVP (< 5%, [*Nagy*, 1997, 2000]) corresponds to <1 mm/yr and thus is not depicted in the vector diagrams. Although the active San Pedro Mártir fault has extensive Quaternary scarps, there is no evidence to date that slip rates are greater than ~1 mm/yr [*Brown*, 1978].

The extensional (6 mm/yr) and corresponding shear (18 mm/yr) components predicted by the oblique divergence model sum to 19 mm/yr oriented N45°W. This does not necessarily represent present-day motion given the uncertainty in the timing of rotational deformation. The remaining vector needed to sum to the total plate motion is oriented N31°W at 32 mm/yr (dashed line in Figure 4). On the basis of north trending bathymetric contours and geophysical observations precluding active rifting, we infer the presence of north to NNW striking dextral-oblique normal slip faults in the northern gulf which are not necessarily associated with incipient spreading centers. Depending on the age of the submerged structures, they may have originally accommodated ENE directed extension via dip-slip motion and now experience dextral oblique-slip since the faults are not parallel to the plate motion vector direction. This interpretation agrees with oblique rifting models for the Gulf of California which predict dextral-oblique normal slip along faults striking between north (normal slip predicted) and NW (dextral strike-slip predicted) [e.g., *Withjack and Jamison*, 1986].

6. Wagner Transition Zone and Spreading Center Formation

We define the Wagner Transition Zone [see also *Nagy*, 1997; *Nagy and Stock*, 1998] as a region of diffuse, transtensional deformation northwest of Delfín basin and south of the Agua Blanca fault, which includes the portion of the gulf seafloor containing the Wagner and Consag basins (Figure 2) and Basin and Range-type bathymetric features. The orientations of the northwestern and southeastern boundaries are chosen perpendicular to Pacific-North America relative plate motion because offsets summed across any zone perpendicular to the plate motion direction should yield a consistent value. We infer that the region southeast of the Wagner Transition Zone accommodates essentially all relative plate motion discretely along oceanic-type transform faults and spreading centers. This interpretation is supported by Plio-Quaternary deformation related to the nearby spreading center system subaerially exposed in areas such as Bahia de Remedios (Figure 2) [*Parkin*, 1998; *Parkin and Axen*, 1998].

For simplicity, we restrict the Wagner Transition Zone model to regions south of the Agua Blanca fault, although the transitional style of deformation in the Wagner Transition Zone is largely continuous with the area to the north (the relationship between the Wagner Transition Zone and the region north of the Agua Blanca fault is discussed in section 7.1). The Wagner Transition Zone is bounded on the west by the San Pedro Mártir fault north of the PVP and by major north to NNW striking, east dipping faults within the PVP (e.g., Cuervo Negro and Santa Isabel fault systems). The paucity of active deformation in Sonora and southern Arizona suggests that the eastern limit of modern plate boundary deformation is submerged beneath the gulf.

Time-progressive reconstructions illustrating the evolution of Pacific-North America plate boundary structures in the Wagner Transition Zone since 12 Ma are depicted in Figure 5,

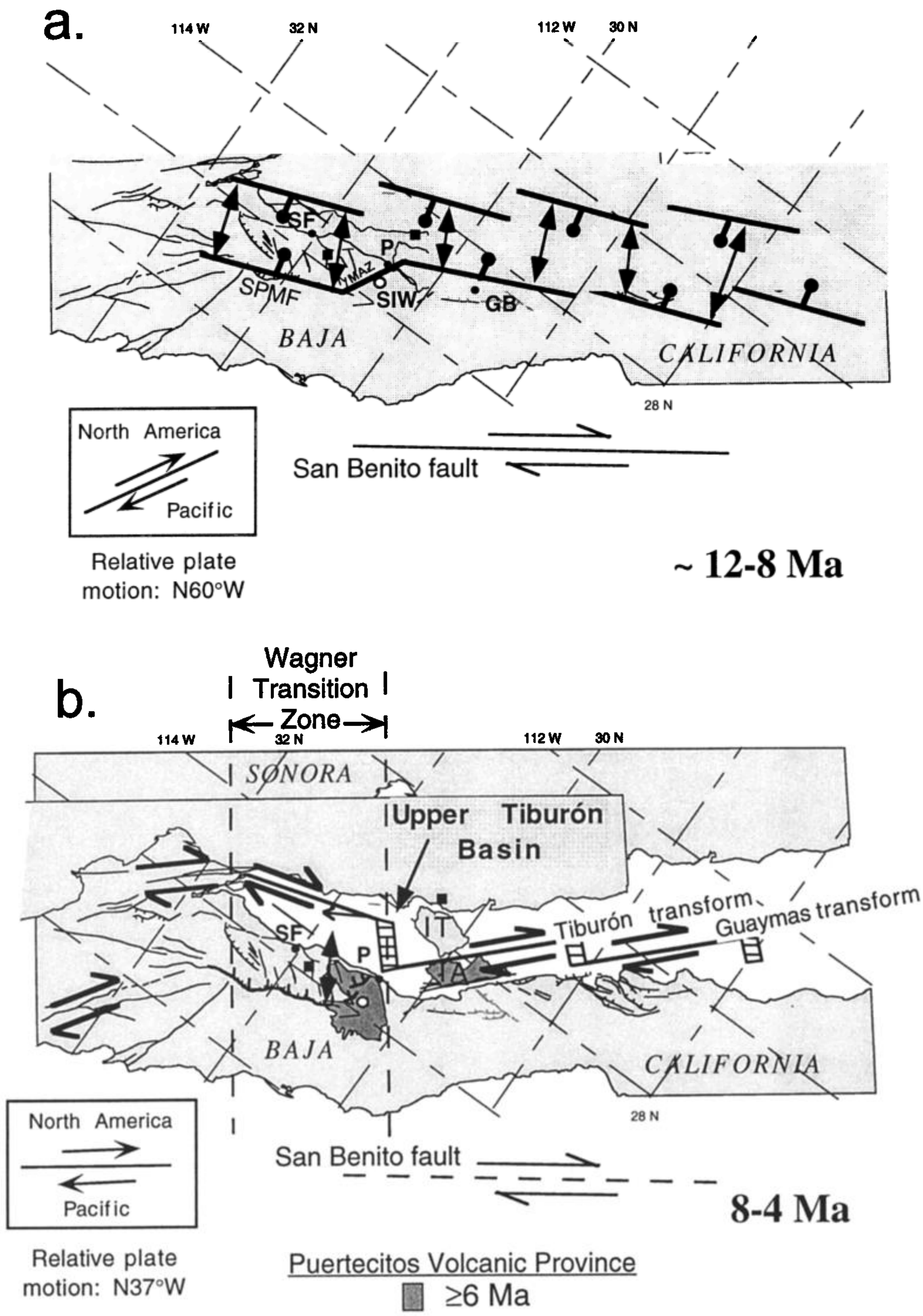
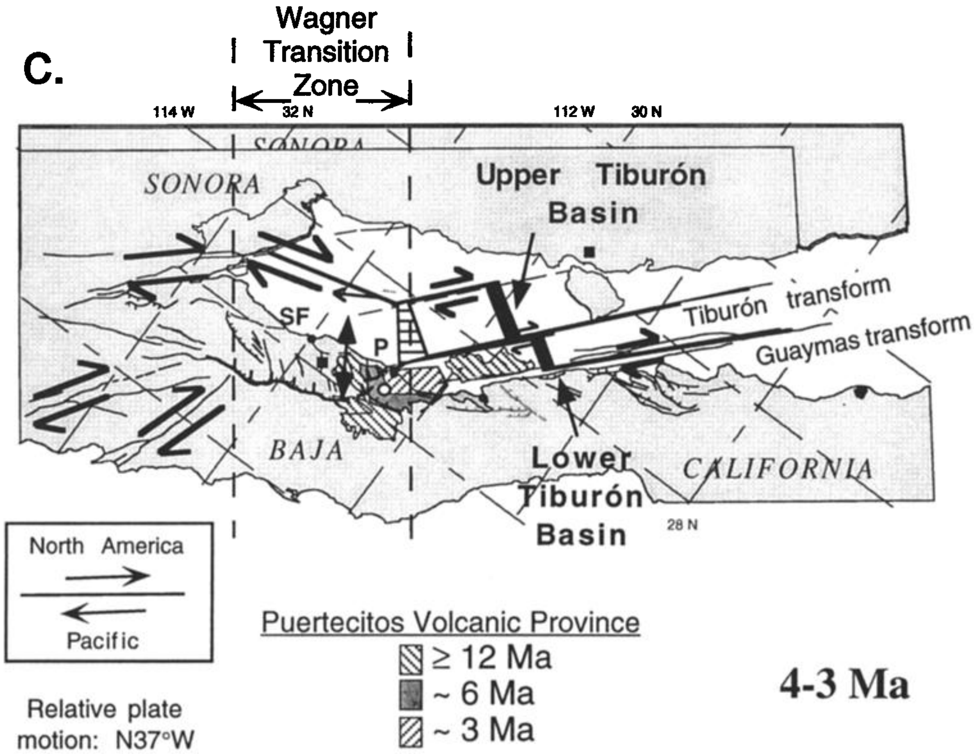


Figure 5. Miocene to present-day reconstructions of the Wagner Transition Zone in the northern Gulf. Most significantly, the model provides a mechanism for the evolution of Upper and Lower Tiburón and Delfín basins. Double-headed arrows indicate extension. Fault notation is as in Figure 3. Solid squares mark the location of a pre-15 Ma geologic tie point [*Gastil et al.*, 1973]. Zones of basin formation are marked with thin horizontal lines; active spreading centers are solid; extinct spreading centers are shown with thick horizontal lines. Small arrow on dextral fault in northernmost Gulf of California (Figures 5b-5e) indicates slip direction required to meet plate motion vector constraints as calculated in Figure 4. Abbreviations are GB, Gonzaga Bay; IA, Isla Angel de la Guarda; IT, Isla Tiburón; MAZ, Matomí accommodation zone; P, town of Puertecitos; SF, town of San Felipe; SIW, Santa Isabel Wash (open circle); WTZ, Wagner Transition Zone. (a) ENE directed extension on NNW striking structures (proto-gulf extension). (b) Upper Tiburón basin created in a zone of divergence (likely source of 6 Ma PVP tuffs). (c) New basin created in zone of divergence at SE margin of WTZ (likely source of 3 Ma PVP tuffs). (d) Upper Tiburón basin abandoned and upper Delfín basin created. (e) Lower Delfín basin created, Lower Tiburón basin abandoned, and Ballenas transform connects to PVP. (f) Extension in upper and lower Delfín basins.



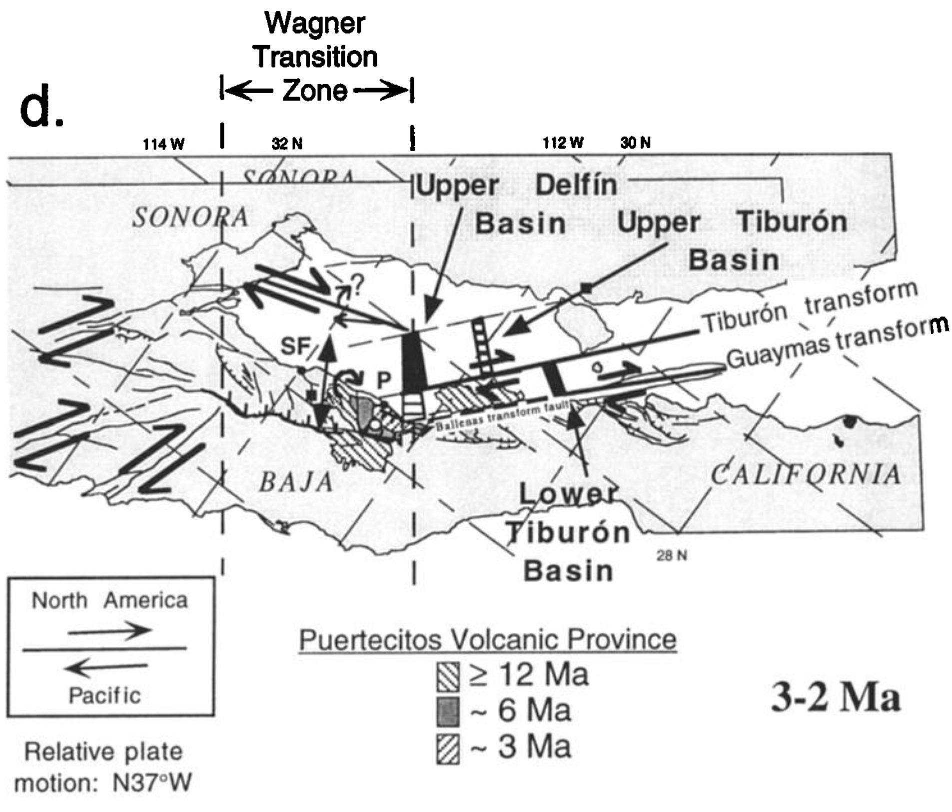
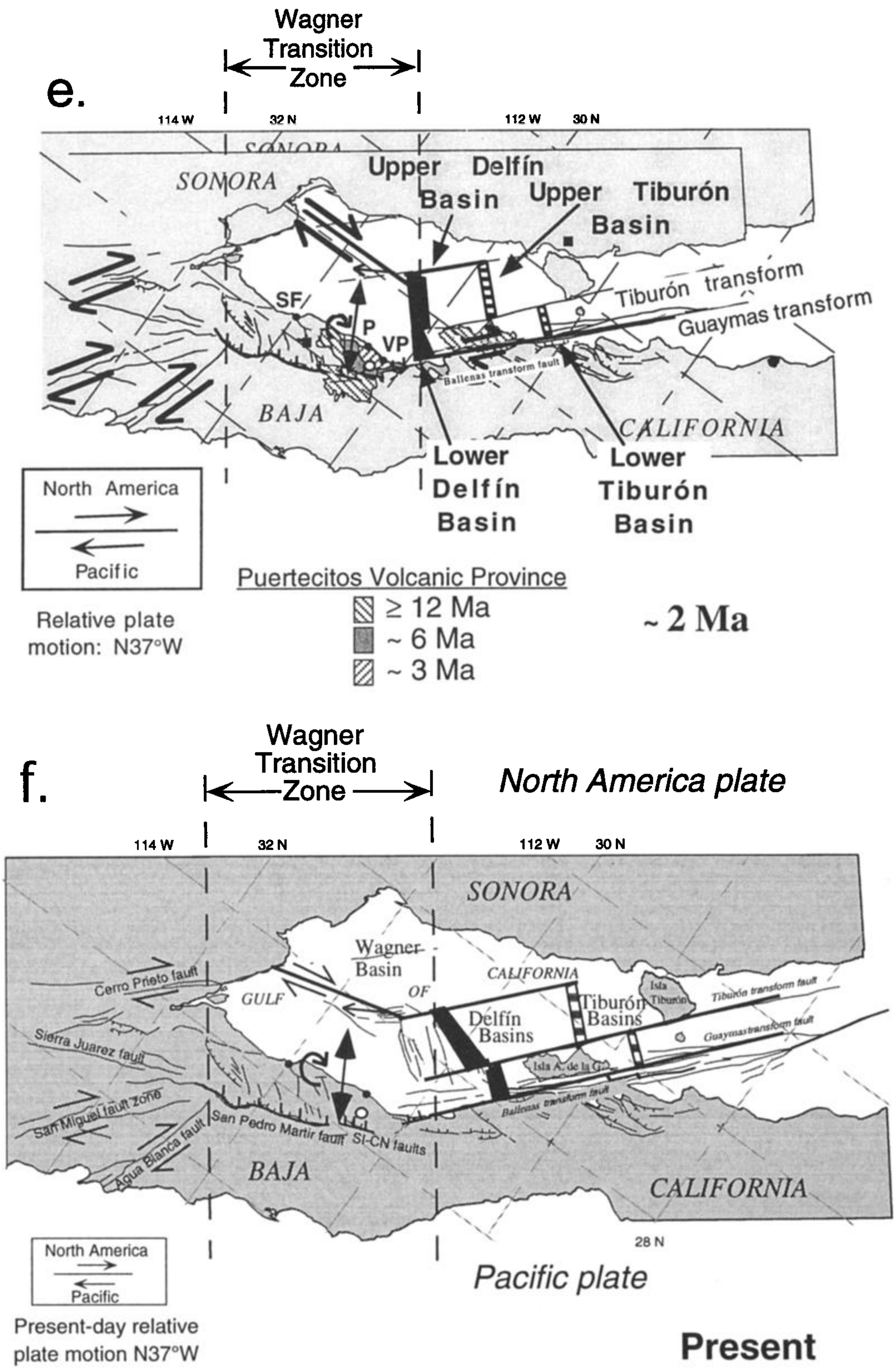


Figure 5. (continued)

and an enlargement showing key kinematic details is given in Figure 6. Restoration of gulf extension for each time interval is made on the basis of the pre-15 Ma geologic tie point of *Gastil et al.* [1973]. Note that the Wagner Transition Zone widens with time perpendicular and parallel to the plate motion direction, thus making the entire region a zone of dilation such as previously noted by *Gastil and Fenby* [1991]. The Santa Isabel Wash region in the PVP is identified in each frame to emphasize changes in the local GEP rift margin over time related to the Matomí accommodation zone. The PVP region is an important area to understand because of its position near the southern and western margins of the Wagner Transition Zone, its recent history of extensional deformation and volcanism, and its relationship to the region of block rotations along its northern margin.

6.1. Between 12 and 8 Ma (Figure 5a)

Between 12 and 8 Ma, Pacific-North America relative plate motion occurred at a rate of ~52 mm/yr oriented ~N60°W [*Atwater and Stock*, 1998]. As a consequence of the obliquity



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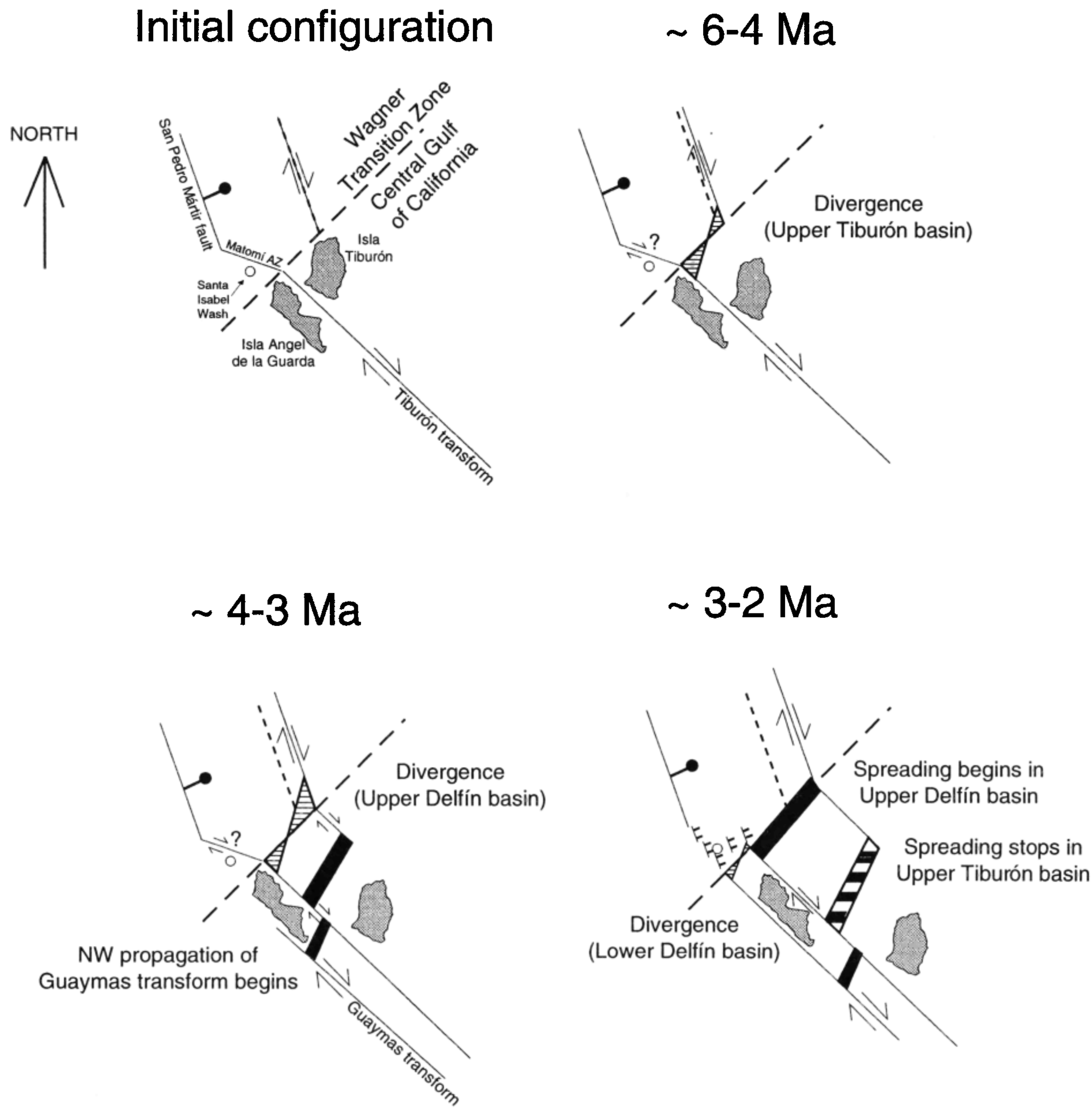

Figure 6. Schematic diagrams detailing how NE striking accommodation zones may have been created at the southern boundary of the Wagner Transition Zone in order to maintain strain compatibility between a domain of diffuse transtensional deformation and another with more localized slip on transform faults. The accommodation zones developed into NW divergent basins, or spreading centers. ENE directed extension causes the Wagner Transition Zone to widen with time as shown by the original position (dashed line) of the dextral oblique-slip fault east of the San Pedro Mártir fault. Spreading center patterns as in Figure 5. Post-6 Ma Matomí accommodation zone structures have not been identified, although their presence is required along the southern boundary of vertical axis block rotations in the hanging wall of the San Pedro Mártir fault [*Lewis and Stock*, 1998b; *Nagy*, 2000].

between plate motion and transform fault orientations west of Baja California, slip is inferred to have been partitioned between these faults and ENE directed proto-gulf extension [*Stock and Hodges*, 1989]. For simplicity, we do not account for potential normal displacement along the offshore transform faults, but we note that this possibility exists. NNW striking normal faults such as the San Pedro Mártir fault developed along the western GEP margin [e.g., *Stock*, 1989]. Transfer structures connected offset portions of the GEP rift margin such as at the southern end of the San Pedro Mártir fault along the approximately NW striking Matomí accommodation zone [*Stock*, 2000; *Nagy*, 2000].

6.2. Between 8 and 4 Ma (Figure 5b)

The Pacific-North America relative plate motion direction changed from N60°W to N37°W around 8 Ma in association with a change in the Pacific-Antarctica spreading direction [*Atwater and Stock*, 1998]. The transform faults to the west of Baja California were still active but may have accommodated smaller amounts of plate motion with time as the plate boundary gradually shifted eastwards into the gulf. Newly oriented structures nascent to the gulf spreading center system developed at 6-4 Ma within the central and southern gulf region, including the Tiburón and Guaymas fracture zone systems and Upper Tiburón basin [*Lonsdale*, 1989]. In contrast to regions to the south, ENE directed extension continued in the Wagner Transition Zone, and we propose that dextral-oblique motion initiated on late Miocene normal faults in the northern gulf to accommodate relative plate motion. A NE striking accommodation zone thus formed at the southeastern margin of the Wagner Transition Zone where east to NE directed transtensional deformation met the region of SE directed motion north of the Tiburón fracture zone. The geometric relationships are shown schematically in Figure 6. The accommodation zone developed NW divergence, localizing the position of a nascent spreading center (Upper Tiburón basin) and triggering the pulse of ~6 Ma volcanism preserved in the PVP and nearby regions [e.g., *Stock*, 1989; *Lewis*, 1996; *Stock*, 2000; *Nagy et al.*, 1999]. The abandonment of some pre-6 Ma Matomí accommodation zone structures in the northern PVP occurred at this time, although a diffuse zone of extensional shear may have subsequently formed in the northeastern PVP to accommodate rotational deformation to the north [*Nagy*, 2000].

6.3. Between 4 and 3 Ma (Figure 5c)

Prior to 3 Ma, the central axis of the NW divergent Upper Tiburón spreading center was displaced to the southeast along the Tiburón fracture zone and thus away from the Wagner Transition Zone (see also Figure 6). Lower Tiburón basin formed east of Isla Angel de la Guarda. While spreading continued in Upper Tiburón basin, a zone of divergence again formed on the southeast margin of the Wagner Transition Zone (future Upper Delfín basin), perhaps associated with the eruption of extensive 3 Ma tuffs in the eastern PVP [e.g., *Martín-Barajas et al.*, 1995]. The timing of new basin development probably depended upon the rate and net direction of extension distributed along the southeastern limit of the Wagner Transition Zone. Incorporation of the PVP into the region of GEP extension may have occurred during this time or, as suggested next, after 3 Ma.

6.4. Between 3 and 2 Ma (Figure 5d)

Spreading shifted completely from Upper Tiburón basin to Upper Delfín basin. Between 2 and 3 Ma, the Guaymas fracture zone propagated to the northwest along the Ballenas channel, possibly in an effort to link with a westward spreading center jump from Lower Tiburón basin east of Isla Angel de la Guarda into Lower Delfín basin between Isla Angel de la Guarda and the eastern margin of the PVP [*Stock*, 1999]. Alternatively, the northwestward propagation of the Ballenas fracture zone into the Wagner Transition Zone may have caused the divergence that created Lower Delfín basin, in the same way that a zone of divergence led to the development of Upper Tiburón and Delfín basins (Figure 6). In either case, this process transferred Isla Angel de la Guarda from the Pacific plate to the North America plate, creating a new position for the GEP rift margin farther to the southwest and increasing the length of contact between the southeastern margin of the Wagner Transition Zone and the gulf spreading center system. The new position of the rift margin thus incorporated the PVP into the GEP, exposing it to the same ENE directed extension that had been occurring to the north since ~12 Ma, and activated new north to NNW striking faults such as the Santa Isabel and Cuervo Negro faults. Vertical axis clockwise rotations north of the PVP either occurred over a subhorizontal detachment surface or within a vertical shear zone [*Lewis and Stock*, 1998b]. If rotations occurred over a detachment surface, rotational deformation may have extended offshore to include the submerged portions of the Wagner Transition Zone. If so, this could have rotated NNW striking normal faults clockwise, resulting in the north trending bathymetric contours.

6.5. At 2 Ma (Figure 5e)

Spreading continued in Upper Delfín basin. The extension that separated Isla Angel de la Guarda from the eastern margin of the PVP developed into a spreading center (Lower Delfín basin) at ~2 Ma [*Lonsdale*, 1989], and spreading accordingly stopped in Lower Tiburón basin. The eruption of the 2.6 ± 0.1 Ma Volcán Prieto at the intersection of the Ballenas transform and the zone of divergence of the Wagner Transition Zone may have been related to this adjustment in the GEP margin. Upper and Lower Delfín basins formed an approximately continuous axis of spreading [*Stock*, 2000]. It is unknown if vertical axis rotations in northeastern Baja California were occurring at this time.

6.6. Present (Figure 5f)

Upper and Lower Delfín basins are presently offset along a small transform which may have formed in response to a counterclockwise rotation of the direction of relative motion of the two sides of the gulf that began at 3.5 Ma [*Lonsdale*, 1989] and/or an increase in seafloor spreading rates in the mouth of the gulf since 3.5 Ma [*DeMets*, 1995]. A fanning of bathymetric contours to more northerly trends on the southeast side of Upper Delfín basin may indicate asymmetric spreading associated with its proximity to distributed deformation in the Wagner Transition Zone. Recent structural developments include the formation of small pull-apart basins southwest of Isla Angel de la Guarda along the Ballenas transform fault [*Lonsdale*, 1989].

7. Discussion

7.1. Wagner Transition Zone and Continental Deformation to the North

The Wagner Transition Zone represents the beginning of a major south-to-north structural change in the Pacific-North America plate boundary. Localized slip along transform faults in the southern and central gulf is replaced northward by a broad, wrench-dominated plate boundary system within heterogeneous continental or transitional crust. Diffuse deformation in northern Mexico and southern California includes late Miocene-Pleistocene (possibly ongoing) detachment faulting in Laguna Salada [*Axen and Fletcher*, 1998], late Cenozoic east directed extension along NNW striking transtensional faults in the inner California continental borderland [*Legg et al.*, 1991], active dextral strike-slip to oblique reverse-slip along the San Andreas fault zone [e.g., *Dickinson*, 1996; *Spotila et al.*, 1998], active block rotations in the Western Transverse Ranges and the Mojave Desert (Figure 1a) [e.g., *Jackson and Molnar*, 1990; *Luyendyk*, 1991; *Nur et al.*, 1993], and inland Basin and Range extension [e.g., *Atwater*, 1989; *Christiansen and Yeats*, 1992; *Henry and Aranda-Gómez*, 1992; *Wernicke*, 1992]. The absence of a single, discrete NW striking continental transform fault in southern California has previously been interpreted to indicate that faults such as the Agua Blanca and San Miguel are breaking around a "knot" caused by the bend in the San Andreas fault to the north [*Allen et al.*, 1960]. We suggest that this broad region of diffuse deformation south of the San Andreas bend extends as far south as the Delfín basins, widening north of the Agua Blanca fault.

Diffuse extensional deformation within continental or transitional crust can precede the establishment of favorably oriented transform faults which accommodate plate boundary deformation in a more discrete manner. Indeed, the Pacific-North America plate boundary near California initiated as an extensional province at ~23 Ma, constrained by the age of pull-apart basins and related volcanism, and evolved into a more orderly system of major, throughgoing strike-slip faults that migrated inland from the California borderland over time [*Atwater*, 1989; *Dickinson*, 1996]. Active, diffuse deformation in southern California and northern Mexico, including in the Wagner Transition Zone, suggests that major structural adjustments are continuing along this portion of the plate boundary.

NW striking transform faults and/or NE striking spreading centers could develop within thinned continental or transitional crust in the Wagner Transition Zone and link to the existing spreading center system to the south. Alternatively, ongoing differential movement at the southeastern margin of the Wagner Transition Zone, which we suggest controlled spreading center jumps from Upper and Lower Tiburón basins into Upper and Lower Delfín basins, could continue if newly oriented structures do not form in the Wagner Transition Zone. In this case, Upper and Lower Delfín basins would continue to migrate to the southeast away from the Wagner Transition Zone, perhaps to be replaced eventually by new spreading centers to the northwest. Whether newly oriented transform faults and spreading centers or more distributed structures develop in the Wagner Transition Zone and in the nearby regions of detachment faulting, they would need to link northward to continental plate boundary structures either by (1) connecting to the San Andreas fault system or (2) abandoning San Andreas fault system structures and connecting eastward to the region of Basin and Range extensional deformation, thereby moving the plate boundary farther to the east. The latter [e.g., *Nur et al.*, 1993] could explain active deformation in the Mojave Desert and regions east of the Sierra Nevada batholith.

7.2 Role of Preexisting Plate Boundary Features

The prerift geologic history along the Pacific-North America plate boundary which might have controlled the geometry of the gulf spreading center system since 6 Ma, in particular, the location of its northern termination at the Wagner Transition Zone, includes (1) inland extension or continental Borderland extension migrating southward with the Rivera triple junction, (2) related southern Basin and Range extensional deformation, (3) the trajectory of the Rivera triple junction with respect to the North American continent, (4) Miocene subduction-related arc magmatism, and (5) the position and geometry of the Oligocene Sierra Madre Occidental volcanic field.

1. From the time of its development (26-28 Ma) until ~8 Ma, the Pacific-North America plate boundary experienced transtension due to differences in the relative plate motion direction and the orientation of principal plate boundary structures [*Atwater and Stock*, 1998]. Deformation included slip partitioning between a dextral strike-slip system, lengthening over time between the migrating Mendocino and Rivera triple junctions, and inland extension. The initiation of extension thus apparently migrated southward with the Rivera triple junction [e.g., *Henry and Aranda-Gómez*, 2000], although this is complicated by back arc extension which also occurred inland of subduction such as southeast of the Rivera triple junction in Mexico [e.g., *Stewart*, 1998]. Subduction ended at 20-13 Ma west of the northern half of the Baja California peninsula and at ~12.5 Ma west of the southern half of the peninsula [*Stock and Lee*, 1994]. Correspondingly, extension related to the transtensional plate boundary should have begun earlier at the latitude of northern Baja California relative to the south, thus creating a zone of diffuse, middle Miocene extensional deformation east or west of the northern proto-gulf which did not have a counterpart to the south until 12 Ma. In present-day coordinates, the latitude of the Rivera triple junction at ~12 Ma was ~30°N relative to Baja California and ~27°N relative to Sonora.

2. The total width and amount of extension across the entire GEP and southern Basin and Range Province are greater at the latitude of the northern gulf relative to the south [e.g., *Stewart*, 1998; *Henry and Aranda-Gómez*, 2000]. Additionally, plate motion models predict a greater amount of late Miocene (12-5 Ma) ENE directed extension across the northern gulf than in the south [*Stock and Hodges*, 1989]. Evidence for NE directed extension in the northern part of the province includes core complex extension in southern Arizona (30-24 Ma) [e.g., *Gehrels and Smith*, 1991] and Sonora (25-18 Ma) [e.g., *Nourse et al.*, 1994]. ENE directed extension continued in these areas until 15 to 10 Ma [*Eberly and Stanley*, 1978; *McDowell et al.*, 1997; *Stewart*, 1998]. Middle Miocene extension began sometime between 16 and 11 Ma in the southern Sierra Juárez of northeastern Baja California [*Lee et al.*, 1996]. East of the Sierra Madre Occidental in western Mexico, ENE directed extension began between 30 and 17 Ma (Figure 1, inset) [*Henry and Aranda-Gómez*, 1992, 2000]. Extension generally began later to the south. Two phases of extensional faulting occurred in south central Sonora (NE directed, 26-20 Ma; east directed, 20-17 Ma) [*Gans*, 1997; *McDowell et al.*, 1997], and ENE directed extension occurred prior to 11 Ma in southern Sinaloa and 12-9 Ma at the south end and east of the Sierra Madre Occidental (Figure 1, inset) [*Henry and Aranda-Gómez*, 2000]. There is little evidence for pre-12 Ma deformation in southern Baja California.

3. Instead of a steady southward migration, the Rivera triple junction, in fact, migrated north and south at the latitudes of northern Baja California and southern California from the time of its development until about 16 Ma due to ridges and transform faults alternately encountering the trench [*Atwater*, 1989; *Atwater and Stock*, 1998]. The area north of the Rivera triple junction may have been underlain by slab-free regions, as suggested by plate reconstruction models for its mirror image: the region south of the northward migrating Mendocino triple junction [e.g., *Atwater and Stock*, 1998]. In California, three migratory magmatic pulses at 23-24 Ma, ~16 Ma, and 12-0 Ma are correlated to decompression melting of upwelling mantle below the slab windows [e.g., *Dickinson*, 1997]. The absence of similar postsubduction volcanic pulses in the wake of the migrating Rivera triple junction in the gulf region [e.g., *Sawlan*, 1991] might indicate that a slab-free region did not form beneath the area. Alternatively, it may take time for the volcanism to penetrate the overlying crust which could, in fact, be thickened above a slab window as a result of magmatic underplating. If a slab window did exist north of the Rivera triple junction, this provided a significant difference between the southern gulf region (underlain by subducting slab until at least 12 Ma) and the northern gulf and southern California regions (potentially underlain by a slab-free region since 16 Ma or as early as 26-28 Ma).

4. High temperatures in the lower and middle crust associated with continental margin arc magmatism may have controlled upper crustal extension by weakening the crust. The age of the Miocene magmatic arc preserved along the eastern Baja California peninsula, the Midriff Islands, and coastal Sonora [*Gastil and Krummenacher*, 1977; *Gastil et al.*, 1979; *Hausback*, 1984; *Neuhaus et al.*, 1988; *Stock*, 1989; *Sawlan*, 1991; *Dorsey and Burns*, 1994; *Lee et al.*, 1996; *Lewis*, 1996; *Nagy et al.*, 1999] reflects the southward migration of the Rivera triple junction. The arc developed 23-24 Ma along the entire length of the peninsula, and volcanism ceased at ~16 Ma in the north and ~11 Ma in the south [e.g., *Sawlan*, 1991]. The northern gulf region thus experienced protracted cooling (and associated strengthening of the lithosphere) relative to the south prior to the major episode of southern Basin and Range extension at ~12 Ma. Similarly, an elevated thermal regime allowed extensional structures of the Lake Turkana rift to

effectively modify prerift anisotropies, in contrast to the western branch of the East African Rift system [*Rosendahl et al.*, 1992].

5. The shape of the unextended Sierra Madre Occidental east of the Gulf of California, which formed in the volcanic arc position during Oligocene subduction [e.g., *Sawlan*, 1991], may have imparted geometric constraints on extension as well. The range retains a uniform width at central and southern gulf latitudes and narrows northward to terminate near the international border (Figure 1, inset), although scattered volcanic fields of similar age are present in Arizona and New Mexico [e.g., *Christiansen and Yeats*, 1992]. If the shape of the range is original, extension in the northern gulf remained relatively unconstrained to the east, in contrast to the central and southern gulf regions. Conversely, a more protracted history of extension in Sonora and the Wagner Transition Zone region relative to the south may have extended the northern portions of the Sierra Madre Occidental, leading to its present geometry.

In summary, the presence of prerift extensional structures over a broad region at the latitude of the northern gulf, as well as a cooling period following the cessation of arc magmatism at ~16 Ma, may have inhibited crustal thinning and thereby forced post-12 Ma deformation to remain diffuse. In contrast, the central and southern proto-gulf areas did not experience significant pre-12 Ma extension, and arc magmatism continued until ~11 Ma. Post-12 Ma extensional deformation in the central and southern gulf thus focused within a relatively narrow zone west of the unextended Sierra Madre Occidental, accelerating crustal thinning and lithospheric necking and facilitating the development of oceanic-type structures.

7.3 Fault Reactivation and Rift Propagation in Continental Crust

Late Miocene and Pliocene plate boundary deformation in the central and southern gulf may have been accommodated on reactivated normal faults developed during earlier extension, as we infer for the Wagner Transition Zone. Oblique reactivation of normal faults has been documented in other continental rift settings, such as in the central Kenya, Ethiopian, and Lakes Tanganyika and Malawi rift zones of the East African Rift system, and is attributed to rotation of the regional extension direction or to reactivation of preexisting basement structures oblique to the direction of extension [e.g., *Strecker et al.*, 1990; *Rosendahl et al.*, 1992; *Scott et al.*, 1992; *Ring and Betzler*, 1995; *Boccaletti et al.*, 1998]. In order to characterize reactivation of preexisting structures during later rifting events, *Keep and McClay* [1997] describe scaled analogue models in which orthogonal extension is followed by oblique extension at strain rates that vary with the angle of obliquity. Their experiments show that first-phase structures initially accommodate the second, oblique phase of deformation, but that after reaching a critical strain, they are replaced by newly oriented second-phase structures concentrated in the central sections of the rifts. Since the Gulf of California was originally an orthogonal rift zone which subsequently accommodated highly oblique dextral shear, the southern and central Gulf of California may be analogous to the localized central zone of second-phase structures found in these experiments, whereas north of 30°N the critical strain necessary for second stage structures to develop is yet to be attained.

The gulf transform faults and intervening basins as far north as Tiburón basin developed contemporaneously (4-6 Ma) with the spreading center system in the mouth of the gulf [e.g., *Curray and Moore*, 1984; *Lonsdale*, 1989; *DeMets*, 1995]. This implies that the rift system did not propagate northward over time [e.g., *Vink*, 1982] but rather became established simultaneously along much of the length of the gulf and remained in a stable configuration since its inception. As suggested here, shifts from Upper and Lower Tiburón basins to Upper and Lower Delfín basins were not due to rift propagation *per se* but were rather the consequence of the juxtaposition of a domain of diffuse transtensional deformation and another domain with more localized slip on transform faults. Our structural model of the northern gulf implies that spreading centers can develop along the margins of extensional fault domains at continent-ocean transitions. However, this may be a function of the particularly high obliquity of rifting in the gulf system whose geometry, dominated by major transform faults in transtension, is primarily the result of exploitation of structural and thermal heterogeneities.

There is a fundamental difference in geometry between the northern end of the Gulf of California spreading center system and other rift systems in regions of continental breakup. Rift propagation in oceanic crust generally proceeds from one end of a rift (or even at both ends, e.g., the Red Sea) in a direction parallel to the rift axis with oceanic crust forming in the wake of the rift tip [e.g., *Courtillot*, 1982; *Dunbar and Sawyer*, 1996]. Modern examples of oceanic rifts propagating into continents in this manner include the western Woodlark basin near Papua New Guinea and the Gulf of Aden from 30 Ma until the Pliocene [e.g., *Benes et al.*, 1994; *Mutter et al.*, 1996; *Manighetti et al.*, 1997]. A recent change to highly oblique propagation at the western tip of the Aden rift at the Gulf of Tadjoura is attributed to exploitation of regions experiencing lithospheric thinning related to the presence of the Ethiopian hot spot under Afar [*Manighetti et al.*, 1998]. In contrast to these examples, the Gulf of California system appears to be lengthening (or propagating) in a direction perpendicular to the ridge axes (i.e., parallel to the transform faults). Clearly rift propagation at the Gulf of California ocean-continent transition is strongly influenced by the prerift state of the continental lithosphere rather than by stresses concentrated at the rift tip.

8. Summary

The transtensional Wagner Transition Zone is the southernmost region clearly experiencing diffuse deformation adjacent to continental portions of the Pacific-North America plate boundary and thus marks the location of a key continent-ocean structural transition in the Gulf of California. The key points of the Wagner Transition Zone model include the following:

1. ENE directed extension occurred throughout the Gulf of California from 12 to 4-6 Ma and produced approximately NNW striking normal faults. Since this time, a nascent oceanic spreading center system developed south of latitude 30°N. In contrast, diffuse transtensional deformation continued along the late Miocene north to NNW striking normal faults within the Wagner Transition Zone and regions to the north. Deformation within the Wagner Transition Zone varies from ENE directed extension in the west to dextral-oblique slip along structures to the east and includes dextral shear (block rotations) between the two extremities. A distinct bend in the coastline geometry and offshore bathymetry north and south of the PVP reflects the regional change from NW striking transform fault-dominated topography south of 30°N to north to NNW striking, Basin and Range-type extensional structures in the Wagner Transition Zone. The longer history of ENE directed extension in the Wagner Transition Zone relative to regions to the south explains the greater width (ENE to WSW) of the northernmost gulf relative to the central gulf.

2. The juxtaposition of localized slip along transform faults in the central gulf with extensional deformation in the Wagner

Transition Zone has been a stable configuration for the past 4-6 Myr. The result has been to influence the positions and history of spreading center jumps between Upper and Lower Tiburón and Delfín basins by producing NE striking accommodation zones that developed into NW divergent basins. These changes had been previously attributed to a change in relative plate motion around 3.5 Ma [*Lonsdale*, 1989] but may be the result of these kinematically partitioned structural domains. The ~6-6.5 Ma and 3 Ma pulses of volcanism recorded in the PVP may also be related to the development of the offshore extensional basins.

3. The northwestward extension of the Ballenas transform fault at 2-3 Ma into the southern boundary of the Wagner Transition Zone widened the region of GEP extension by abandoning the Matomí accommodation zone and incorporating the PVP into the region of ENE directed extension. Major post-6 Ma deformation in the northern PVP and vertical axis rotations in the hanging wall of the San Pedro Mártir fault may have begun at this time.

4. By accounting for the contributions of rotational and extensional deformation within the Wagner Transition Zone to the total amount and direction of relative plate motion, vector constraints require that submerged structures in the northern gulf accommodate ~30 mm/yr of slip in a direction slightly clockwise of Pacific-North America relative plate motion. Some of this may occur as dextral-oblique slip on reactivated normal faults developed during late Miocene or Pliocene extension. Similarly, reactivation of such normal faults to accommodate dextral-oblique slip may have preceded the development of the spreading center system in the central and southern Gulf of California. Continued crustal thinning in the Wagner Transition Zone could permit the establishment of oceanic-type plate boundary structures that would connect northward to the broader region of diffuse deformation in southern California and the offshore borderland. Alternatively, the present geometry between the diffuse Wagner Transition Zone and the spreading center system to the south could persist, thereby controlling the evolution of new basins at its southeastern margin in a manner similar to the scenario proposed for Tiburón and Delfín basins.

5. A broader and earlier (pre-12 Ma) history of extension east of northern Baja California relative to the south may have permitted proto-gulf extension to remain diffuse north of latitude 30°N. In contrast, extension localized within a relatively narrower zone in the central and southern gulf, structurally bounded to the east by the Sierra Madre Occidental, resulting in greater crustal thinning and thus earlier development of a discrete, localized plate boundary. The history of continental-margin arc magmatism may also have influenced the location of the subsequent continent-ocean transition.

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