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PRE-PLIOCENE EXTENSION AROUND THE GULF OF CALIFORNIA AND THE TRANSFER OF BAJA CALIFORNIA TO THE PACIFIC PLATE

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Abstract. Late Miocene (12-5 Ma) extension around the edges of the Gulf of California has been alternatively attributed to "Basin and Range" extension, back arc extension, or development of the Pacific-North America plate boundary. This extension was ENE directed and similar in structural style to extension in the Basin and Range province. Timing constraints permit nearly synchronous onset of this deformation in a belt extending SSE from northernmost Baja California to the mouth of the gulf. Where this extensional faulting continued through Pliocene time to the present, synchronous with motion on the modern transform plate boundary in the Gulf of California, no change in direction of extension can be resolved. Revised constraints on Pacific-North America plate motion support the development of this late Miocene extension as a component of Pacific-North America displacement that could not be accommodated by strike-slip displacement along the existing plate boundary west of the Baja California peninsula. This scenario implies that transfer of Baja California from the North America plate to the Pacific plate was a gradual process, beginning about 12-10 Ma, when motion of the Pacific plate relative to North America was partitioned into separate regimes of strike-slip and dip-slip displacement on opposite sides of Baja California.

INTRODUCTION

Opening of the Gulf of California is often attributed to two sequential extensional events: middle to late Miocene "protogulf" extension [Moore and Buffington, 1968; Karig and Jensky, 1972; Moore, 1973] and the Pliocene development of the Pacific-North America plate boundary, from about 5.5 Ma to the present [Larson et al., 1968; Curray and Moore, 1984].

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Originally, the protogulf concept was used to explain an area of anomalously old oceanic crust adjacent to the Mexican margin at the mouth of the Gulf of California [Moore and Buffington, 1968]. More recently, this concept has been expanded to include late Miocene extensional faulting and marine sediments from areas surrounding the northern and central parts of the Gulf of California [e.g., Karig and Jensky, 1972; Moore, 1973; Gastil et al., 1979]. These late Miocene extensional structures and sediments are exposed around the gulf in the "Gulf Extensional Province" [Gastil et al., 1975] on the east side of Baja California and the west coast of mainland Mexico (Figure 1). The amount and direction of extension of the pre-5.5 Ma protogulf, and its relation to Pacific-North America motion, is not well known.

Several causes have been proposed for late Miocene circumgulf extension. Karig and Jensky [1972] suggested that it was back arc extension, but more precise constraints on the timing of cessation of subduction west of Baja California [Mammerickx and Klitgord, 1982; Lonsdale, 1989b] show that it was not contemporaneous with active subduction. The geographic continuity, and similarity in extension direction, of the Gulf Extensional Province and the southern Basin and Range extensional province (in Arizona and Sonora) invited suggestions that this entire Miocene extensional belt resulted from the same process of "Basin and Range extension" [Gastil, 1968; Dokka and Merriam, 1982; Curray and Moore, 1984]. In both of these scenarios, late Miocene circumgulf extension is assumed to have been oblique to Pliocene extension associated with the development of the Pacific-North America plate boundary, and it is thought to have weakened the crust and hence facilitated the propagation of the Pacific-North America plate boundary into the gulf. By contrast, Gastil and Krummenacher [1977] viewed post-10 Ma extension in Sonora as a continuous interval of "rhombochasmic extension", implicitly related to the development of the Pacific-North America plate boundary. Spencer and Normark [1979] and Hausback [1984] proposed that late Miocene circumgulf extension accommodated the component of Pacific-North America displacement perpendicular to the preexisting strike-slip faults west of Baja California, after counterclockwise

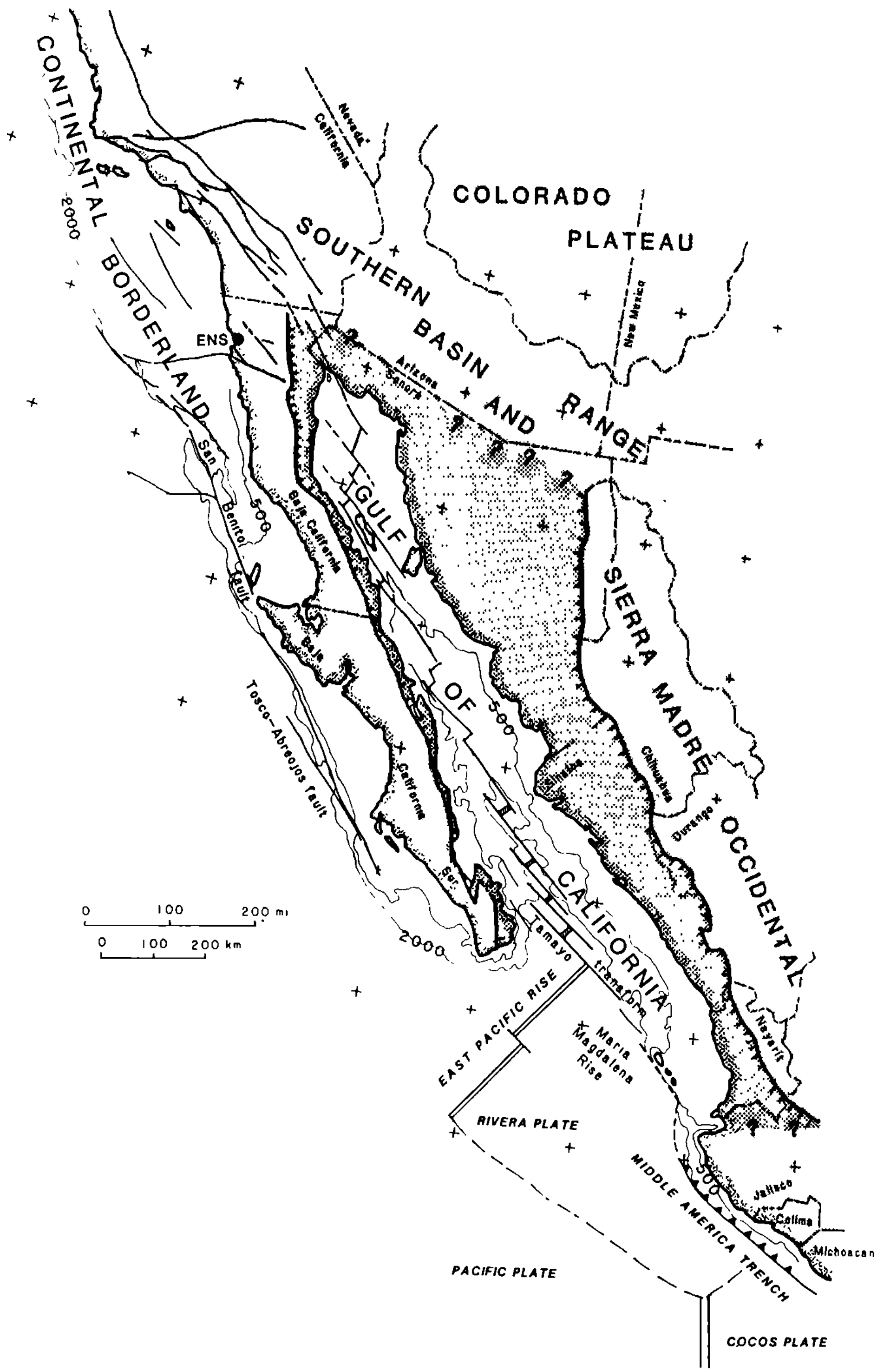


Fig. 1. Map of the Baja California peninsula and adjacent mainland North America, showing the coastline, the southern Basin and Range province, and the Gulf Extensional Province. The Tosco-Abreojos fault zone is located according to Spencer and Normark [1979]; other borderland faults are generalized from Krause [1965]. Gulf plate boundary faults and limits of the circumgulf extensional province (dark ticked lines) are generalized from references in the text. Bathymetric contours (500 m, 2000 m) and base map are from the North American Map Committee [1965]. ENS is Ensenada.

rotation of the direction of Pacific-North America plate motion.

Possible explanations for the widespread Tertiary extension in western North America have been summarized by Stewart [1978] and Christiansen and McKee [1978]. Some of these, as well as more recent explanations, invoke mechanisms related to the geometry and kinematics of the Pacific-North America plate boundary: extension within a broad zone of right-lateral shear [Atwater, 1970], extension above a "slab window" [Dickinson and Snyder, 1979], extension due to the geometric instability of triple junctions [Ingersoll, 1982], or extension due to flexure above the Mendocino fracture zone [Glazner and Bartley, 1984]. Others invoke lithospheric or asthenospheric causes unrelated to the development of the Pacific-North America plate boundary: extension due to relaxation of crust thickened under compression [Molnar and Chen, 1983; Wernicke et al., 1987] or extension due to steepening of a formerly shallowly dipping subducted slab [Davis, 1980]. Probably, Tertiary extension in western North America had multiple causes. Observation of extension in areas surrounding the Gulf of California, where both "Basin and Range" extension and Pliocene extension related to the Pacific-North America plate boundary have occurred, may provide some constraints on possible causal links between extension and the development of the Pacific-North America plate boundary elsewhere.

This paper examines (1) the differences in style and direction between late Miocene circumgulf extensional structures and later structures of the Pacific-North America boundary zone in regions where Miocene to Recent deformation has occurred, (2) the timing of late Miocene circumgulf extension and cessation of subduction, and (3) the direction and amount of Pacific-North America plate motion in Miocene time. Extension and tectonic disruption in this area were much simpler than in areas to the north, so the earlier shape of the plate margin can be reconstructed and incorporated in the analysis.

We suggest that late Miocene extension in the Gulf Extensional Province was similar in style to that in the Basin and Range province but may have been kinematically a component of Pacific-North America plate boundary displacement. This implies that, in late Miocene time, plate boundary displacement occurred both on the borderland faults west of Baja California and on extensional faults east of Baja California, isolating Baja California as a rigid block within the Pacific-North America plate boundary zone.

LATE MIOCENE EXTENSION IN THE GULF EXTENSIONAL PROVINCE

The Gulf Extensional Province [Gastil et al., 1975] encompasses the eastern edge of the Baja California peninsula and the part of mainland Mexico bordering the Gulf of California, including parts of the states of Baja California, Baja California Sur, Sonora, Sinaloa, Nayarit, Jalisco, and Durango (Figures 1 and 2). We draw the western limit of the Gulf Extensional Province at the western limit of known continuous or pervasive Miocene or Pliocene normal faults along the west side of the gulf, inferred from geologic summaries referenced in the text. In the central part of the Baja California peninsula there is no evidence of Miocene extension; Miocene extensional structures on the west side of the peninsula and in the continental borderland therefore belong to a separate geologic province. The western limit of the Gulf Extensional Province (GEP) in the state of Baja California coincides approximately with the Main Gulf Escarpment, a topographic break of varying steepness that follows the length

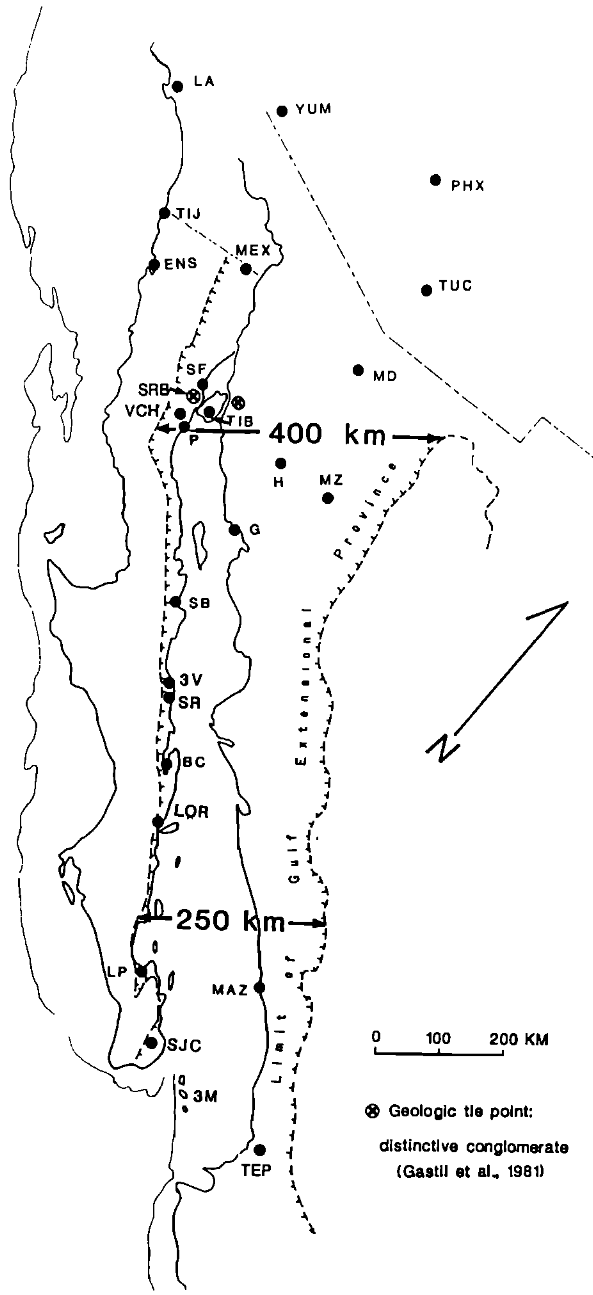


Fig. 2. Reconstructed width of the Gulf Extensional Province, after closure of the gulf transform faults by 300 km (using the 5.5 Ma reconstruction discussed in the text). Base map as in Figure 1. MD, MZ are Sonoran "metamorphic core complexes" [Anderson et al., 1980]. Other abbreviations: BC is Bahía Concepción; ENS is Ensenada; LA is Los Angeles; LOR is Loreto; LP is La Paz; MAZ is Mazatlán; MEX is Mexicali; P is Puertecitos; PHX is Phoenix; SB is San Borja; SF is San Felipe; SJC is San José del Cabo Trough; SR is Santa Rosalía; SRB is Santa Rosa Basin; TEP is Tepic, in Nayarit; TIB is Isla Tiburón; TIJ is Tijuana; TUC is Tucson; VCH is Valle Chico; YUM is Yuma; 3V is Tres Vírgenes; 3M is Islas Tres Marías. Geologic tie point across the gulf (circled x) is a distinctive conglomerate [Gastil et al., 1981].

of the Baja California peninsula and is generally fault-controlled [Gastil et al., 1975; Lindgren, 1888, 1890]. We draw the eastern limit of the GEP as the eastern limit of known extensional structures east of the gulf, as deduced from references in the text; there is no pronounced topographic escarpment along this eastern boundary. On mainland Mexico the northern and southern limits of the Gulf Extensional Province are gradational; the GEP merges with extensional structures of the Trans-Mexican volcanic belt on the south and with the southern Basin and Range province on the north. On the west side of the gulf the northern limit of extensional structures is the San Andreas fault.

In much of the Gulf Extensional Province the structures and timing of Tertiary extension have not been studied in detail. Regional syntheses of available data [Gastil et al., 1975, 1979] and more recent mapping and geochronology provide the constraints summarized below. For most of these areas, detailed fault slip data and regional transport directions are not available; thus, although fault orientations are known, the exact direction of extension is not.

Baja California

Sierra San Felipe and Sierra Santa Rosa. East of the Sierra San Felipe, in the Santa Rosa Basin, a sequence (up to 1 km thick) of alluvial sediments interbedded with middle to upper Miocene volcanic strata is tilted 30° to the west above a planar low-angle normal fault dipping 20° to the east with 3-5 km of normal displacement. The extension direction was approximately SE [Bryant, 1986]. No evidence for progressive tilting, growth faulting, or unconformities is found within the section. Pliocene fanglomerates overlie the fault trace and unconformably overlie the tilted Miocene strata, suggesting late Miocene-early Pliocene slip on this fault. A monolithologic megabreccia of granitic rocks deposited between tuffs dated at 12.3±1.8 Ma and 14.9±0.9 Ma [Bryant, 1986; Gastil et al., 1979] is the oldest indication of Miocene tectonism. (Uncertainties in ages are given as ±1σ throughout this paper. All ages are conventional K/Ar unless noted otherwise.) A change in the provenance of basin deposits occurred just above a basalt horizon dated at 8.9±1.2 Ma and was interpreted by Gastil et al. [1979] as indicative of normal-fault related uplift of ranges to the west. Minor ENE, NNE, and NNW striking high-angle strike-slip faults disrupt all of the units present and are attributed to accommodation of extension, or to conjugate strike-slip faulting, that postdates the low-angle normal fault and is still active. Pliocene marine strata west of the Sierra San Felipe dip up to 45° and contain interbedded megabreccias of tonalite, suggesting that significant deformation continued locally into Pliocene time [Gastil et al., 1979].

Southern Sierra San Pedro Mártir and Valle Chico. Dokka and Merriam [1982] estimated that extensional faulting began here sometime between 17 and 9 Ma and that it was approximately E-W directed because the dominant strike of the normal faults is north-south. More detailed mapping and geochronology constrain the initiation of extension to the interval between deposition of two rhyolite tuffs dated at 10.85±0.16 Ma ($^{40}Ar/^{39}Ar$ total fusion of anorthoclase) and 6.10±0.06 Ma (average of two K/Ar ages on anorthoclase) [Stock, 1989]. This time of onset of extension is based on the absence of regional unconformities in a 17-11 Ma ignimbrite sequence, absence of changes in thickness of this sequence across the current structures of the Main Gulf Escarpment, and absence of faults predating the 10.85 Ma ignimbrite [J. M. Stock and K. V. Hodges, Miocene to recent structural development of an extensional accommodation zone, NE Baja California, Mexico, submitted to Journal of Structural Geology, 1988]. Extension in this area occurred by high-angle normal faulting east of listric faults along the Main Gulf Escarpment, which had no topographic relief until after 11 Ma. About 10% extension occurred in this area, with about half prior to 6 Ma and half since, on the same set of NNW striking normal faults. A change in extension direction with time was not recognized but cannot be ruled out. In this area, Holocene scarps indicate continued normal faulting on the NNW striking San Pedro Mártir fault (Main Gulf Escarpment) [Gastil et al., 1975; Brown, 1978].

Puertecitos region. Sommer and García [1970] and Gastil et al. [1975, 1979] reported ages of 3.1±0.5 Ma and 5.9±0.2 Ma for flat-lying rhyolites overlying a series of steeply dipping acidic volcanic rocks yielding ages from 7.3±1.5 Ma to 8.3±0.8 Ma [Gastil et al., 1975, 1979]. They thus inferred that the major phase of tilting in this area is late Miocene (post-9 Ma) in age. About 6 km north of their study area, undated (probably Miocene) volcanics and unconformably overlying Pliocene marine beds, capped by water-lain ash, are tilted west up to 30° on a series of east dipping normal faults, and similar faults cut Quaternary deposits (J. M. Stock and J. T. Smith, unpublished mapping, 1987). This suggests considerable variability in the amounts of faulting and tilting affecting Pliocene to Recent strata in this region and indicates that post-Miocene normal faults may be locally significant and of the same orientation as late Miocene normal faults.

Dokka and Merriam [1982] observed that Miocene strata near Puertecitos dip 25° to 40° east or west beneath more shallowly dipping Pliocene volcanic strata and inferred that these Miocene units correlated with the 7.3 to 8.3 Ma sequence described above. If all of the faults in the poorly mapped Puertecitos volcanic province are inferred to dip 60°, the area experienced 10-18% extension since deposition of the Miocene strata (see, e.g., Figure 3 of Wernicke and Burchfiel [1982]). Lower assumed dip angles would correspond to more extension. Dokka and Merriam [1982] found that only a single geometry of normal faults has been active since this time. Many of these NNW to north striking normal faults cut the post-6 Ma volcanic strata [Dokka and Merriam, 1982; Gastil et al., 1975], indicating the importance of post-Miocene deformation.

Santa Rosalía. In this region a conformable sequence of Miocene volcanic strata was tilted up to 45° along a few north to NNW striking, west dipping normal faults [Wilson and Veytia, 1949] prior to the deposition of overlying lower Pliocene [Wilson and Rocha, 1955] or uppermost Miocene [Sawlan and Smith, 1984] Boleo Formation. Here the tilted volcanic units yielded K/Ar dates from 19.9±0.6 Ma to 10.7±0.3 Ma (andesite of Sierra Santa Lucía; Sawlan and Smith [1984]). The Main Gulf Escarpment near Tres Vírgenes, immediately to the north, postdated 10 Ma basalt [Sawlan and Smith, 1984]. NNW striking normal faults affected 10 Ma units but not 3 Ma units; however, upper Pliocene to Holocene alkalic volcanism in NNW trending grabens appears to have been coeval with faulting of the graben margins [Sawlan and Smith, 1984], suggesting more recent activity on some NNW striking normal faults. Wilson [1948] and Wilson and Rocha [1955] reported numerous normal faults striking N10°W to N45°W. These cut Pliocene units and tilted them up to 15° near Santa Rosalía. Pleistocene units in the same area were generally unaffected; thus the age of this episode of normal faulting must be Pliocene. A study of fault striae in this area [Angelier et al., 1981] showed that the late Miocene NNW striking normal faults were a response to ENE oriented least horizontal principal stress (σ_h) and that Pliocene motion on faults of the same orientation was more oblique, with the σ_h direction oriented WNW-ESE or E-W .

Bahía Concepción and Sierra de la Giganta. Near Bahía Concepción, McFall [1968] documented NE tilting of up to 45° in upper Miocene volcanic rocks affected by NW and NE striking normal faults. The uppermost strata in this conformable section (Ricasón Formation of McFall [1968]) yielded dates of 9.8±1.6 Ma and 8.0±3.7 Ma [Gastil et al., 1979]. Volcanic deposits correlated with the entire sequence yielded ages ranging from 19.9±0.6 Ma to 10.7±0.3 Ma (andesite of Sierra Santa Lucía; Sawlan and Smith [1984]). On the Concepción peninsula the lower part of this sequence is intruded by diorite dikes striking N70°W and N10°E and numerous NE to ENE striking pyroclastic dikes [McFall, 1968]. These dikes are not observed in either the lower or upper part of the sequence where it is exposed elsewhere, and they have not been dated, so their implications for the late Miocene stress direction cannot be assessed at present. Pliocene marine strata overlie these units in angular unconformity, suggesting that tilting and normal faulting occurred before the end of Pliocene time. If these Pliocene strata correlate with 3.3 Ma to 1.9 Ma strata of the Loreto embayment to the south [McLean, 1988], the normal faulting predates 3.3 Ma. Fresh fault scarps occur along the N45°W striking Bahía Concepción fault zone, which may have about 30 km of right-lateral strike-slip displacement [McFall, 1968].

West of Bahía Concepción, in the Sierra Giganta, normal faults striking N10°W to N35°W cut the Comondú Formation and overlying basalts [McLean et al., 1985, 1987]. This set of faults does not persist very far west of the peninsular drainage divide, and hence we include it within the Gulf Extensional Province. The basalts have not been dated where they are cut by the faults, but flows in similar stratigraphic positions nearby yield ages from 15 to 7 Ma [McLean et al., 1985]. No other generations of faults affect the area. As these faults have only been mapped in reconnaissance, mainly from air photo identification, their exact displacement directions, dips, and the amount of extension they represent are unknown.

Loreto. About 50 km south of Bahía Concepción, NW to N striking normal faults east of the peninsular drainage divide displace Neogene volcanics and sediments down to both the east and west [McLean, 1988]. One of the major faults which cuts Quaternary alluvium along part of its trace occurs at the western edge of a depositional basin of Pliocene marine strata including tuffs 1.9 and 3.3 Ma in age [McLean, 1988]. Dips of Pliocene strata are typically 10° to 30°. Upper Oligocene to middle Miocene strata locally dip more steeply, indicating some pre-Pliocene deformation. McLean [1988] suggests that the major offsets on these faults involve pre-Pliocene strata, but the exact age of initiation of this faulting is not well constrained by the existing data.

La Paz. The Gulf Extensional Province is confined to a narrow strip along the east coast of Baja California Sur (Figure 1). Even within this region, Miocene units may be flat-lying and little deformed. East dipping normal faults striking N15°W-N35°W in the La Paz area postdate the Comondú Formation and may still be active. The youngest dated unit in the Comondú Formation here has yielded a K/Ar age of 12.5±1.4 Ma [Hausback, 1984], thus limiting the earliest possible onset of extensional faulting. The latest possible onset is not well constrained because of the absence of younger units. Hausback [1984] reported a local angular unconformity beneath the 18-16 Ma San Juan tuff, but the regional significance of the corresponding deformational event is probably small.

Strike-slip faulting has also been important in this area. Offset facies trends suggest some tens of kilometers of left-lateral displacement on the La Paz fault [Hausback, 1984]. Part of this fault is still seismically active [Molnar, 1973], and geologic relations indicate post-12 Ma normal displacement [Hausback, 1984]. The timing of initial displacement along this fault is not well known but may have preceded deposition of Miocene volcanics [Hausback, 1984].

Mainland Mexico

Coastal Sonora. Extensional faulting and tilting in a variety of directions affected Isla Tiburón and adjacent Sonora between 12 and 9 Ma [Gastil and Krummenacher, 1977]. Volcanic and sedimentary rocks 10 Ma and older are tilted up to 60° to the east along a series of NW striking normal faults [Gastil et al., 1974]. Locally, on Isla Tiburón, 19-15 Ma units are tilted more steeply than 13-11 Ma units, suggesting that extensional faulting began between 15 and 13 Ma [Neuhaus et al., 1988]. Post-7 Ma units in coastal Sonora are flat-lying, suggesting that tilting and major extension there was mostly pre-Pliocene in age. NE striking faults on Isla Tiburón cut young alluvium and were related by Gastil and Krummenacher [1977] to modern dilatation of the Gulf; faults of this strike are not recognized further east in mainland Sonora. Some major faults striking N30°W to N40°W east of Isla Tiburón are likely to have significant strike-slip displacement, although the amount has not been established [Gastil and Krummenacher, 1977].

Coastal Sinaloa. An area extending 50 to 100 km inland from the west coast of southern Sinaloa, adjacent to Mazatlán, is broken into east tilted blocks bounded by NNW to NW striking normal faults [Henry and Fredrikson, 1987]. The tilt of Oligocene to middle Miocene strata reaches 60° in places, and extension is estimated to be 20-50% [C. D. Henry, Late Cenozoic Basin and Range structure adjacent to the Gulf of California, submitted to Geological Society of America Bulletin, 1988]. This extension postdates 16.8±0.3 Ma because this is the youngest date obtained from a conformable sequence of equally tilted volcanic strata. These strata form fault-bounded basins filled by unconformably overlying nonmarine sediments that may be Miocene or Pliocene in age [Henry and Fredrikson, 1987]. Unfaulted Quaternary basalts postdate these sediments. In the absence of further information the time of faulting is only bracketed between 17 and 2 Ma.

Nayarit. In southern Nayarit, SE of the mouth of the gulf, pre-Pliocene strata, including a regional volcanic package yielding dates from 21.3±0.9 Ma to 13.8±3.0 Ma, are tilted 20°-30° to the NE along NW striking normal faults [Gastil et al., 1978]. 10-8 Ma basalt lies in angular unconformity above the older strata [Gastil et al., 1979]. The normal faults are overlain by, and rarely cut, Pliocene to Holocene volcanic rocks. The reconnaissance nature of the study precluded tight constraints on the timing of this faulting, and it is possible that it is similar in timing and orientation to the late Miocene faulting known from elsewhere around the gulf. Fault-bedding relationships shown on interpretive cross sections by Gastil et al. [1978] limit the extension caused by this faulting to <10%.

Southern Basin and Range Province

The Gulf Extensional Province widens northward into the southern Basin and Range province of Arizona and northern Sonora (Figure 1). The geology of most of this part of Mexico is not well studied, and it is premature to conclude that the studied areas adequately represent the entire extensional province. It is also important to note that if the Baja

California peninsula is restored to its pre-5.5 Ma position relative to mainland Mexico, by closure of the Gulf of California by 300 km, the northern extent of the Gulf Extensional Province in Baja California (Mexicali) lies adjacent to northern Sonora, 250 km south of Yuma and 280 km west of Tucson (Figure 2). Thus in late Miocene time, southern Arizona was not geographically close to the limits of the extensional province presently exposed west of the gulf.

Low-angle detachment faulting in southern Arizona began at about 24-20 Ma [Glazner and Bartley, 1984]; direction of transport on these faults was generally NE-SW to ENE-WSW [Wust, 1986]. Younger Miocene sediments from SE Arizona contain unconformities and megabreccias indicating continued extensional faulting [Eberly and Stanley, 1978; Zoback et al., 1981]. A distinct post-13 Ma faulting event, forming NW striking structural troughs and associated with a major regional unconformity, ended sometime between 10.5 and 6 Ma [Eberly and Stanley, 1978]. Although the 24-20 Ma extension in southern Arizona predates extension in the Gulf Extensional Province, post-13 Ma extension in southern Arizona may be coeval with late Miocene circumgulf extension; the orientation of structures is similar.

Late Cretaceous and early Tertiary plutons in NW Sonora crop out in "metamorphic core complexes", associated with NE trending lineations [Anderson et al., 1980] suggesting SW-NE extension [Wust, 1986]. The age of this extension is not well constrained. This region is often included within the southern Basin and Range physiographic province; note that the southernmost of these core complexes lies 200 km east of Isla Tiburón and coastal Sonora where late Miocene extension began at about 12 Ma (Figure 1).

Protogulf Marine Sediments

The record of Miocene marine sediments from around the gulf sheds additional light on the distribution of extended and subsiding regions near the gulf. The oldest known Miocene marine deposits, about 13 Ma in age, are interbedded with 12.9±0.4 Ma volcanics and underlie 11.2±1.3 Ma volcanics on Isla Tiburón [Gastil et al., 1979; Smith et al., 1985; Neuhaus et al., 1988]. Upper Miocene marine rocks on Isla María Madre in the southernmost gulf (location 3M, Figure 2) indicate a pre-8.2 Ma subsidence event [McCloy, 1987]. Uppermost Miocene (6.0 to 5.5 Ma) diatomites occur in a Miocene-Pliocene marine sequence near San Felipe [Boehm, 1984], and upper Miocene strata are reported from wells beneath the coastal plain of western Sonora [Gómez, 1971]. Pliocene deposits in SW Arizona and the Salton Trough are underlain by uppermost Miocene marine sediments [Olmsted et al., 1973; Mattick et al., 1973; Ingle, 1987]. The upper Miocene Hualapai limestone in the Grand Wash Trough near Lake Mead, Nevada, has also been attributed to the marine protogulf [e.g., Blair, 1978], although a lacustrine origin for this unit has not been ruled out (see discussion by Bohannon [1984]).

The depositional trough represented by these upper Miocene marine sediments may have been close to the present axis of the gulf, with an outlet to the Pacific near the present mouth of the gulf [e.g., Winker and Kidwell, 1986; Smith, 1987]. Further paleontological studies are needed to detail the temporal development of this marine basin.

STYLE AND DIRECTION OF LATE MIOCENE EXTENSION

Post-12 Ma extension in the Gulf Extensional Province produced topographic basins and ranges in NE Baja California which are oriented NNW, parallel to those in the southern Basin and Range province. Just as in the Basin and Range province, extension-related faults in the Gulf Extensional Province include high-angle, listric, and planar low-angle normal faults, as well as strike-slip faults accommodating differential motion of crustal blocks.

The dominant strike of the high-angle normal faults in the Gulf Extensional Province was NNW. Because regional mapping has not yet revealed piercing points on most of these faults, the net extension direction is unknown. The simplest assumption is that dip-slip displacement dominated and hence that extension was ENE directed in late Miocene time. This direction of extensional strain, perpendicular to the present axis of the Gulf of California and to the late Miocene continental margin to the west, is consistent with observations of fault striae [Angelier et al., 1981; J. M. Stock and K. V. Hodges, Miocene to recent structural development of an extensional accommodation zone, NE Baja California, Mexico, submitted to Journal of Structural Geology, 1988]. Without more detailed geologic study this direction is subject to considerable uncertainty, because extensional displacement may be oblique to the dip direction of both bedding and faults [e.g., Walker et al., 1986]. Although dikes have been observed in several studies [e.g., McLean, 1988; McFall, 1968], dike swarms suitable for estimating the direction of least horizontal principal stress σ_h have not been dated. Again, the simplest assumption is that σ_h was oriented ENE near the Gulf Extensional Province in late Miocene time, although this stress direction cannot be confirmed to the level of detail possible to the north in the Basin and Range province [e.g., Zoback et al., 1981].

The σ_h direction in the southern Basin and Range province was ENE-WSW in the interval 20-10 Ma and rotated to the present ESE-WNW direction at about 10 Ma [Zoback et al., 1981]. The principal faults in the southern Basin and Range province strike NW to NNW and most likely formed under a pre-10 Ma ENE-WSW extension direction, prior to the circa 10 Ma rotation of the stress field [Zoback et al., 1981]. These faults are similar in strike to the late Miocene circumgulf extensional faults. If the circumgulf extensional faults indicate an ENE-WSW direction for σ_h, it appears that the southern Basin and Range province and the circumgulf extensional province experienced extension directions that may have differed by as much as 45° in late Miocene time, despite their similar tectonic settings east of the strike-slip Pacific-North America plate boundary.

AMOUNT OF EXTENSION

In two areas around the gulf with well-constrained estimates for the amount of late Miocene extension on high-angle faults, local values range from 5% [J. M. Stock and K. V. Hodges, Miocene to recent structural development of an extensional accommodation zone, NE Baja California, Mexico, submitted to Journal of Structural Geology, 1988] to 20-50% [C. D. Henry, Late Cenozoic Basin and Range structure adjacent to the Gulf of California, submitted to Geological Society of America Bulletin, 1988]. Dips of faults and bedding on published cross sections of other areas may be interpreted to indicate extension values between these amounts (see discussion above). The difficulty in obtaining accurate estimates of extension from such techniques, in areas of detachment faulting, is illustrated by a comparison of published estimates from the northern Basin and Range province (10% to 100%, or 75 to 325 km; see summaries by Davis [1980] and Wernicke et al. [1982]) with a value obtained from geologic piercing points across detachment faults further south (250-300 km, or 250%, at the latitude of Las Vegas [Wernicke et al., 1988]). More detailed mapping around the Gulf of California is needed for an accurate assessment of the net extension there.

The present geographic limits of the Gulf Extensional Province include 300-350 km of post-Miocene transform displacement within the gulf (see discussion below). This transform displacement was accompanied by diffuse extension of continental crust and the formation of "transitional" crust within the gulf, as well as by the formation of some true oceanic crust in the southern gulf. The excess area generated by this displacement must be removed to reconstruct the latest Miocene width of the extensional province. This is straightforward if the boundaries of the extensional province have not changed since the end of Miocene time, as indicated by the available structural data [e.g., J. M. Stock and K. V. Hodges, Miocene to recent structural development of an extensional accommodation zone, NE Baja California, Mexico, submitted to Journal of Structural Geology, 1988; Hausback, 1984]. Then, regardless of how the Pliocene displacement was partitioned within the Gulf Extensional Province, its effect on the width of the province can be estimated by closing up the edges of the Gulf Extensional Province by the 5.5 Ma (300 km) reconstruction (Figure 2). If this properly accounts for the Pliocene deformation, it indicates that at the end of Miocene time the Gulf Extensional Province varied in width from ~400 km in the northwest to ~250 km at its southern end (Figure 2). Note that these boundaries include a large area of Sonora, including the "metamorphic core complexes", where the age of extension is not known. Within the Gulf Extensional Province, 200% ENE extension would correspond to 270 km in the north and 170 km in the south; 20% extension corresponds to 70 km and 40 km, respectively. These values merely illustrate the possible range in values of extension that might have occurred within the late Miocene Gulf Extensional Province. There is no reason to believe that either the total amount of extension, or total percentage of extension, was constant throughout the extensional province.

TERTIARY PLATE TECTONIC SETTING OF BAJA CALIFORNIA

The history of plate interactions west of Baja California may have affected the timing and location of extension within the Gulf Extensional Province. During most of Tertiary time, Baja California was attached to western North America, and the Farallon plate was being subducted eastward beneath the Baja-Mexico margin. Volcanism related to this subduction occurred in the Sierra Madre Occidental of mainland Mexico from 100-45 Ma and 34-23 Ma [McDowell and Clabaugh, 1979] and in eastern Baja California and westernmost Sonora from 24 to 10 or 8 Ma [Gastil et al., 1979; Sawlan and Smith, 1984; Hausback, 1984]. Baja California crust lay west of the Cenozoic volcanic arc until Miocene time; much of the east side of the Baja California peninsula contains strata from the west side of the Miocene volcanic arc.

The Pacific plate came into direct contact with North America at the latitude of California sometime after 28.5 Ma [Atwater, 1970] and probably closer to 25 Ma [Atwater, 1989] at a point north of Baja California [Atwater and Molnar, 1973; Stock and Molnar, 1988] if the Gulf of California is closed by 300 km. The new Pacific-North America strike-slip plate boundary had a triple junction at both ends [Atwater, 1970]: the Mendocino (trench-transform-transform) triple junction, adjacent to the northern fragment of the Farallon plate, and the Rivera (ridge-trench-transform) triple junction, adjacent to the southern fragment of the Farallon plate [e.g., Dickinson and Snyder, 1979]. South of the Rivera triple junction, subduction of Farallon plate crust (the Guadalupe plate of Menard [1978] and smaller microplates that broke from it [Lonsdale, 1989b]) continued. The length of this subduction zone decreased as the Rivera triple junction moved southward by unevenly timed ridge deaths and microplate capture along the Baja California margin [Lonsdale, 1989b].

At 13 Ma, subduction was still occurring from the Vizcaíno Peninsula south to the tip of Baja California. This subduction stopped at about 12 Ma, when this part of the Pacific-Guadalupe ridge stopped spreading [Mammerickx and Klitgord, 1982; Lonsdale, 1989a,b]. The margin adjacent to the former Guadalupe-North America trench developed a strike-slip fault zone (the Tosco-Abreojos fault) of the Pacific-North America plate boundary [Spencer and Normark, 1979]. Many models of gulf evolution portray this fault zone as the plate boundary from 12 Ma until the time that the plate boundary began to move into the Gulf of California. This is thought to have occurred at about 5.5 Ma, because extension and subsidence of this age occurred at the mouth of the Gulf of California, possibly linked to similar diffuse extension further north in the gulf [Curray and Moore, 1984; Lonsdale, 1989a]. About 300 km of right-lateral displacement on the southern San Andreas system and gulf transform faults [Larson et al., 1968; Gastil et al., 1981] are usually attributed to post-5.5 Ma motion of the Baja California peninsula, on the Pacific plate, away from North America.

The following reconstructions of the Miocene plate tectonic configurations west of Baja California (Figure 3) address constraints on three issues: (1) the position of the Rivera triple junction with time, relative to Baja California; (2) the constraints on directions of relative plate motion; and (3) the orientation of the plate boundaries. These reconstructions differ from previous global plate circuit reconstructions of the Rivera triple junction [Atwater, 1970; Atwater and Molnar, 1973; Blake et al., 1978; Dickinson and Snyder, 1979; Klitgord and Mammerickx, 1982; Hausback, 1984] because they are based on updated Pacific-North America reconstructions and uncertainties [Stock and Molnar, 1988] for the times of anomalies 5 and 6. (These anomalies correspond to 10.59 Ma and 19.96 Ma, respectively, on the Decade of North American Geology (DNAG) time scale of Berggren et al. [1985]. This magnetic reversal time scale is used throughout the following dicussion.). The reconstructions and uncertainties presented here are for more closely spaced and slightly different times, in order to take advantage of the most informative parts of the seafloor spreading record west of Baja California. Implications for the position of the Rivera triple junction are similar to the results of Lonsdale [1989b].

Reconstructed Position of Baja California at 5.5 Ma

In the following discussion and figures, Pacific plate crust west of the present San Andreas fault and west of the gulf spreading centers has been reconstructed to the margin of mainland Mexico by a rotation of 4.69° about 48.62°N, 75.15° W (Figures 2 and 3). This 5.5 Ma reconstruction was extrapolated from Minster and Jordan's [1978] Relative Motion 2 (RM2) angular velocities and uncertainties for the Pacific-North America plate circuit (see Stock and Molnar [1988] for details of this extrapolation.) This reconstruction removes 290 km of displacement along the San Andreas fault in the Salton trough and closes the mouth of the Gulf of California by 308 km along an azimuth of 127°. The shelf edge north of the María Magdalena rise is then aligned with the shelf edge of Baja California Sur at 23.7°N, 109.3°W, following the detailed

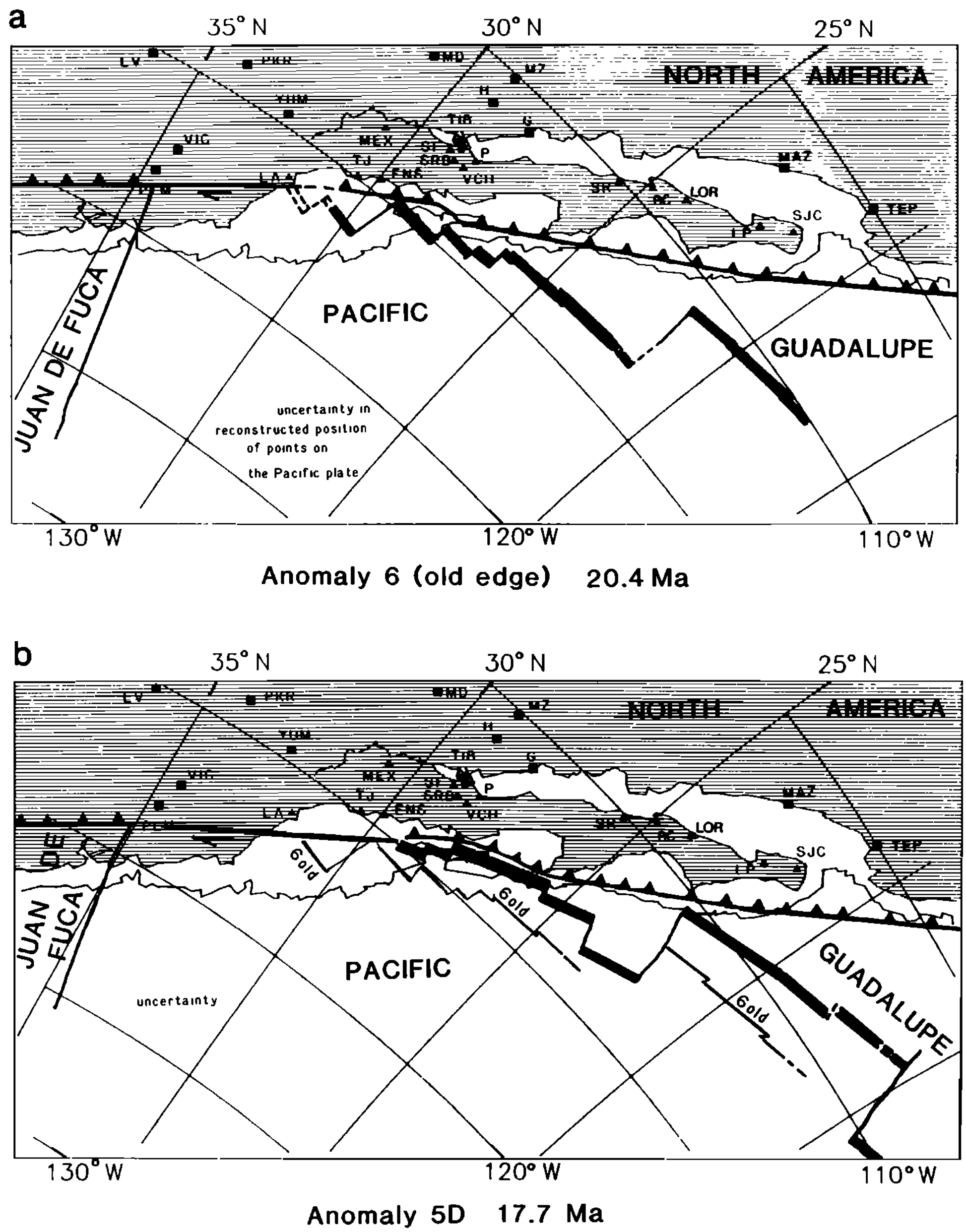
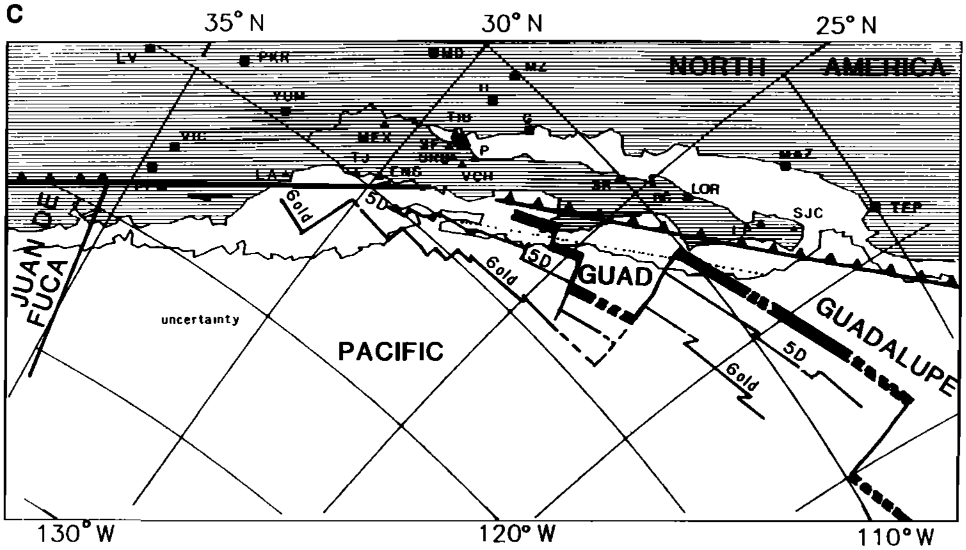
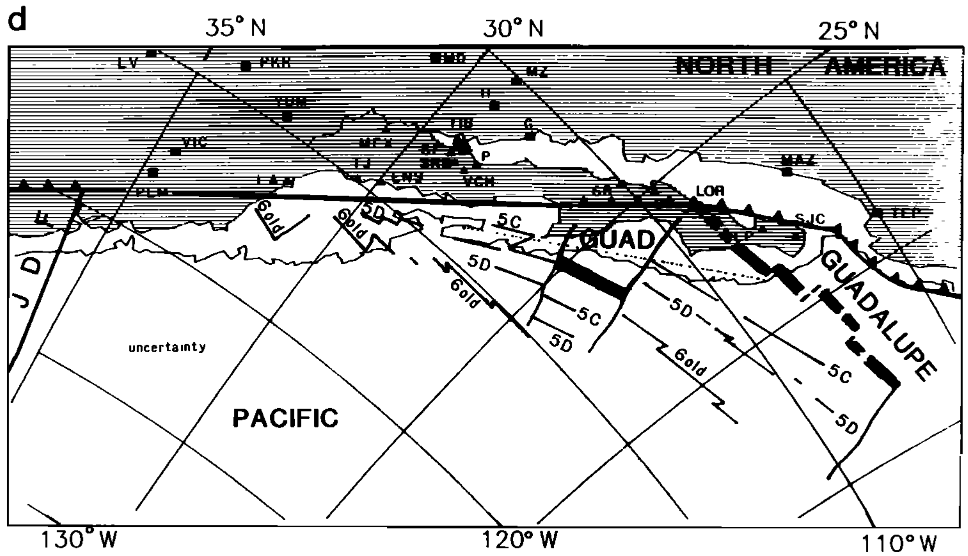


Fig. 3. Reconstructions of the Pacific plate relative to the fixed North America plate in the Miocene and Pliocene, for the times of (a) the old edge of anomaly 6, 20.45 Ma on the DNAG time scale of Berggren et al. [1985]; (b) center of anomaly 5D, 17.74 Ma; (c) center of anomaly 5C, 16.22 Ma; (d) center of anomaly 5AA, 12.92 Ma; (e) old edge of anomaly 5, 10.59 Ma; (f) old edge of anomaly 3A, 5.89 Ma. Map is an oblique Mercator projection about 44.02°N, 83.71°W, the stage pole for Pacific-North America motion between 20 and 10 Ma [Stock and Molnar, 1988]. The Gulf of California is closed as in Figure 2, with the 1000 fathom (1828 m) contour shown. Locations, abbreviated as in Figure 2, are squares (on North America) and triangles (on Baja California). Heavy line indicates position of Pacific-Rivera spreading center and is dashed where inferred. Position of subduction zone and Pacific-North America strike-slip margin is schematic. Thin lines are isochrons on the Pacific plate [Atwater and Severinghaus, 1989]. Rotation data and shaded uncertainty ellipses, representing 95% confidence limits of the reconstructed position of the Pacific plate, are based on the global plate circuit (see Stock and Molnar [1988] and discussion in text). See text for discussion of uncertainties. The unacceptable overlap of Pacific plate oceanic crust onto North American continental crust (Figures 3a-3e) results from assuming a rigid North America plate and would be removed by including Basin and Range extension in the reconstructions (see discussion in text).



Anomaly 5C 16.2 Ma



Anomaly 5AA 12.9 Ma

Fig. 3 (continued)

bathymetry of Mammerickx [1980] and reconstructions of Lonsdale [1989a], and is similar to the reconstruction of Curray and Moore [1984].

This reconstruction assumes complete rigidity of the present Pacific plate (Baja California and southern California) west of the San Andreas fault. The Baja California peninsula south of the Agua Blanca fault (near Ensenada, Figure 1), between the Main Gulf Escarpment and the continental borderland, has been essentially rigid in Miocene and younger time. Although Miocene extension occurred in the continental borderland [Normark et al., 1988], we assume that this extension did not significantly reorient the western margin of the Baja California peninsula. In this case the reconstructed orientation of this part of the plate margin should be adequate for times between 20 and 5 Ma. (The presence of a possible transpeninsular strike-slip fault in Baja California Sur, [e.g., Crouch, 1979] has not been conclusively established.) The continental margin north of Ensenada, including the California continental borderland and the Transverse Ranges, was more highly deformed in Miocene and Pliocene time [Doyle and Gorsline, 1977; Crouch, 1981; Hornafius et al., 1986]. Thus the shape of this part of the margin, as determined by rigid plate reconstructions (Figure 2), is less valid for older times.

This reconstruction includes within its uncertainties the extrapolation of the instantaneous Pacific-North America angular velocity of Chase [1978]. An extrapolation using a

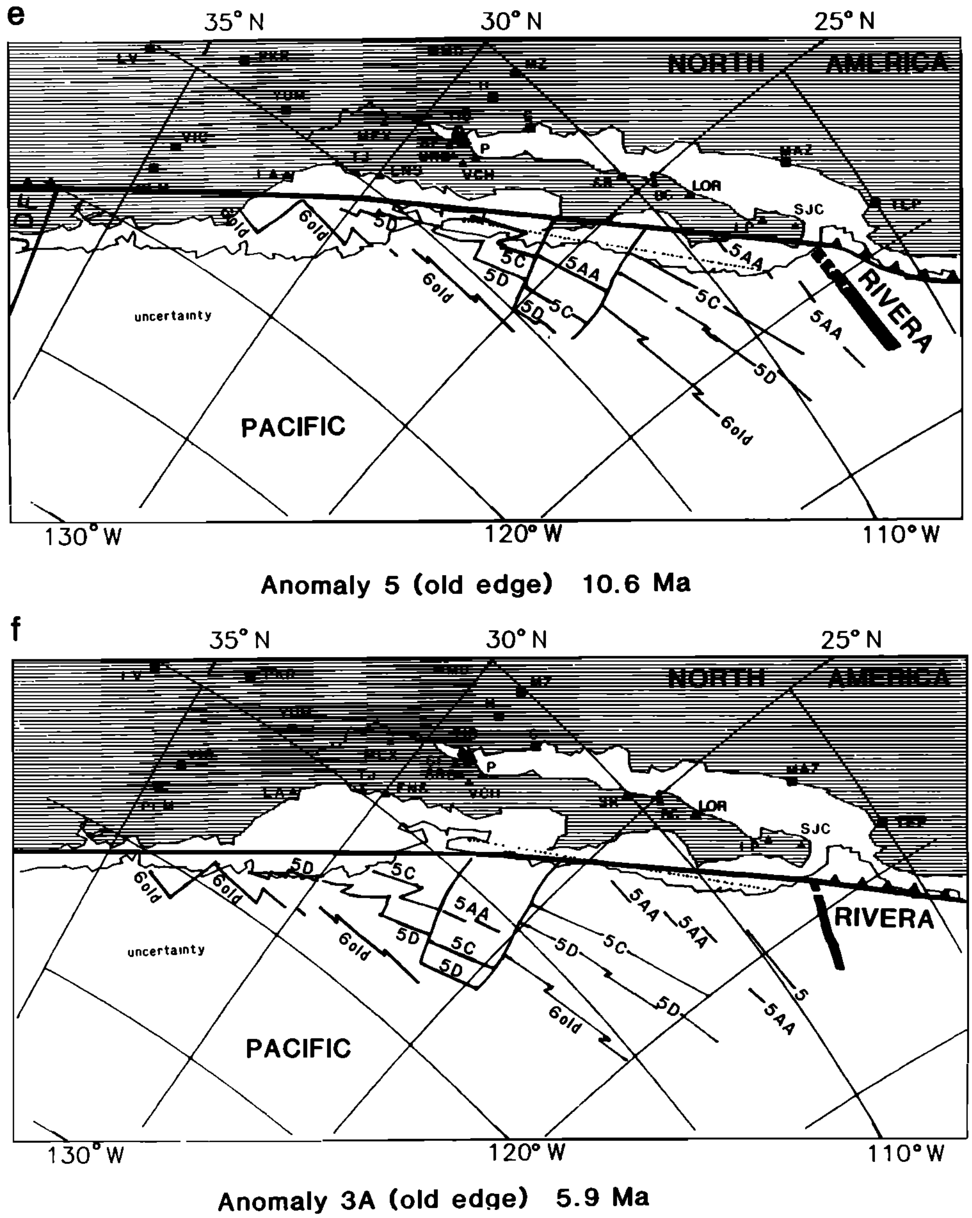


Fig. 3 (continued)

more recent instantaneous angular velocity model known as NUVEL-1 [DeMets et al., 1987] would close the mouth of the gulf by only about 260 km but along the same azimuth as this reconstruction. All of these reconstructions result in overlap of extended continental crust within the gulf because crust between the Pliocene transform faults has extended by the formation of "transitional", rather than true oceanic, crust [Larson et al., 1972; Moore, 1973].

A value of about 300-350 km for strike-slip motion on the gulf transform faults seems to be constrained well by displacements on major faults in southern California [Crowell, 1981] and is consistent with the amount of oceanic crust, and extended continental crust, present at the mouth of the Gulf of California [Lonsdale, 1989a]. Geologic constraints from the Gulf Extensional Province [Gastil et al., 1981] include the separation of a pre-15 Ma conglomerate channel with distinctive Permian clasts, found on both sides of the Gulf of California (Figure 2). Our 5.5 Ma reconstruction appears to overrotate the outcrops of the conglomerate with respect to one another; however, major NW striking strike-slip faults occur east of the Sonoran outcrop [Gastil and Krummenacher, 1977] and may account for some of this discrepancy. Three hundred kilometers of motion is about 30 km less than the total displacement on the San Andreas, San Gabriel, San Jacinto, and Elsinore faults in southern California [Crowell, 1981; Hornafius et al., 1986]. However, pre-5.5 Ma displacement on

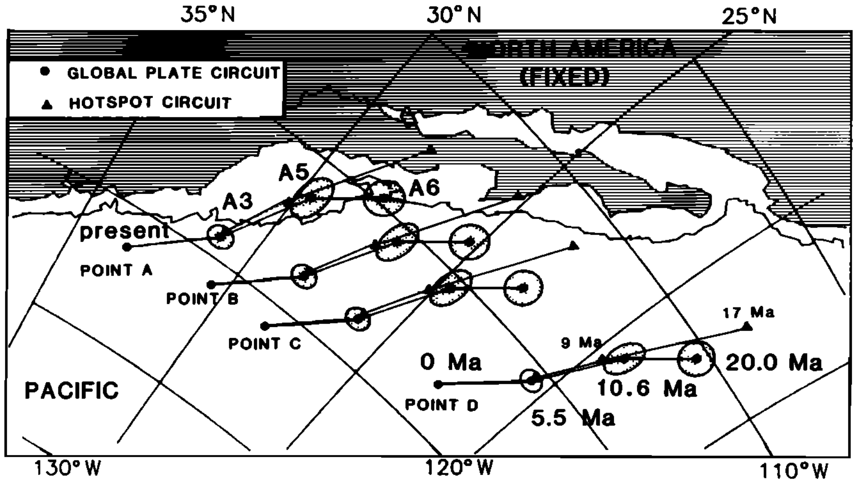


Fig. 4. Uncertainties in past positions of four points on the Pacific plate relative to fixed North America since Miocene time. Baja California has been moved back to North America 300 km by the reconstruction discussed in the text. Ellipses are 95% confidence regions for point positions at 5.5 Ma, 10.6 Ma, and 20.0 Ma from global plate circuit reconstructions [Stock and Molnar, 1988]. Triangles are positions of same points at 5, 9, and 17 Ma, according to the fixed hotspot reconstructions of Engebretson et al. [1985]. Note that for both sets of reconstructions the average direction of motion in the interval 5-10 Ma is oblique to the trend of the continental margin west of Baja California (the San Benito-Tosco-Abreojos fault zone). Map projection as in Figure 3.

the San Gabriel fault should not be included in the 5.5 Ma reconstruction.

The exact timing of this 300-350 km of motion is not constrained well. In the southern gulf, north of the Tamayo transform fault, the spacing of anomalies 0, 2 (2 Ma), and 2A (2.5 Ma to 3.4 Ma) indicates the formation of about 175 km of oceanic crust between the Pacific and North America plates since 3.4 Ma [Larson et al., 1968; Klitgord and Mammerickx, 1982; DeMets et al., 1987; Lonsdale, 1989a]. South of the Tamayo fracture zone, 300 km of seafloor formed since about 5 Ma [Mammerickx and Klitgord, 1982], but this represents Pacific-Rivera spreading which was faster than Pacific-North America spreading due to convergence between the Rivera and North America plates [Atwater, 1970; Larson, 1972; Molnar, 1973; Nixon, 1982]. The additional 125-175 km of transform motion in the Gulf of California is inferred to have occurred in the interval 5.5-3.4 Ma [e.g., Lonsdale, 1989a; Curray and Moore, 1984], but the time of initiation of this motion is not known directly and may be older than 5.5 Ma. The 8 Ma (or earlier) initiation of motion on the San Gabriel fault [Crowell, 1981] suggests that pre-3.4-Ma strike-slip displacement in the Gulf of California may have been distributed throughout the interval 8-3.4 Ma, perhaps partly accommodated within the Gulf Extensional Province.

Past Position of the Rivera Triple Junction

Reconstructions for times in the Miocene (Figures 3a-3e) were interpolated from the reconstructions of Stock and Molnar [1988], assuming constant relative motion between the Pacific and North America plates throughout this interval. Uncertainties in these reconstructions are at least ±50 km in latitude and ±70 km in longitude and are estimated to be larger (±100 km) if the reconstruction was not close in time to the end points of the interpolation. A reconstruction for the time of the Miocene-Pliocene boundary (the old edge of anomaly 3A, 5.9 Ma; Figure 3f) was derived from Minster and Jordan's [1978] RM2 model and uncertainties, as described above for the 5.5 Ma fit of Baja California to mainland Mexico.

In these reconstructions the plates in the global plate circuit (Pacific, Antarctica, Africa, and North America) are assumed to have been rigid since 20 Ma. For 10.6 Ma and older times (Figures 3a-3e), reconstructed oceanic crust of the Pacific plate overlaps continental crust of the Baja California and southern California margins. The amount of overlap for some times exceeds the uncertainty in the reconstructions, indicating some problem with either the reconstruction parameters or the assumption of rigid plates in the plate circuit. This overlap also occurs in reconstructions based on the assumption of fixed hotspots (e.g., Engebretson et al. [1985]; Figure 4), suggesting that it is unlikely to be due to nonrigid deformation in the Africa or Antarctica plates. It is most likely due to nonrigid deformation of the North America plate, considering the several hundred kilometers of Neogene extension known from the Basin and Range province [Wernicke et al., 1988]. Extensional and strike-slip deformation here and along the plate boundary limits the level of precision of the reconstructions of Figure 3.

Despite these limitations, some general inferences can be made regarding the position and the length of the strike-slip Pacific-North America plate boundary. At 20.4 Ma the Rivera triple junction (RTJ) was near the reconstructed position of Los Angeles, so subduction was still occurring along the entire Baja California peninsula. The strike-slip margin north of this subduction zone was only about 400 km long. By 17.7 Ma the RTJ could not have been much further south than Ensenada; the strike-slip margin to the north was about 750 km long, and subduction was still occurring under most of the Baja California peninsula. Synchronous with this subduction, between 22 and 15 Ma, Neogene basins on the continental margin west of Baja California experienced their major episode

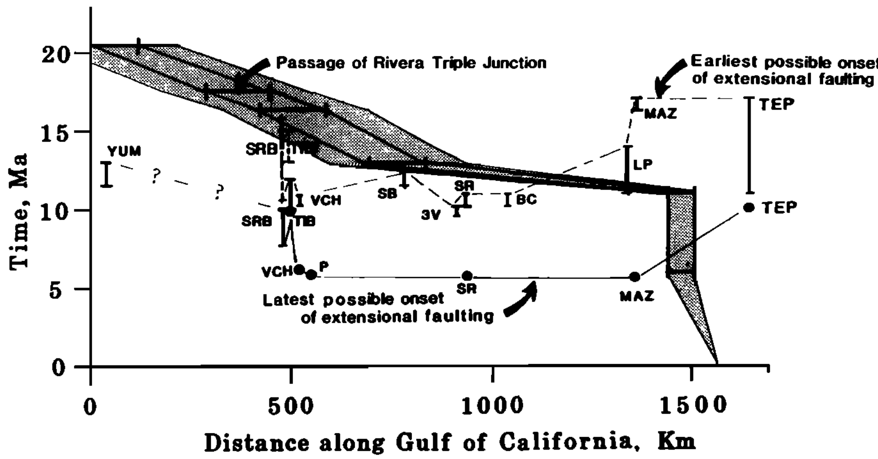


Fig. 5. Comparison of the time of onset of extensional faulting in the Gulf Extensional Province with the time of passage of the Rivera triple junction to the west. Locations (abbreviated as in Figure 2) are projected parallel to the west coast of the Baja California Peninsula (and parallel to the trend of the San Benito-Tosco-Abreojos fault zone) TIB and SRB are observations of local deformation (see discussion in text) whose regional significance has not been established.

of subsidence [Normark et al., 1988]. Between 17.4 and 12.9 Ma, subduction ceased along all of northern Baja California, and the strike-slip margin north of the Rivera triple junction grew to 1400 km in length, extending south through the southern California borderland to the Vizcaíno peninsula. At 12.9 Ma, subduction was still ocurring west of the Vizcaíno peninsula. By 10.6 Ma, subduction had ceased along most of southern Baja California, and the former continental slope west of Baja California Sur (the Tosco-Abreojos fault of Spencer and Normark [1979]) was part of the 2100-km-long strike-slip margin. Thus the strike-slip margin lengthened by about 1700 km between 20 and 10 Ma, even though the relative displacement between the Pacific and North America plates, west of Baja California, was only 235±100 km during this interval.

A comparison between the time of onset of extensional faulting and the time that the Rivera triple junction lay west of points in the (reconstructed) Gulf Extensional Province (Figure 5) shows no clear evidence for late Miocene circumgulf extension while subduction was active to the west. There may be a temporal correlation between the initial late Miocene circumgulf extension and the southward motion of the Rivera triple junction west of Baja California, although this cannot be confirmed by existing data. It is also possible that late Miocene circumgulf extension started approximately synchronously throughout the length of the gulf and, at least in some areas, considerably later than the passage of the Rivera triple junction to the west.

Direction and Amount of Pacific-North America Motion

The above reconstructions can be used to obtain the average direction of Pacific-North America motion, and its uncertainties, for the time intervals between reconstructions (Figure 4). Such a computation for the intervals 0-5.5 Ma, 5.5-10.6 Ma, and 10.6 to 20 Ma (Figure 6) indicates that between 20.0 and 10.6 Ma, total Pacific-North America motion was 25±10 mm/yr at an azimuth varying from 303°±20° to 317°±20° along the west coast of Baja California Sur. These azimuths include within their uncertainties the 320° azimuth of the San Benito-Tosco-Abreojos fault zone (SBTAFZ) after reconstruction of the Baja Peninsula to mainland Mexico and are consistent with all of the plate motion occurring as strike-slip displacement along the SBTAFZ. However, for the period 5.5-10.6 Ma, the net azimuth of displacement of the Pacific plate varied from 294°±11° to 298°±12°, demonstrably at an angle to the azimuth of the SBTAFZ (Figure 6). Between about 10 and 5 Ma, the net plate displacement was oblique to the SBTAFZ in an orientation that should have caused oblique extension across it. However, neither the Tosco-Abreojos fault nor the former trench extended obliquely [Spencer and Normark, 1979; Lonsdale, 1989b], and subsidence of the continental margin was minor [Normark et al., 1988]. This lack of a component of extension on the plate boundary, noted by Spencer and Normark [1979] and Hausback [1984], indicates that additional displacement, sufficient to sum to the total relative plate motion, must have occurred elsewhere within the plate boundary zone. The plate reconstructions suggest that the amount of this displacement, measured in an ENE direction (perpendicular to the trend of the Tosco-Abreojos fault zone), varied from 160±80 km to 110±80 km along the plate boundary west of Baja California (Figure 6). The closest obvious place for this displacement is in the Gulf Extensional Province.

Although the dominant extensional faults in the Gulf Extensional Province strike NNW, the exact direction of extension is not known. If we assume that this extension direction was ENE, then the plate reconstructions imply 160±80 km of extension in the northern part of the Gulf Extensional Province, decreasing to 110±80 km of extension in the southern part of the Gulf Extensional Province. This corresponds to 66% extension in the north and 78% extension in the south, with upper and lower limits of 150%-25% in the north and 300%-13% in the south. A different overall extension direction in the Gulf Extensional Province would imply slightly higher percentages of extension. These values are within reasonable limits of the extension that might have occurred in the Gulf Extensional Province (20%-200%) and are consistent with a kinematic model in which the Gulf Extensional Province accommodated the "missing" component of plate boundary motion. A northward increase in absolute

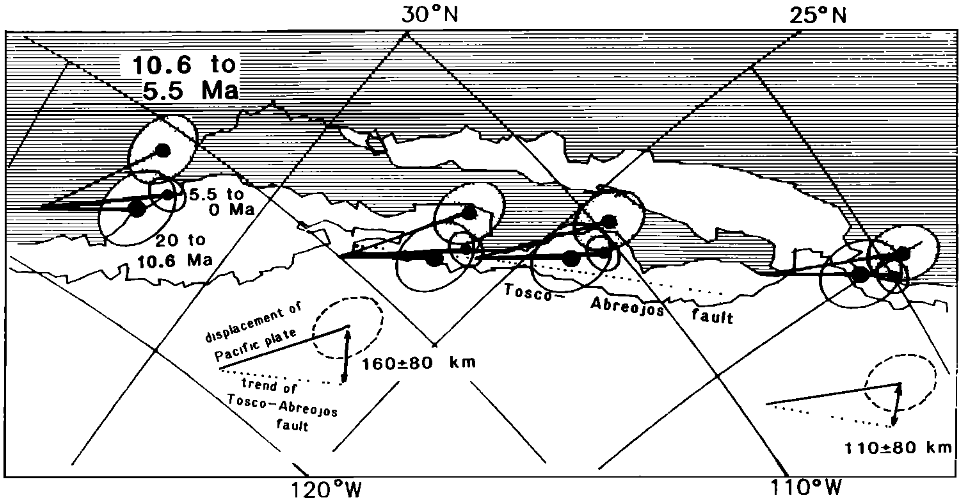


Fig. 6. Interval velocities and uncertainties for Pacific plate points west of Baja California, for the intervals 20.0 to 10.6 Ma (large ellipses), 10.6 to 5.5 Ma (medium ellipses, shaded) and 5.5 to 0 Ma (small ellipses). Map projection as in Figure 3. The San Benito-Tosco-Abreojos fault zone is dotted. Vector diagrams in the lower part of the plot show the best fit and uncertainties in the displacement of the Pacific plate relative to North America for the time interval 10.6-5.5 Ma, the direction of the SBTAFZ, and the amount of plate motion that could not have been accommodated by strike-slip motion along the SBTAFZ but which might have been accommodated within the Gulf Extensional Province.

extension in the Gulf Extensional Province is suggested by the relative plate motions (Figure 6) and can be tested with improved geologic constraints from the Gulf Extensional Province.

Because these reconstructions correspond to specific times in the past, the difference between two reconstructions indicates the net displacement, not the actual displacement path, for plate motion between these two times. The time interval during which Pacific-North America plate motion was oblique to the SBTAFZ is not precisely constrained and could have been 15 to 7 Ma or 9 to 5 Ma rather than the 10.6 to 5.5 Ma interval shown by the reconstructions. More precise constraint on this time interval awaits both closer time spacings of global plate reconstructions and more detailed chronology of the Miocene extension within the Gulf Extensional Province.

DISCUSSION

Of all the extended areas in western North America the Gulf Extensional Province shows the best constrained correlation between the onset of extension outside of the existing plate boundary zone and a change in the direction of relative motion between the Pacific and North America plates. The onset of extension here may be linked to the transition from subduction to strike-slip tectonics, as inferred for other extensional areas in western North America [Dickinson and Snyder, 1979; Glazner and Bartley, 1984]. However, geometric considerations suggest that the extension reflects a resolvable change in the direction of relative plate motion after the strike-slip regime was already established along part of the margin.

The localization of this extension inland, well removed from the former plate boundary, is intriguing. The geometry of late Miocene plate motion should have caused oblique extension along the San Benito-Tosco-Abreojos fault, which might have become reoriented into en echelon transform faults. This did not happen; instead, the plate boundary displacement was partitioned between continued strike-slip motion along the Tosco-Abreojos fault zone and extension further inland. There are two obvious reasons for such kinematics: either the plate boundary at depth was not confined to the Tosco-Abreojos fault or else a zone within the continent was closer to failure by extension than was the plate boundary. The earlier history of the strike-slip boundary as a subduction zone, and of the Gulf Extensional Province as an active volcanic arc, may have contributed to either of these situations. The former arc on the North America plate had been recently active, so it may have been both thermally weak and topographically high. The subducted Guadalupe plate lay some distance beneath Baja California, so the attachment of microplates (broken from the Guadalupe plate) to the Pacific plate as the Pacific-Guadelupe ridge died may have provided a mechanism for widening the Pacific-North America boundary at depth.

The strain partitioning we infer for this part of the Pacific-North America plate boundary is similar in scale to the partitioning of displacement observed along obliquely convergent plate boundaries (Figure 7). Often, in these regions, subduction is not parallel to the plate motion but rather perpendicular to the plate boundary; the component of strike-slip displacement is accommodated on faults parallel to the subduction zone in the arc region [Fitch, 1972]. The similarity in scale of these two processes may reflect typical arc-trench distances.

If this kinematic picture applies to extension in the Gulf Extensional Province, what are the consequences for other extended areas in western North America? The northernmost limit of extension attributable to plate boundary displacement is difficult to identify, because later deformation north of Ensenada prevents accurate reconstruction of the Miocene shape of the plate boundary along the continental margin. If, north of Ensenada, the continental margin accommodated all of the plate boundary displacement, then the Gulf Extensional Province should have a well-defined northern limit bounded by

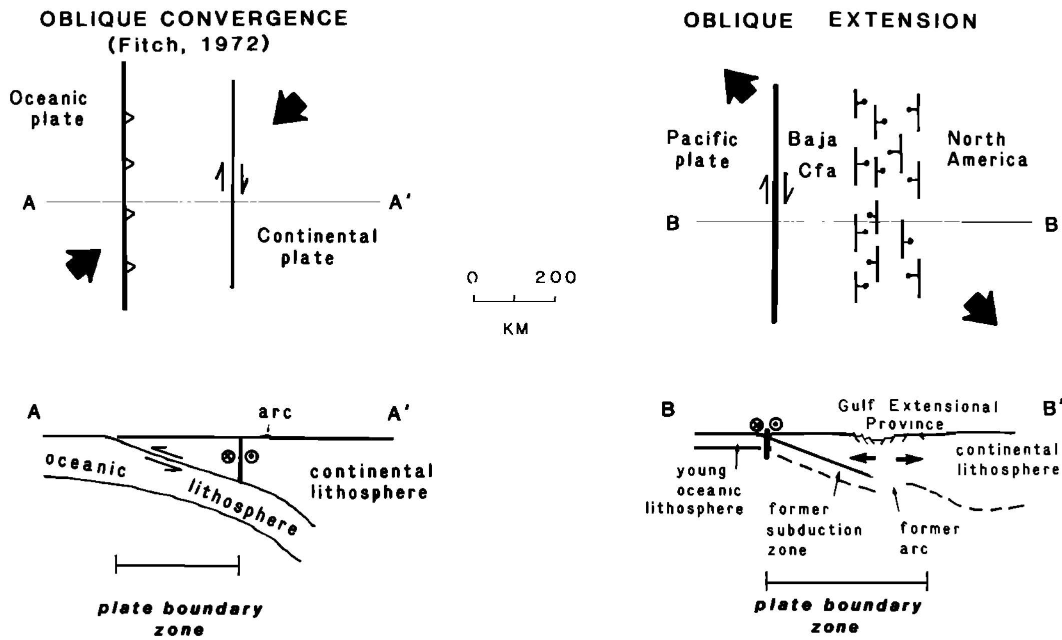


Fig. 7. Comparison of partitioning of relative plate displacement in oblique strike-slip regimes [Fitch, 1972] and in the case of the Gulf of California. Note similarity of scale. Thickness of the lithosphere beneath Baja California and adjacent North America is not well constrained, and the direction of plate motion (heavy arrows) is schematic.

transfer structures (probably strike-slip faults) extending west across the Baja California Peninsula to join the plate boundary in the continental borderland. The Agua Blanca fault, north of Ensenada, is of a likely orientation to be such a transfer structure, but it does not correspond to any structural discontinuity in the extensional province to the east. The continuity between the Gulf Extensional Province and the southern Basin and Range province suggests that late Miocene Pacific-North America displacement (manifested as extension) also continued further north. The direction of this extension need not have been perpendicular to the plate boundary to the west, as long the sum of the extension and the strike-slip displacement equaled the total displacement between the Pacific and North America plates. Thus, late Miocene WNW directed extension further north in the Basin and Range province [Zoback et al., 1981] may have been an expression of the same change in direction of plate motion superposed on earlier extensional structures.

ENE directed normal faulting continued into the Pliocene in many areas around the Gulf of California; in some areas of NE Baja California it continues today [Gastil et al., 1975; Dokka and Merriam, 1982]. Thus this direction and style of extensional faulting persisted even after Pacific-North America transform motion was well established within the gulf, although it appears to have caused much less extension. Its occurrence today may be a smaller scale example of strain partitioning in the Pacific-North America boundary zone.

SUMMARY

Since about 12 Ma, NNW striking normal faults adjacent to the present Gulf of California have caused extension in a broadly ENE direction, perpendicular to the Pacific-North America plate boundary and to the present orientation of the Gulf of California. In widely separated areas the amount of local extension, computed by reconstruction of displacements on high-angle normal faults, or inferred from fault-bedding relationships, varies from 5% to 50%. This extension may have begun synchronously all along the margins of the present gulf or may have closely followed the time of passage of the Rivera triple junction and the transition to a strike-slip plate boundary. None of this extension occurred during active subduction. This 12-6 Ma ENE extension is the earliest episode of Miocene extension recognized immediately adjacent to the Gulf of California; its relationship to early to mid-Miocene "metamorphic core complexes" known from southern Arizona, and similar undated structures in NW Sonora, is unknown.

Plate tectonic constraints are consistent with a plate kinematic cause for this extension, as follows. When subduction ceased west of Baja California at about 12 Ma, by cessation of spreading on part of the Pacific-Guadalupe ridge, Pacific-North America motion was accommodated by strike-slip motion on fault zones parallel to, and close to, the former trench (the San Benito-Tosco-Abreojos fault zone). However, at or after about 12-10 Ma, the direction of Pacific-America motion became oriented oblique to these strike-slip fault zones and should have caused oblique extension along them. Instead, the plate boundary displacement was partitioned between strike-slip motion on NNW striking faults west of Baja California, and broadly ENE directed extension on NNW striking faults east of Baja California, along the trace of the former volcanic arc. This extension could have displaced Baja California as much as 100-150 km WSW relative to North America before about 5.5 Ma. If more extension occurred to the north than to the south, Baja California would also have been rotated very slightly counterclockwise. During this extensional faulting, Baja California may also have been displaced NNW relative to North America by minor strike-slip faulting within the extensional belt, linked to the post-8 Ma strike-slip motion along the San Gabriel fault in southern California. Thus for the period between about 12 Ma and perhaps 3.5 Ma, Baja California was a rigid "microplate" bounded on both sides by displacement between the Pacific and North America plates. The partitioning of displacement between these two parallel zones of the Pacific-North America plate boundary changed slowly with time, until by perhaps about 3.5 Ma most of the plate boundary motion was occurring east of Baja California. The transfer of the Baja California peninsula from the North America plate to the Pacific plate was a gradual process, which took at least the period 12-4 Ma, and perhaps is not entirely complete today.

Existing geologic constraints are consistent with, but do not prove, this scenario. Clearly, much better constraints are needed on the timing and amount of extension in the Gulf Extensional Province and on its relationship to areas further north in the Basin and Range province. The implications of this kinematic model for the dynamics and scale of strike-slip plate margins can be tested with future acquisition of geologic and geophysical data and may be useful for understanding plate margin processes elsewhere.

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