Late Cenozoic Basin and Range structure in western Mexico adjacent to the Gulf of California

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ABSTRACT

The area that surrounds the Gulf of California was intensely faulted during the late Cenozoic prior to opening of the gulf. In a representative 10,000-km^2 area of southern Sinaloa, the faults consist of a predominant north-northwest-striking set having normal displacement and a subsidiary east-northeast set having largely strike-slip displacement. Two domains are recognized: one in which both fault trends are abundant and one in which east-northeast faults are minor. In the former, north-northwest faults form a series of mostly southwest-tilted half-grabens filled with upper Tertiary sediments. Displacement on individual faults is commonly as much as several kilometers. East-northeast faults probably represent accommodation zones between areas of differential extension. In the second domain, north-northwest faults form an extensive graben system. Major faults, dipping 40° to 70° into the graben and having several kilometers of cumulative displacement, are spaced every 5 to 10 km. Bedding attitudes indicate that fault blocks are rotated as much as 65°. Dependent upon assumptions about subsurface geometry of the faults, total extension may range from 20% to 50%. Fault geometry and stress orientations calculated from fault-slip data indicate that the least principal stress was east-northeast.

K-Ar ages of three north-northwest-striking dikes indicate that east-northeast extension began as early as 32 Ma. Ages of tilted volcanic rocks, however, indicate that measurable tilting, and therefore most faulting, began after about 17 Ma.

Faulting having similar timing, style, and orientation occurred throughout the area surrounding the Gulf of California, as far south as Nayarit on the Mexican mainland and as far north as areas in Sonora that are unequivocally within the Basin and Range province. This continuity and similarity in characteristics of faulting around the gulf to those of early Basin and Range faulting in the United States indicate that the area around the gulf is part of the Basin and Range province. This Basin and Range faulting probably created the widely recognized but debated proto-Gulf of California. The present Gulf of California opened by ocean-floor spreading and transform faulting in a zone already weakened by Basin and Range extension. The lack of correspondence between areas of extension and likely areas of crustal thickening related either to Laramide contraction or magmatism argues against a model of Basin and Range extension related solely to spreading of overthickened crust.

INTRODUCTION

It has long been recognized that the Gulf of California opened as a result of ocean-floor spreading and transform faulting along the East Pacific Rise (Larson and others, 1968). Recent syntheses indicate that the gulf opened within the past 5 to 6 m.y. (Curray and Moore, 1984); however, the gulf formed in an area of earlier, largely Miocene, rifting, generally termed the "proto-gulf" (Moore and Buffington, 1968; Karig and Jensky, 1972). Karig and Jensky considered the proto-gulf to be a possible example of back-arc spreading, related to active subduction. More recently, it was recognized that the Basin and Range province continues into areas bounding the Gulf of California (Stewart, 1978; Dokka and Merriam, 1982; Curray and Moore, 1984). The province has been extensively studied in the United States and in parts of northernmost Mexico (Stewart, 1978; Zoback and others, 1981; Eaton, 1982). It has been little studied elsewhere in northern Mexico, however, and its characteristics and even existence there are much more poorly known. Stewart (1978) has shown two distinct bands of late Cenozoic extensional faults of the Basin and Range province in northern Mexico: (1) a narrow arm around part of the Gulf of California in both Baja California and the mainland of Mexico and (2) a broader belt continuing south from the Rio Grande rift (Fig. 1). These two areas are separated by the relatively unfaulted Sierra Madre Occidental. Basin and Range structure in both of these bands south of northern Mexico is poorly known and largely generalized from regional maps. Stewart's (1978) regional compilation shows only three normal faults in Sinaloa; the southern extent of Basin and Range extension is

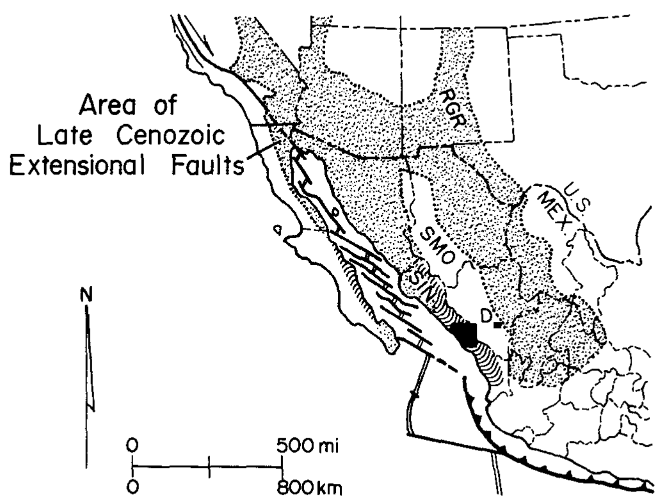

Figure 1. Index map of the Gulf of California and Basin and Range province in southwestern North America, and present-day plate boundaries. Area of late Cenozoic extensional faults (stipple) from Stewart (1978). Additional areas of late Cenozoic extension from this study shown by wavy lines. SMO, Sierra Madre Occidental; SIN, Sinaloa; RGR, Rio Grande rift; D, city of Durango. Shaded box in Sinaloa is area shown in Figures 2 and 3.

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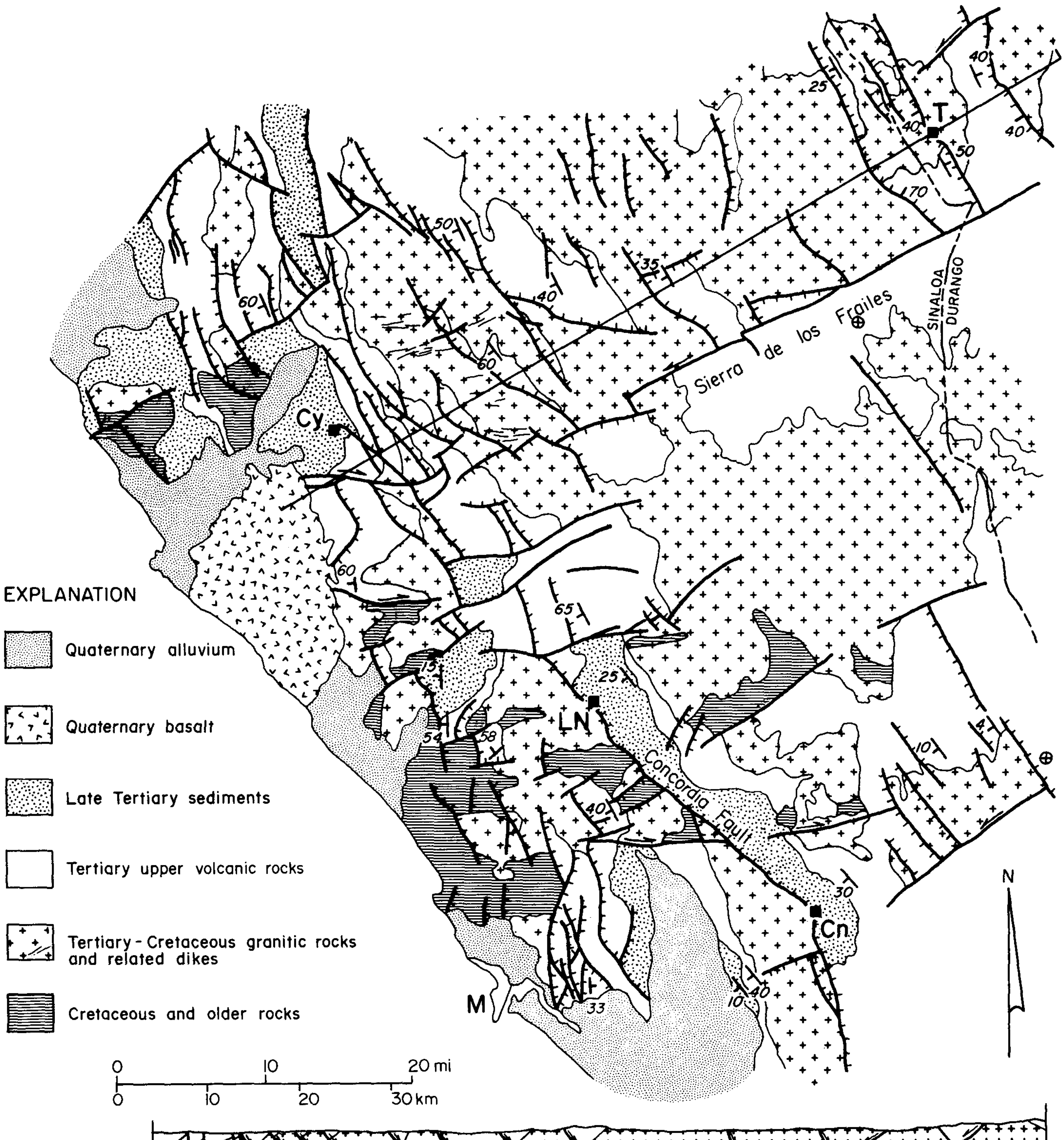

Figure 2. Generalized geologic map of part of southern Sinaloa and adjacent Durango, Mexico (modified from Henry and Fredrikson, 1987). North-northwest-striking faults show predominantly normal displacement. East-northeast faults show lateral to oblique displacement; arrows are shown only for those east-northeast faults for which displacement is known. Cross section has no vertical exaggeration; for ease of interpretation of the cross section, Cretaceous and older rocks and Tertiary-Cretaceous batholithic rocks are consolidated into a single unit, and Quaternary units are not shown. Dips of the three northeasternmost faults of cross section were measured in the field. Fault planes of other major faults along cross section are not exposed; their dips are schematic or inferred from dips of Tertiary upper volcanic rocks. Labeled cities and towns include M, Mazatlan; Cn, Concordia; LN, La Noria; Cy, Coyotitan; and T, Tayoltita.

largely inferred. The Gulf of California's early history of Miocene rifting must be documented for complete understanding of the gulf's origin; similarly, this information must be considered in any discussion of the full extent and character of Basin and Range extension.

This report examines the narrow zone of faulting around the Gulf of California, especially a relatively thoroughly studied area in southern Sinaloa, to demonstrate two points: (1) the area around the gulf underwent extension, appropriate to and contiguous with the Basin and Range province, and (2) the proto-gulf developed as a result of early Basin and Range extension. The Gulf of California later formed within this previously extended area, an interpretation proposed earlier by Curray and Moore (1984).

GEOLOGY OF SOUTHERN SINALOA

The oldest exposed rocks in southern Sinaloa are variably metamorphosed lower than Upper Cretaceous sedimentary and igneous rocks (Fig. 2; Henry, 1986). Granitic batholithic rocks ranging in composition from diorite to granite were emplaced into the older rocks between 100 and at least 45 Ma (Henry, 1975; Henry and Fredrikson, 1987). These batholithic rocks and probably cogenetic volcanic rocks have been termed the "lower volcanic complex" (McDowell and Keizer, 1977). The granitic rocks are progressively younger toward the east. Pre-Oligocene unroofing of the batholith produced a surface of low relief (less than a few tens of meters) on the western part and of slightly greater but still modest relief on the eastern part.

An overlying, middle to upper Cenozoic volcanic sequence, termed the "upper volcanic supergroup" by McDowell and Keizer (1977) and herein called "upper volcanic rocks," is composed of rhyolitic ash-flow tuff, tuffaceous sediment, and minor silicic to intermediate lava flows. Upper volcanic rocks in a thoroughly studied area in Durango immediately east of Sinaloa are 32 to 23 m.y. old (McDowell and Keizer, 1977), but in southern Sinoloa, they are as young as about 18 m.y. (Henry and Fredrikson, 1987). These ash-flow tuffs were deposited as extensive, flat-lying sheets upon the low-relief surface developed on the older rocks and before the late Cenozoic faulting that is the principal subject of this report. Consequently, they are the primary stratigraphic markers that delineate faulting.

Upper Tertiary sediments, consisting predominantly of coarse fanglomerates, were deposited in normal fault-bounded basins; they overlie the volcanic rocks either conformably or unconformably with angular discordance of as much as 25°. Some faults extend through fanglomerates. Age of the sediments may range from mid-Miocene through Pliocene. Quaternary deposits, including a 300-km^2 alkalic basalt field, overlie older rocks and are not faulted.

BASIN AND RANGE STRUCTURE IN SOUTHERN SINALOA

Fault Geometry

Southern Sinaloa is intensely faulted in an area as much as 120 km wide bordering the Gulf of California (Figs. 2 and 3). The relatively unfaulted Sierra Madre Occidental borders this faulted area on the east. Within the faulted area, late Cenozoic faults having two predominant orientations, north-northwest and east-northeast, are the major structural features. Strike of the predominantly north-northwest faults ranges from slightly east of north to northwest; they dip mostly to the northeast. These faults have normal displacement of as much as several kilometers and are commonly marked by ridges of upper volcanic rocks, tilted as much as 65°, that dip into and are juxtaposed against older metamorphic, granitic, and volcanic rocks (Fig. 4). The strike of east-northeast faults ranges from east to northeast; these faults are commonly vertical. On the basis of mapped offsets and orientation of slickenside striations, they show at least some strike-slip motion and are parallel to and probably in part reactivated from pre–Late Cretaceous faults (Henry, 1986).

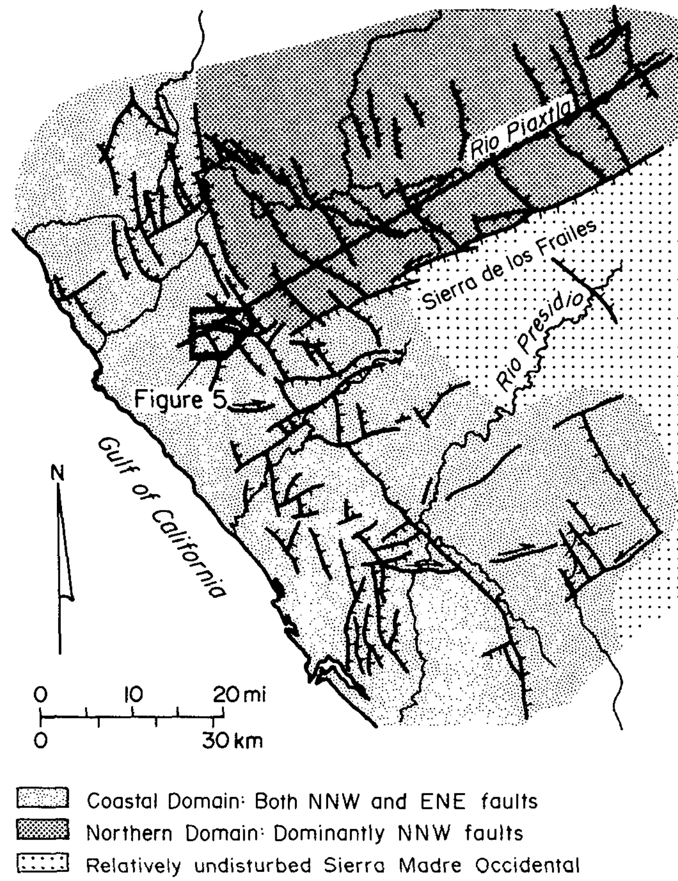

Figure 3. Fault domain map of same area as shown in Figure 2. Coastal domain has both north-northwest- and east-northeast-striking faults. Northern domain has predominantly north-northwest faults. Upper volcanic rocks in both domains are tilted as much as 65°. The Sierra Madre Occidental is cut only by high-angle normal faults having minor displacement; upper volcanic rocks there are flat lying. Box outlines area shown in Figure 5.

Many more faults exist than are shown in Figure 2 or could be incorporated in the 1:250,000-scale map of Henry and Fredrikson (1987). Almost all faults depicted in Figure 2 have displacements of more than a kilometer. Many faults of lesser displacement were identified in the field. In addition, because of deep weathering caused by the semitropical climate of southern Sinaloa, faults that do not juxtapose contrasting rock types are difficult to identify either on aerial photographs or in the field. For example, granitic rocks are typically weathered to a deep grus; faults exclusively within granitic rocks would not be identified except under particularly favorable circumstances, such as in rapidly eroding areas along major drainages or in man-made exposures.

Figure 4. Tilted upper volcanic rocks in central part of northern domain (Fig. 3). View is to southeast of southwest-dipping volcanic rocks.

The Sierra Madre Occidental (Fig. 3) was relatively unaffected by late Cenozoic faulting. Upper volcanic rocks there are flat lying. Minor north-northwest–striking, steeply dipping normal faults have maximum displacements of about 100 m. Waitt (1970) and Wahl (1973) found similar faults cutting flat-lying upper volcanic rocks immediately east of the area shown in Figures 2 and 3, in the central part of the Sierra Madre Occidental. Still farther east, near Durango City (Fig. 1), Basin and Range–style faults reappear (McDowell and Keizer, 1977; Swanson and others, 1978) in what is part of the Basin and Range province of north-central Mexico.

The faulted area in southern Sinaloa is divided into coastal and northern structural domains (Fig. 3), distinguished by (1) the relative abundance of east-northeast–striking faults, (2) the geometry of north-northwest faults, and (3) the degree of tilting and probably the amount of extension. East-northeast–striking faults are common only in the coastal domain. These faults also form boundaries between the two domains and between the domains and the Sierra Madre Occidental. North-northwest–striking faults are abundant in both domains but form a major graben system in the northern domain. Upper volcanic rocks are on average more steeply tilted in the northern domain. Although fault characteristics in these two domains differ slightly, they appear to be simply different manifestations of the same regional extension.

In the coastal domain, both north-northwest– and east-northeast–striking faults are abundant. The mapped north-northwest faults have as much as several kilometers of almost exclusively normal displacement, which is predominantly down to the east. Fault planes of major north-northwest–striking faults are rarely exposed. Attitudes of major faults and of minor-displacement faults exposed in roadcuts or quarries range from as low as 22° to near vertical. Most faults can be traced for a few to as much as 20 km; some may connect across areas of poor exposure. The Concordia fault zone, the western boundary of a half-graben containing faulted upper Tertiary sediments, continues as a single distinct zone for at least 50 km from south of the area shown in Figure 2 past Concordia to La Noria. In places, this zone consists of several splays, but it is no more than a kilometer wide. Total normal displacement across the zone is at least 5 km.

Upper volcanic rocks in the coastal domain generally dip 20° to 40°, rarely to 65°. Strata are tilted to the southwest, except for a few fault blocks 10 to 20 km east and northeast of Mazatlan. East of the major Concordia fault zone, upper volcanic rocks are tilted at progressively shallower angles, culminating in the flat-lying rocks of the Sierra Madre.

At least some and possibly all east-northeast–striking faults show considerable lateral displacement. Strike-slip motion is best demonstrated by the faults immediately south of Coyotitan (Figs. 2 and 5) and by sparse slickenside-bearing outcrops throughout the area shown in Figure 2. South of Coyotitan, upper volcanic rocks bend from southwest dipping, the regional attitude, to northwest dipping adjacent to the major east-striking faults (Fig. 5). This reorientation is consistent with either right-lateral displacement or normal displacement, down to the north. Planes of the larger faults are not exposed, but striations on a few small, east-striking faults plunge consistently at low angles, indicating lateral motion. The east- and northwest-striking faults probably join immediately east of the area shown in Figure 5 (see Fig. 2) but cannot be traced through the deeply weathered granitic rocks. Net right-lateral displacement on the entire east-striking fault system is at least 8 km. The northwest-striking faults also appear to have a component of right-lateral motion, but no fault planes are exposed. Displacement on the small, northeast-striking faults is left lateral or down to the south. Because maximum extension was probably east-northeast, these northeast faults are probably left-lateral oblique. Similar patterns in upper volcanic rocks adjacent to other east-northeast faults also suggest strike-slip displacement. The sense of displacement on most east-northeast faults, whether right or left lateral, however, could not be determined from field relations.

Abutting relations throughout southern Sinaloa indicate that the north-northwest and east-northeast faults were broadly contemporaneous. For example, the north-northwest–striking fault in the south-central part shown in Figure 5 does not carry across the east-striking fault system. Therefore, these faults were active contemporaneously.

In the northern domain, north-northwest–striking faults form an extensive graben system that is symmetrical about an axis roughly through Tayoltita (Fig. 2); east-northeast faults are nearly absent. Several major faults of this system are well exposed near the axis of the graben (northeastern area, Fig. 2), where rapid downcutting in major drainages has kept pace with weathering. These faults dip 40° to 70° into the axis; fault blocks are tilted 25° to 50° outward. Near the center of this structure, individual blocks are irregularly tilted; some are flat lying. Displacement on individual faults is at least several kilometers and ranges as high as 7 km, as determined by offset of the base of upper volcanic rocks. It is not known whether these faults are planar or listric at depth. By either configuration, the major faults near the axis of the graben must intersect at depths of no more than about 5 km. Wisser (1966) interpreted the structure at Tayoltita as a faulted anticline. Although the rocks do dip outward from a central axis, there is no closure, and the structure is a result of extension, not shortening.

Fault planes in the western part of the northern domain are not exposed but are well marked by thick sequences of upper volcanic rocks that dip into and are downfaulted against older granitic rocks (Fig. 4). Individual fault blocks dip 30° to 60° to the west; therefore, faults must dip moderately to the east.

A rectilinear boundary between the two faulted domains and the Sierra Madre Occidental parallels the north-northwest and east-northeast fault trends (Fig. 3). The boundary is expressed differently, dependent upon which orientation it follows. The best studied north-northwest–trending boundary is within the re-entrant of the coastal domain into the Sierra Madre Occidental in the area shown in the southeast corner of Figure 3. Upper volcanic rocks in the Sierra Madre are flat lying. To the southwest, upper volcanic rocks dip southwestward at shallow but progressively greater angles. Areas of different dips are separated by northwest-striking normal faults that are conspicuous on aerial photographs but that show little displacement of the upper volcanic rocks. The easternmost faults seem to be hinge lines with negligible offset. Farther west, individual faults have generally greater displacement, culminating in the large half-graben at Concordia. Upper volcanic rocks dip no more than about 10° except within about 5 km of the half-graben, where dip increases over a few kilometers to as much as 30°. The north-northwest–trending boundary at the southwest end of the Sierra de Los Frailes was not studied as thoroughly but probably is similar.

East-northeast–trending boundaries with the Sierra Madre Occidental are faults that separate flat-lying upper volcanic rocks from variably tilted volcanic rocks. North-northwest faults typically terminate against these boundaries. The best example is the east-northeast–striking fault zone along the northwest edge of the Sierra de los Frailes (Figs. 2 and 3). Blocks on the north side appear to have rotated against the relatively undisturbed south side. The amount of extension perpendicular to this boundary and to other east-northeast–trending boundaries such as in the area shown in the southeast corner of Figure 2 appears to be negligible.

These major east-northeast faults probably represent accommodation zones between areas of differential extension, as was postulated for similar faults in northern Baja California (Dokka and Merriam, 1982) and in the United States (Anderson, 1973; Davis and Burchfiel, 1973; Wernicke and Burchfiel, 1982). By this interpretation, the area north of the Sierra de los Frailes boundary fault, which clearly was more extended than the area to the south, has been translated westward with respect to the Sierra Madre Occidental and to a greater extent than the area to the south. This implies a substantial left-lateral component of motion to the boundary. Because the faults south of Coyotitan show right-lateral displacement, they must not be part of the boundary fault system, even though they are nearly on trend.

The boundary between the faulted northern domain and the undeformed Sierra Madre to the northeast (Fig. 1) is outside the area mapped by Henry and Fredrikson (1987). It must differ from the north-northwest–trending transition farther south because upper volcanic rocks are strongly tilted toward the Sierra Madre Occidental.

The relative abundance of east-northeast–striking faults in the two areas probably partly reflects the abundance of two types of older east-northeast–trending structures. Bedding, foliation, and contacts of pre-batholithic basement rocks strike east-northeast (Henry, 1986), as do dikes and veins related to emplacement of the granitic batholiths. The former, however, appear to have had a much greater influence on late Cenozoic faulting. In the coastal area, pre-batholithic basement rocks crop out over large areas (Fig. 2), and east-northeast–striking faults are abundant. The structural fabric of the basement may have influenced their development.

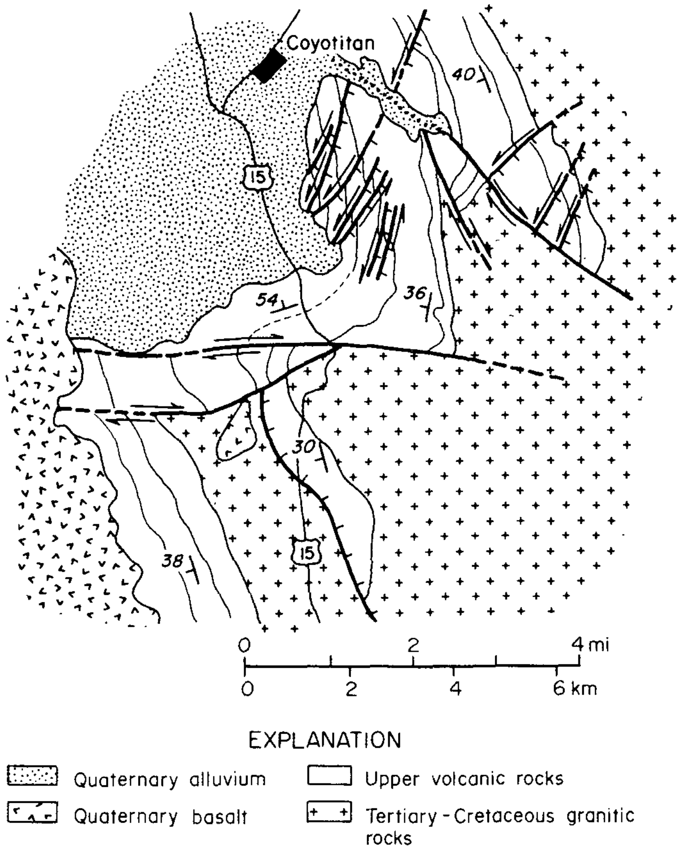

Figure 5. Generalized geologic map of a major east-striking fault system (see Fig. 3 for location). Lines within outcrop of upper volcanic rocks represent marker beds. Apparent displacement of main east-striking faults is right-lateral strike slip or normal down to the north. Slickenside striations on small east-trending faults exposed in roadcuts indicate right-lateral motion. Apparent displacement on small northeast-striking faults was left oblique.

In the northern area, no outcrops of pre-batholithic basement rocks are known; extensive batholithic intrusion apparently displaced all former basement rocks. East-northeast faults are sparse. The few that do occur include some faults with small (less than 1 km) displacement that cut major north-northwest faults in an area of abundant east-northeast–striking dikes northeast of Coyotitan (Fig. 2).

Stress Orientations

Regional fault and tilt geometry, orientations of upper Tertiary dikes, and fault-slip data indicate that the fault system represents east-northeast–oriented extension, suggesting that the least principal stress (σ_3) was east-northeast. The predominant north-northwest strike of normal faults and tilt of upper volcanic rocks to the west-southwest suggest that extension must have been east-northeast, perpendicular to the normal faults. The north-northwest fault trend is not simply inherited from older structures, as no older north-northwest structures have been identified in southern Sinaloa (Henry and Fredrikson, 1987). In contrast, the east-northeast–striking faults could be in part inherited from the east-northeast–striking basement structures (Henry, 1986). Nevertheless, apparent displacement on east-northeast and other faults that were deter-

TABLE 1. CALCULATED STRESS ORIENTATIONS

	σ_1	σ_2	σ_3	Δ	% discordant
All data N = 54	N53°W 89.2	S13°W 0.3	S77°E 0.7	37	31
Two areas N = 15	N19°W 72	S22°E 18	S68°W 1.1	8	0

mined from field relations, for example, the faults south of Coyotitan (Fig. 5), is consistent with east-northeast extension. Additionally, the north-northwest trend of upper Tertiary dikes associated with the upper volcanic rocks and of a variety of still younger mafic dikes is also consistent with east-northeast extension.

To test these more qualitative indicators of the direction of extension, paleostress orientations (Table 1) were calculated using the method of Angelier (1979) and Angelier and others (1985). Fault and fault-slip indicators were measured on 54 fault planes within 5 areas in southern Sinaloa (Fig. 6). All measurements were made in roadcuts and quarries, mostly on faults of small displacement (less than a few tens of meters) adjacent to major faults. Few major faults recognized by outcrop patterns are well exposed in southern Sinaloa. Fault orientations vary widely at each locality, a requirement of the calculation method (Angelier and others, 1985); however, slip directions also scatter widely.

The total fault-slip data indicate that σ_1 plunges steeply and σ_3 is nearly horizontal, consistent with normal faulting (Table 1); however, several features of the total data suggest that they do not represent a single stress field. First, calculated σ_3 trends N77°W, distinctly oblique to the predominant north-northwest regional trend of major normal faults. Additionally, two measures of population homogeneity indicate that the data are inhomogeneous (Table 1; Angelier and others, 1985). The average angle (Δ) between actual striations and the theoretical shear stress determined from the reduced stress tensor is 37°, and 31% of the measurements are more than 45° discordant to the calculated stress tensor.

This inhomogeneity probably results from three factors: (1) tilting of faults about horizontal axes after initial displacement and formation of striations, (2) rotation of faults about vertical axes after displacement, and (3) change in orientation and magnitude of tectonic stress with time. Conclusive evidence exists for the first two. Several steeply dipping, east-northeast faults show more than one set of striations with markedly different rakes, probably a result of tilting of the rocks during faulting. Several other faults are near major east-northeast–trending fault zones where upper volcanic rocks and therefore faults within them have been substantially rotated.

To avoid these problems, similar calculations were made using a subset of the data, consisting of all 15 faults present in two of the 5 areas (Fig. 6). These faults were exclusively in upper volcanic rocks that have been tilted but not rotated about vertical axes and should, therefore, better preserve evidence of the stress field in which they initially formed. For these data, σ_1 is again vertical but σ_3 is N68°E (Table 1), consistent with the regional fault geometry. Although the number of measurements is barely minimal for this type of analysis, the more restricted data set probably approximates the stress field more accurately than does the entire data set.

Fault orientations and other data also suggest both older and younger stress fields. Dikes related to lower Tertiary granitic rocks northeast of Coyotitan strike predominantly east to east-northeast (Fig. 2). Also, the extensive vein system at Tayoltita, Mexico's largest gold producer, strikes predominantly east-northeast (Keller, 1974; Smith and Hall, 1974; Smith and others, 1982), as do vein systems in several other deposits in the area. Although both the San Ignacio area dikes and Tayoltita veins have been tilted during east-northeast extension, the axis of tilting was nearly perpendicular to them, and so their original strike should not be much different from the present strike. Several measured faults in granitic rocks trend northeast and have northwest-oriented striations. Together, these data suggest that σ_3 was oriented northwest during granite emplacement. The maximum principal stress (σ_1) was probably east-northeast, consistent with nearly horizontal compression driven by rapid, normal convergence between the Farallon and North American plates between about 70 and 40 Ma (Jurdy, 1984; Engebretson and others, 1984). Price and Henry (1984) interpreted σ_1 to be east-northeast during Eocene and early Oligocene volcanism in Trans-Pecos Texas that was in part contemporaneous with the granitic magmatism of Sinaloa.

Younger, northwest-oriented extension is suggested by several faults that displace upper Tertiary sediments in area 2 of Figure 6. These faults trend north to northeast and have striations that indicate northwest exten-

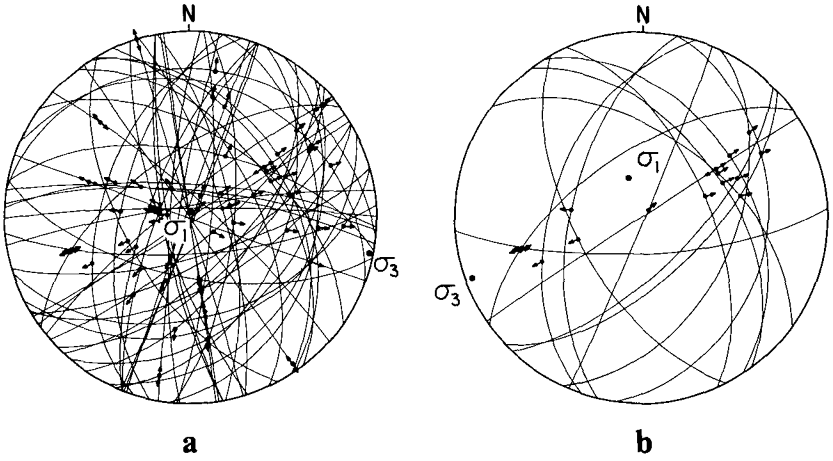

Figure 6. Wulff lower-hemisphere plots of fault and slip orientations and calculated maximum (σ_1) and least (σ_3) principal stresses. Arrows on fault planes indicate direction of slip. Single arrows indicate predominantly normal slip; double arrows indicate predominantly lateral slip. a. 54 faults and slip orientations from 5 locations: (1) quarries in upper volcanic rocks immediately north and east of Mazatlan, (2) roadcuts in upper Tertiary sediments along Mexico Highway 45 approximately 25 km east of Mazatlan, (3) a quarry in upper volcanic rocks approximately 30 km north of Mazatlan, (4) roadcuts in a broad area along the major fault zone between Concordia and La Noria, and (5) roadcuts in upper volcanic and granitic rocks northeast of Coyotitan. Both fault and slip vectors scatter widely, probably as a result of (1) tilting of faults about horizontal axes after displacement, (2) rotation of faults about vertical axes after displacement, and (3) formation during more than one stress regime. b. 15 faults from locations 3 and 4. These faults represent a more homogeneous population that is exclusively in upper volcanic rocks and has not been rotated.

sion. The sediments are the youngest demonstrably faulted rocks in the region, are not rotated, and are tilted no more than 15°. Therefore, the orientation of the faults and striations is that in which they formed. Any late northwest extension must have been minor, as east-northeast–trending faults show negligible normal displacement.

Amount of East-Northeast Extension

Tilt angles of upper volcanic rocks of as much as 65° and the moderate dip of many observed faults indicate considerable extension in southern Sinaloa. The total amount of extension must be greater in the northern domain than in the coastal domain, because rocks are more greatly and uniformly tilted there and because the extended area is wider. Because it is not known whether the faults are planar or listric, however, precise determination of amount of extension is impossible (Wernicke and Burchfiel, 1982). If the faults are planar and both faults and volcanic rocks are tilted, calculations using the equations of Wernicke and Burchfiel (1982) suggest that the northern domain has extended at least 50%. If faults are listric and only the rocks are tilted, total extension may be only about 20%.

Tilting of upper volcanic rocks throughout the western part of the southern domain is comparable to or slightly less than in the northern domain. Therefore, these areas have probably had comparable extension. Because upper volcanic rocks in the area east of the Concordia fault in the southeastern part of the coastal domain are only modestly tilted, total extension there is probably less than 10%.

Timing of East-Northeast Extension

K-Ar ages of various upper Cenozoic igneous rocks (Henry and Fredrikson, 1987) constrain both the timing of initial extension and of major faulting and tilting. Ages of three north-northwest–trending dikes, petrographically related to upper volcanic rocks, range from 32 to 24 m.y., indicating east-northeast extension as early as 32 Ma. A maximum age is uncertain but is no greater than 40 m.y. K-Ar ages of pre-mineralization rocks around Tayoltita and of adularia from the east-northeast–striking vein system are as young as 40 m.y. (Henry, 1975; C. D. Henry and F. W. McDowell, unpub. data). Therefore, east-northeast extension must have begun after 40 Ma. Ballard (1980) suggested that a brief episode of east-northeast extension occurred approximately 42 Ma, based on the north-northwest orientation of a minor part of the Tayoltita vein system. Most of the vein system there, however, trends east-northeast (Smith and others, 1982) and probably formed during batholithic emplacement while the least principal stress (σ_3) was oriented north-northwest. I suggest that the change in σ_3 from north-northwest to east-northeast was either nearly coincident with initial contact of the East Pacific Rise with the paleotrench about 30 Ma (Atwater, 1970; Engebretson and others, 1985) or possibly during initiation of the ignimbrite flare-up of the Sierra Madre Occidental about 34 Ma (McDowell and Keizer, 1977).

Stratigraphic constraints and K-Ar ages of tilted upper volcanic rocks indicate that faulting began much later than initial stress reorientation. Upper volcanic rocks that are now intensely faulted and steeply tilted were deposited upon a surface of little relief (less than a few tens of meters). Major faulting and tilting must have postdated deposition of these rocks, which are as young as 17 to 19 m.y. (Henry and Fredrikson, 1987). The youngest upper volcanic rocks are as steeply tilted as the oldest. Any earlier faulting must have produced negligible tilting.

Upper Tertiary sediments, the age of which could range from mid-Miocene through Pliocene, span the time of faulting. Faulted coarse fanglomerates were clearly deposited in half-grabens, for example, the half-graben near Concordia. These deposits commonly dip less steeply than the underlying volcanic rocks; for example, fanglomerates southwest of Concordia dip less than 20° to the southwest, whereas underlying upper volcanic rocks dip 40° to 47° (Fig. 2). Faulting entirely preceded eruption of 2 Ma alkalic basalts that form the extensive field adjacent to the Gulf of California (Fig. 2; Henry and Fredrikson, 1987). Although the basalts dip about 2° to the southwest, the dip is probably primary and not a result of faulting, as there is no evidence of a young fault along its eastern edge. No faults that cut the basalt field were found, and several faults, including both north-northwest and east-northeast faults, that trend into the field are overlain by unfaulted basalt. No Quaternary scarps were identified in southern Sinaloa. Further study of the timing and structure of upper Cenozoic sediments could help elucidate the history of deformation.

BASIN AND RANGE STRUCTURE AROUND THE GULF OF CALIFORNIA

Late Cenozoic, north- to northwest-striking fault systems and associated tilting, similar to those found in Sinaloa, are prominent around the

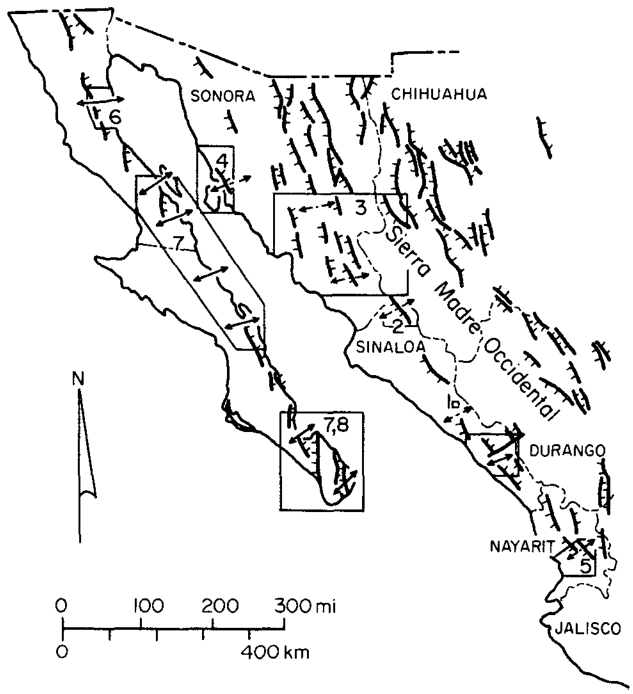

Figure 7. Areas of north- to northwest-striking, late Cenozoic normal faults around the Gulf of California. Arrows show directions of extension determined from regional fault and tilt patterns only (dashed arrows) or from fault patterns and fault-slip data (solid arrows). Faults were compiled from sources listed below and from Gastil and others (1975) for the state of Baja California, 1:1,000,000-scale maps of northwestern Mexico by the Secretaria de Programacion y Presupuesto, and reconnaissance by the author in coastal parts of Sinaloa and northern Nayarit. Outlined areas on mainland in addition to southern Sinaloa are central Sinaloa (1 is Garcia and others, 1983), northern Sinaloa (2 is Fredrikson, 1971), Sonora (3 is King, 1939; 4 is Gastil and Krummenacher, 1977), and as far south as Nayarit (5 is Gastil and Krummenacher, 1978; Gastil and others, 1978). Studies on the Baja California peninsula include northern Baja California (6 is Dokka and Merriam, 1982), central and southern Baja California (7 is Angelier and others, 1981), and La Paz area (8 is Hausback, 1984).

Gulf of California (Fig. 7). Only Dokka and Merriam (1982), among the works listed for Figure 7, and Curray and Moore (1948) considered these faults to be part of the Basin and Range province. Contemporaneous east- to northeast-striking fault zones have also been identified in the northern part of Baja California by Dokka and Merriam (1982), who considered them to be accommodation zones between areas of differential extension, and in the La Paz area by Hausback (1984). My reconnaissance indicates that north-northwest–striking faults and tilted upper volcanic rocks are prominent throughout coastal parts of Sinaloa and northern Nayarit.

The eastern limit of faulting on the mainland follows an abrupt but irregular boundary along the relatively unfaulted Sierra Madre Occidental (Fig. 3). The location of this boundary and style of transition outside of southern Sinaloa are poorly known. Major north-northwest–striking normal faults reappear east of the Sierra Madre along its entire length (Fig. 7).

The structural pattern bordering the Gulf of California terminates at its southern end in southern Nayarit in the area mapped by Gastil and Krummenacher (1978) and Gastil and others (1978) or in northern Jalisco. Faulting in Jalisco at the western end of the Trans-Mexican volcanic belt may have begun in the Pliocene, consists of a graben triple junction, and, although vertical displacement is as much as 2.5 km, has produced at most modest tilting (Luhr and others, 1985; Allan, 1986). These features are significantly different from those described above; Luhr and others (1985) and Allan (1986) suggest that the rifting in Jalisco may foretell an eastward jump of the East Pacific Rise into the continent.

All studies indicate that faulting around the gulf occurred in the Miocene; however, the time of initial faulting is commonly not tightly constrained, and faulting may not have begun synchronously throughout the gulf region. For example, K-Ar ages of tilted and flat-lying volcanic rocks in northern Baja California (Dokka and Merriam, 1982), coastal Sonora (Gastil and Krummenacher, 1977), and Isla Tiburon (Gastil and others, 1979) indicate that tilting and therefore faulting occurred after 17 Ma and before 9 Ma. Similarly, faulting in Sinaloa is constrained only between 17 and 2 Ma. Stock and Hodges (1989) indicated that faulting began no earlier than 12 Ma in northern Baja California. In contrast, faulting on Isla Tiburon appears to have begun significantly before 13 Ma. Neuhaus and others (1988) reported that 19 to 15 Ma rocks are tilted as much as 50°, whereas 13 to 11 Ma rocks are tilted only 25°. Also, the 13 Ma volcanic rocks are interbedded with marine strata (Smith and others, 1985) that are part of the evidence for a proto–Gulf of California that probably formed during subsidence related to extension (M. C. Boehm, 1988, personal commun.). Substantial faulting must have occurred before 13 Ma to generate enough subsidence to allow marine incursion. Evidence for initial east-northeast extension as early as 32 Ma, as found in Sinaloa, has not been sought elsewhere. Clearly, more documentation of the timing of faulting and extension around the gulf is desirable.

Extension and inferred least principal stress directions associated with the north-northwest–striking fault systems were east to northeast throughout the area surrounding the Gulf of California (Fig. 7). These orientations are based on analysis of both fault-slip data and regional fault and tilt trends in Baja California (Angelier and others, 1981; Dokka and Merriam, 1982) and on only regional fault and tilt trends in the other areas.

Several studies indicate a transition to more-northwest extension, probably associated with transform opening of the Gulf of California (Gastil and Krummenacher, 1977; Colletta and Angelier, 1983), but the timing of change is poorly constrained. Inferred least principal stress was west-northwest in Pliocene and Quaternary time in central Baja California (Angelier and others, 1981; Colletta and Angelier, 1983). Although these authors do not specify when the stress change occurred, Colletta and Angelier (their Fig. 2, p. 436) showed the upper Miocene Boleo Formation being unaffected by faults related to the earlier east-northeast extension. Therefore, the change was probably in late Miocene time. Northwest-striking strike-slip faults and northeast-striking normal faults, consistent with northwest extension, formed after about 8 Ma along the Sonora coast (Gastil and Krummenacher, 1977). In contrast, Dokka and Merriam (1982) suggested that extension in northern Baja California after 6 Ma continued to be east-west, because late Cenozoic extension continued along existing faults. This evidence, however, does not preclude reorientation of the stress field, because the younger stress field commonly reactivated existing faults (Angelier and others, 1981). Almost all features of faulting in southern Sinaloa formed during east-northeast extension. Evidence for later northwest extension consists of a few northeast-striking faults having northwest-trending striations in upper Tertiary sediments (Fig. 6).

Quaternary faulting has occurred on Isla Tiburon (Gastil and Krummenacher, 1977), in northern Baja California (Dokka and Merriam, 1982), and possibly near La Paz (Hausback, 1984). The scarps on Isla Tiburon strike northeast and are consistent with northwest extension. Although Dokka and Merriam do not specify the orientation of Quaternary scarps in northern Baja California, they apparently follow existing northwest-striking faults. These scarps could indicate either continuation of east-west extension, as interpreted by Dokka and Merriam, or reactivation of existing faults in a reoriented stress field.

DISCUSSION AND IMPLICATIONS

The characteristics of late Cenozoic extension around the gulf, compiled from the references discussed above and this study, are generally similar to documented characteristics of extension in the Basin and Range province in the United States (Zoback and others, 1981). Comparison is complicated by the diverse expression of extension within the United States part of the province (Zoback and others, 1981; Wernicke and Burchfiel, 1982; Baldridge and others, 1984; Henry and Price, 1986). Features that seem most consistent, and therefore most appropriate for comparison, are (1) development of east-northeast least principal stress and the beginning of east-northeast extension approximately 30 Ma and (2) change to northwest or west-northwest least principal stress and resulting extension about 10 Ma (Zoback and others, 1981; Wernicke and Burchfiel, 1982; Chamberlin, 1983; Baldridge and others, 1984; Angelier and others, 1985; Henry and Price, 1986; Wust, 1986). Zoback and others (1981) used these characteristics to define early (30–10 Ma; what they termed "pre–Basin and Range") and late ("true" Basin and Range) phases of extension. Major faulting began over a wide range of times: approximately 30 Ma in the Rio Grande rift, nearly coincident with the beginning of extension (Chamberlin, 1983; Seager and others, 1984; Baldridge and others, 1984); 23 Ma in Trans-Pecos Texas (Henry and Price, 1986) and possibly Durango, Mexico (Aguirre-Diaz and McDowell, 1988); 17 Ma in much of the Great Basin (Proffett, 1977; Stewart, 1978; Zoback and others, 1981; Shaver and McWilliams, 1987); after 14 Ma in northeastern California (Duffield and McKee, 1986); and approximately 13 to 12 Ma in southwestern Arizona (Eberly and Stanley, 1978).

Clearly, the east-northeast extension around the gulf, as far south as Nayarit (Fig. 7), is similar to the early phase of extension in the United

States. In the gulf area, least principal stress was east-northeast by 32 Ma, but major faulting began after 17 Ma. The least principal stress and direction of extension changed to northwest, probably in the late Miocene.

On the basis of this comparison and because the extensional area around the Gulf of California merges with the Basin and Range province in northern Sonora and Baja California, I propose that early extension around the gulf records the southwestern extent of the early phase of Basin and Range deformation. The Basin and Range province therefore surrounds the entire present gulf (Fig. 7). Curray and Moore (1984) also suggested that north-trending horsts and grabens of the La Paz block and other parts of southern Baja California are part of the Basin and Range province. Notably, Basin and Range faults appear to end in Nayarit (Figs. 1 and 7), coincident with the western edge of the Trans-Mexican volcanic belt and the plate margin along which subduction has continued to the present (Atwater, 1970; Mammerickx and Klitgord, 1982). The Gulf of California formed within this previously extended area by extension and transform faulting that created new oceanic crust. Curray and Moore (1984) suggested that the plate margin jumped to this location largely because it was a zone of weakness. In fact, the margin in the gulf area closely coincides with the western edge of the Basin and Range province. This relation is consistent with the proposal of Luhr and others (1985) and Allan (1986) that rifting in Jalisco is a precursor to a future eastward jump in the spreading ridge into the North American plate.

These observations also have implications for the origin of the proto-gulf and for the Basin and Range province in general. Basin and Range extension is almost certainly the origin of the proto–Gulf of California defined by Moore and Buffington (1968) and Karig and Jensky (1972). Although Karig and Jensky related the proto-gulf to possible back-arc extension, its structural association with the broader Basin and Range province indicates an origin tied to that of the province. Marine deposition, indicating substantial subsidence, occurred throughout much of the area now occupied by the gulf by as early as 13 Ma (Smith and others, 1985; Boehm, 1987; Smith, 1987; M. C. Boehm, 1988, personal commun.). Subsidence at that time is consistent with the Basin and Range extension discussed herein. Warm-water faunal assemblages indicate that connection to the Pacific Ocean was to the south (Boehm, 1987). Continuation of faulting to the southern end of the present gulf certainly could have created such a connection there. The lack of major faults crossing the Baja California peninsula would argue against a connection across the peninsula.

Recent models concerning the origin of late Cenozoic extension in western North America have variably emphasized either plate interactions or stresses generated entirely within the North American plate. Mechanisms of plate interactions include broadly distributed shear related to transform motion (Atwater, 1970), migration of the Mendocin triple junction (Ingersoll, 1982; Glazner and Bartley, 1984), sudden decrease in convergence rates (Engebretson and others, 1984), or changes in North American plate motion (Pollitz, 1988). Intraplate mechanisms call upon gravitational spreading induced by overthickening of the crust resulting from Laramide or earlier contraction or magmatic intrusion (for example, Wernicke and others, 1987). Some models (Coney and Harms, 1984; Coney, 1987) combine the processes.

Although recognition of Basin and Range faults around the Gulf of California does not resolve these issues, it does provide some constraints. Basin and Range extension around the gulf does not coincide with likely regions of overthickened crust. The Laramide deformed belt lies far to the east in northern and eastern Mexico (Drewes, 1978; Coney, 1987) and is separated from the Gulf by the relatively unextended Sierra Madre Occidental. Although nearly all of western Mexico underwent magmatism in the late Mesozoic and Cenozoic (Anderson and Silver, 1974; Henry, 1975; Damon and others, 1981; Gastil and others, 1981), the most intense and voluminous activity is represented by the mid-Tertiary upper volcanic rocks of the Sierra Madre Occidental (McDowell and Keizer, 1977; Clabaugh and McDowell, 1979; Swanson and McDowell, 1984). Yet, the Sierra Madre Occidental is an unextended block surrounded by areas of major extension. Relating extension solely to spreading of overthickened crust seems doubtful.

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REFERENCES CITED

Aguirre-Diaz, G., and McDowell, F. W., 1988, Naure and timing of faulting in the southern Basin and Range, central-eastern Durango, Mexico: EOS (American Geophysical Union Transactions), v. 69, p. 1412–1413.

Allan, J. F., 1986, Geology of the Northern Colima and Zacoalco grabens, southwest Mexico: Late Cenozoic rifting in the Mexican volcanic belt: Geological Society of America Bulletin, v. 97, p. 473–485.

Anderson, R. E., 1973, Large-magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.

Anderson, T. H., and Silver, L. T., 1974, Late Cretaceous plutonism in Sonora, Mexico, and its relationship to Circum-Pacific magmatism: Geological Society of America Abstracts with Programs, v. 6, p. 484.

Angelier, J., 1979, Determination of the mean principal stress for a given fault population: Tectonophysics, v. 56, p. T17 T26.

Angelier, J., Colletta, B., Chorowicz, J., Ortlieb, L., and Rangin, C., 1981, Fault tectonics of the Baja California Peninsula and the opening of the Sea of Cortez, Mexico: Journal of Structural Geology, v. 3, p. 347–357.

Angelier, J., Colletta, B., and Anderson, R. E., 1985, Neogene paleostress changes in the Basin and Range: A case study at Hoover Dam, Nevada-Arizona: Geological Society of America Bulletin, v. 96, p. 347–361.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

Baldridge, W. S., Olsen, K. H., and Callender, J. F., 1984, Rio Grande Rift: Problems and perspectives: New Mexico Geological Society, Annual Field Conference, 35th, Guidebook, p. 1–12.

Ballard, S. N., 1980, Structural geologic controls at the San Luis Mines, Tayoltita, Durango, Mexico [M.S. thesis]: Tucson, Arizona, University of Arizona, 121 p.

Boehm, M. C., 1987, Evidence for a north-verging mid-to-late Miocene proto–Gulf of California: Geological Society of America Abstracts with Programs, v. 19, p. 594.

Chamberlin, R. M., 1983, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico: A summary: New Mexico Geological Society, Annual Field Conference, 34th, Guidebook, p. 111–118.

Clabaugh, S. E., and McDowell, F. W., 1979, Ignimbrites of the Sierra Madre Occidental and their relations to the tectonic history of western Mexico, *in* Chapin, C. E., and Elston, W. E., eds., Ash-flow tuffs: Geological Society of America Special Paper 180, p. 113–124.

Colletta, B., and Angelier, J., 1983, Tectonique cassante dur nord-ouest Mexicain et ouverture du Golfe de California: Bulletin du Centre de Recherches Exploration-Production Elf Aquitaine, v. 7, p. 433–441.

Coney, P. J., 1987, The regional tectonic setting and possible causes of Cenozoic extension in the North American Cordillera, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 177–186.

Coney, P. J., and Harms, T. A., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550–554.

Curray, J. R., and Moore, D. G., 1984, Geologic history of the mouth of the Gulf of California, *in* Crouch, J. K., and Bachman, S. B., eds., Tectonics and sedimentation along the California margin: Society of Economic Paleontologists and Mineralogists, Pacific Section, v. 38, p. 17–36.

Damon, P. E., Shafiqullah, M., and Clark, K. F., 1981, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 137–154.

Davis, G. A., and Burchfiel, B. C., 1973, Garlock fault: An inracontinental transform structure, southern California: Geological Society of America Bulletin, v. 84, p. 1407–1422.

Dokka, R. K., and Merriam, R. H., 1982, Late Cenozoic extension of northeastern Baja California, Mexico: Geological Society of America Bulletin, v. 93, p. 371–378.

Drewes, H., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, p. 641–657.

Duffield, W. A., and McKee, E. H., 1986, Geochronology, structure, and basin-range tectonism of the Warner Range, northeastern California: Geological Society of America Bulletin, v. 97, p. 142–146.

Eaton, G. P., 1982, The Basin and Range province, origin and tectonic significance: Annual Reviews of Earth and Planetary Sciences, v. 10, p. 409–440.

Eberly, L. D., and Stanley, T. B., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921–940.

Engebretson, D. C., Cox, A., and Thompson, G. A., 1984, Correlation of plate motions with continental tectonics: Laramide to Basin-Range: Tectonics, v. 3, p. 115–120.
Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.
Fredrikson, G., 1971, Geology of the Huitis and La Mision quadrangles, northernmost Sinaloa, Mexico [M.S. thesis]: Austin, Texas, University of Texas, 90 p.
Garcia, J., Fernandez, R., and Vazquez, R., 1983, Estudio gravimetrico en la zona geotermica de La Prieta, Culiacan, Mexico: Geofisica Internacional, v. 22, p. 345–388.
Gastil, R. G., and Krummenacher, D., 1977, Reconnaissance geology of coastal Sonora between Puerto Lobos and Bahia Kino: Geological Society of America Bulletin, v. 88, p. 189–198.
——— 1978, Reconnaissance geologic map of the west-central part of the state of Nayarit, Mexico: Geological Society of America *Map and Chart Series, Map MC-24.*
Gastil, R. G., Phillips, R. P., and Allison, E. C., 1975, Reconnaissance geology of the state of Baja California: Geological Society of America Memoir 140, 170 p.
Gastil, R. G., Krummenacher, D., and Jensky, W. E., 1978, Reconnaissance geology of west-central Nayarit, Mexico: Geological Society of America, Text to accompany Map and Chart Series Map MC-24.
Gastil, R. G., Krummenacher, D., and Minch, J., 1979, The record of Cenozoic volcanism around the Gulf of California: Geological Society of America Bulletin, v. 90, p. 839–857.
Gastil, R. G., Morgan, G. J., and Krummenacher, D., 1981, The tectonic history of peninsular California and adjacent Mexico, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 285–306.
Glazner, A. F., and Bartley, J. M., 1984, Timing and tectonic setting of Tertiary low-angle normal faulting and associated magmatism in the southwestern United States: Tectonics, v. 3, p. 385–396.
Hausback, B. P., 1984, Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico, *in* Frizzell, V. A., Jr., ed., Geology of the Baja California Peninsula: Society of Economic Paleontologists and Mineralogists, Pacific Section, v. 39, p. 219–236.
Henry, C. D., 1975, Geology and geochronology of the granitic batholithic complex, Sinaloa, Mexico [Ph.D. dissert.]: Austin, Texas, University of Texas, 158 p.
——— 1986, East-northeast-trending structures in western Mexico: Evidence for oblique convergence in the late Mesozoic: Geology, v. 14, p. 314–317.
Henry, C. D., and Fredrikson, G., 1987, Geology of southern Sinaloa adjacent to the Gulf of California: Geological Society of America Map and Chart Series, Map MCH063, 14 p.
Henry, C. D., and Price, J. G., 1986, Early Basin and Range development in Trans-Pecos Texas and adjacent Chihuahua: Magmatism and orientation, timing, and style of extension: Journal of Geophysical Research, v. 91, p. 6213–6224.
Ingersoll, R. V., 1982, Triple-junction instability as cause for late Cenozoic extension and fragmentation of the western United States: Geology, v. 10, p. 621–624.
Jurdy, D. M., 1984, The subduction of the Farallon plate beneath North America as derived from relative plate motions: Tectonics, v. 3, p. 107–114.
Karig, D. E., and Jensky, W., 1972, The Proto-Gulf of California: Earth and Planetary Science Letters, v. 17, p. 169–174.
Keller, P. C., 1974, Mineralogy of the Tayoltita gold and silver mine, Durango, Mexico [M.S. thesis]: Austin, Texas, University of Texas, 123 p.
King, R. E., 1939, Geological reconnaissance in northern Sierra Madre Occidental of Mexico: Geological Society of America Bulletin, v. 50, p. 1625–1722.
Larson, R. L., Menard, H. W., and Smith, S. M., 1968, Gulf of California: A result of ocean-floor spreading and transform faulting: Science, v. 161, p. 781–784.
Luhr, J. F., Nelson, S. A., Allan, J. F., and Carmichael, I.S.E., 1985, Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading-ridge jump: Geology, v. 13, p. 54–57.
Mammerickx, J., and Klitgord, K. D., 1982, Northern East Pacific Rise: Evolution from 25 m.y. B.P. to the present: Journal of Geophysical Research, v. 87, p. 6751–6759.
McDowell, F. W., and Keizer, R. P., 1977, Timing of mid-Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlan, Mexico: Geological Society of America Bulletin, v. 88, p. 1479–1486.
Moore, D. G., and Buffington, E. C., 1968, Transform faulting and growth of the Gulf of California since late Pliocene: Science, v. 161, p. 1238–1241.
Neuhaus, J. R., Cassidy, M., Krummenacher, D., and Gastil, R. G., 1988, *Timing of Proto-Gulf extension and transtensional rifting through volcanic/sedimentary stratigraphy of S.W. Isla Tiburon, Gulf of Calif., Sonora, Mexico:* Geological Society of America Abstracts with Programs, v. 20, p. 218.
Pollitz, F. F., 1988, Episodic North America and Pacific plate motions: Tectonics, v. 7, p. 711–726.
Price, J. G., and Henry, C. D., 1984, Stress orientations during Oligocene volcanism in Trans-Pecos Texas: Timing the transition from Laramide compression to Basin and Range tension: Geology, v. 12, p. 238–241.
Proffett, J. M., Jr., 1977, Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266.
Sawlan, M. G., and Smith, J. G., 1984, Petrologic characteristics, age and tectonic setting of Neogene volcanic rocks in northern Baja California Sur, Mexico, *in* Frizzell, V. A., Jr., ed., Geology of the Baja California Peninsula: Society of Economic Paleontologists and Mineralogists, Pacific Section, v. 39, p. 237–252.
Seager, W. R., Shafiqullah, M., Hawley, J. W., and Marvin, R. F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87–99.
Shaver, S. A., and McWilliams, M., 1987, Cenozoic extension and tilting recorded in Upper Cretaceous and Tertiary rocks at the Hall molybdenum deposit, northern San Antonio Mountains, Nevada: Geological Society of America Bulletin, v. 99, p. 341–353.
Smith, D. M., and Hall, D. K., 1974, Geology of the Tayoltita mine, Durango, Mexico: Society of Mining Engineers, American Institute of Mining, Metallurgical & Petroleum Engineers preprint 74-1-308, 48 p.
Smith, D. M., Albinson, T., and Sawkins, F. J., 1982, Geologic and fluid inclusion studies of the Tayoltita silver-gold vein deposit, Durango, Mexico: Economic Geology, v. 77, p. 1120–1145.
Smith, J. T., 1987, The paleogeography of the Gulf of California as recorded by Tertiary marine molluscan distributions: Geological Society of America Abstracts with Programs, v. 19, p. 849.
Smith, J. T., Smith, J. G., Ingle, J. C., Gastil, R. G., Boehm, M. C., Roldan-Quintana, J., and Casey, R. E., 1985, Fossil and K-Ar age constraints on upper middle Miocene conglomerate, SW Isla Tiburon, Gulf of California: Geological Society of America Abstracts with Programs, v. 17, p. 409.
Stewart, J. A., 1978, Basin-range structure in western North America, a review, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 1–13.
Stock, J. M., and Hodges, K. V., 1989, Pre-Pleistocene extension around the Gulf of California, and the transfer of Baja California to the Pacific plate: Tectonics, v. 8, p. 99–115.
Swanson, E. R., and McDowell, F. W., 1984, Calderas of the Sierra Madre Occidental volcanic field, western Mexico: Journal of Geophysical Research, v. 89, p. 8787–8799.
Swanson, E. R., Keizer, R. P., Lyons, J. I., and Clabaugh, S. E., 1978, Tertiary volcanism and caldera development near Durango City, Sierra Madre Occidental, Mexico: Geological Society of America Bulletin, v. 89, p. 1000–1012.
Wahl, D. E., 1973, Geology of the El Salto strip, Durango, Mexico [M.S. thesis]: Austin, Texas, University of Texas, 112 p.
Waitt, R. B., 1970, Ignimbrites of the Sierra Madre Occidental between Durango and Mazatlan, Mexico [M.S. thesis]: Austin, Texas, University of Texas, 133 p.
Wernicke, B. P., and Burchfiel, C. B., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, p. 105–115.
Wernicke, B. P., Christiansen, R. L., England, P. C., and Sonder, L. J., 1987, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 203–221.
Wisser, E., 1966, The epithermal precious-metal province of northwestern Mexico: Nevada Bureau of Mines Report 136, p. 63–92.
Wust, S. L., 1986, Regional correlation of extension directions in Cordilleran metamorphic core complexes: Geology, v. 14, p. 828–830.
Zoback, M., Anderson, R. E., and Thompson, G. A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: Royal Society of London Philosophical Transactions, Series A, v. 300, p. 407–434.

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