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Plate interactions control middle–late Miocene, proto-Gulf and Basin and Range extension in the southern Basin and Range

Christopher D. Henry [a,*], J. Jorge Aranda-Gomez [b]

[a] *Nevada Bureau of Mines and Geology, University of Nevada, Reno Reno, NV 89557, USA*
[b] *UNICIT, Instituto de Geologia, Universidad Nacional Autonoma de Mexico, Apartado Postal 1-742, Santiago de Querétaro, Qro. 76001, Mexico*

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Abstract

Middle–late Miocene (proto-Gulf; ~12–6 Ma) extension around the Gulf of California (Gulf Extensional Province) is commonly interpreted as resulting from partitioning of oblique Pacific–North American plate motion into strike–slip displacement along the margin and east–northeast extension perpendicular to the margin within the North American plate. We propose that this mechanism also applies to kinematically similar, predominantly east–northeast extension that occurred at the same time throughout the southern Basin and Range province, from southern Arizona and New Mexico to the Trans-Mexican Volcanic Belt. New field and $^{40}Ar/^{39}Ar$ data in Sinaloa and Durango confirm that this episode of extension occurred on the mainland side of the Gulf and in the Basin and Range east of the Sierra Madre Occidental, which is generally considered the eastern margin of the Gulf Extensional Province. Published data indicate the middle–late Miocene episode also occurred across the northern and southern ends of the Sierra Madre where the Gulf Extensional Province connects with the Basin and Range: (1) from central Sonora into southern Arizona and New Mexico, and (2) from Nayarit into central Mexico north of the Trans-Mexican Volcanic Belt. This episode appears to have affected an area that continues to the eastern edge of the Basin and Range province in Texas and San Luis Potosi. Recognition that this episode of extension affected the entire southern Basin and Range resolves the discrepancy between the amount of extension calculated based on plate reconstructions and that based on field data within the Gulf Extensional Province alone. Published plate reconstructions require 160 to 110 km of east–northeast extension between ~12 and 6 Ma. If taken up solely within the Gulf Extensional Province, this would have generated 66 to 78% extension, which is much greater than observed. Spread across the entire southern Basin and Range it requires only ~20% total extension, which is more consistent with observations of cumulative extension between 12 and 6 Ma. Extension was partitioned into the Gulf Extensional Province because (1) it lies between two stable batholith belts (Mesozoic Peninsular Ranges on the west and mid-Tertiary Sierra Madre Occidental on the east) that resisted extension and (2) the Gulf was thermally weakened by immediately preceding arc magmatism. Extension in the main Basin and Range province in part probably avoided the relatively strong, batholithic crust of the Sierra Madre Occidental. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Basin and Range; Cenozoic; Gulf of California; magmatism; Mexico; tectonics

* Corresponding author. Tel.: +1-775-784-6691; fax: +1-775-784-1709.
E-mail address: chenry@unr.edu (C.D. Henry)

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1. Introduction

The middle to late Cenozoic extension that generated the Basin and Range province of western North America is one of the most prominent tectonic events to affect the North American plate. The characteristics of this extension have been extensively studied, but its origin is equally extensively debated. Proposed origins can be broadly categorized into end members of inter- and intraplate mechanisms. Interplate mechanisms focus on various interactions between the Pacific or Farallon and North American plates (Atwater, 1970; Severinghaus and Atwater, 1990; Atwater and Stock, 1998). Intraplate mechanisms interpret extension to result from gravitational collapse of crust that was overthickened by contractional deformation or magmatism (Coney and Harms, 1984; Glazner and Bartley, 1984; Wernicke et al., 1987; Axen et al., 1993).

The Basin and Range province in western Mexico forms two branches separated by the relatively unextended Sierra Madre Occidental (Fig. 1) (Stewart, 1978; Henry and Aranda-Gomez, 1992; Stewart, 1998). The eastern branch is the southeastern part of the 'main' Basin and Range and occupies most of north-central Mexico east of the Sierra Madre Occidental. The eastern branch has undergone several episodes of extension beginning in the late Oligocene or early Miocene (Henry and Aranda-Gomez, 1992; Aguirre-Diaz and McDowell, 1993; Aranda-Gomez et al., 1997; Ferrari et al., 1997; Jansma and Lang, 1997; Nieto-Samaniego et al., 1999). A western branch borders the Gulf of California west of the Sierra Madre and is also known as the Gulf Extensional Province (Gastil et al., 1975). Except in interior Sonora where extension also began in the late Oligocene (Nourse et al., 1994; Stewart and Roldan-Quintana, 1994; Gans, 1997; McDowell et al., 1997), extension in the Gulf Extensional Province began about 13 or 12 Ma. The two branches are contiguous across both Sonora to the north and Nayarit to the south (Fig. 1).

The Sierra Madre Occidental is both a volcanic and a tectonic province. The volcanic Sierra Madre is the world's largest silicic volcanic province and resulted from Eocene through Miocene, particularly Oligocene, volcanism (McDowell and Keizer, 1977; Swanson et al., 1978; Swanson and McDowell, 1984; Aguirre-Diaz and McDowell, 1991). The tectonic province consists of a smaller, unextended core of the volcanic province that is surrounded by extended terrains around the Gulf of California and in the main Basin and Range. In this paper, our reference to the Sierra Madre Occidental is to this unextended core (Fig. 1). Both provinces overlie and completely obscure the inferred boundary between the Tahue and Tepehuano basement terranes (Sedlock et al., 1993).

1.1. Miocene, proto-Gulf extension

The western branch of the Basin and Range province around the Gulf of California underwent a middle to late Miocene ($\sim$12–6 Ma; proto-Gulf) episode of east to northeast extension that generated the Gulf Extensional Province (Karig and Jensky, 1972; Gastil et al., 1975; Gastil and Krummenacher, 1977; Gastil et al., 1978; Dokka and Merriam, 1982; Hausback, 1984; Stock and Hodges, 1989; Henry, 1989; Sawlan, 1991; Umhoefer et al., 1994; Zanchi, 1994; Martin-Barajas et al., 1995; Lee et al., 1996; Axen and Fletcher, 1998). The present-day Gulf then formed as a result of seafloor spreading and transform faulting since about 5.5 Ma (Curray and Moore, 1984; Lonsdale, 1991).

The Gulf Extensional Province (GEP) includes extended terrain along the eastern side of Baja California and the western side of mainland Mexico (Fig. 1) (Gastil et al., 1975; Stock and Hodges, 1989; Lee et al., 1996). Boundaries to the GEP are relatively clearcut along the western edge with the unextended Peninsular Ranges (i.e. the main Gulf escarpment) and along the eastern margin with the similarly unextended Sierra Madre Occidental. However, the boundaries with the main Basin and Range province both to the north, in Sonora and Arizona, and to the south, in Nayarit, are uncertain (Stock and Hodges, 1989; Lee et al., 1996). Moreover, the genetic relation between the GEP and Basin and Range province remains uncertain despite their apparent continuity.

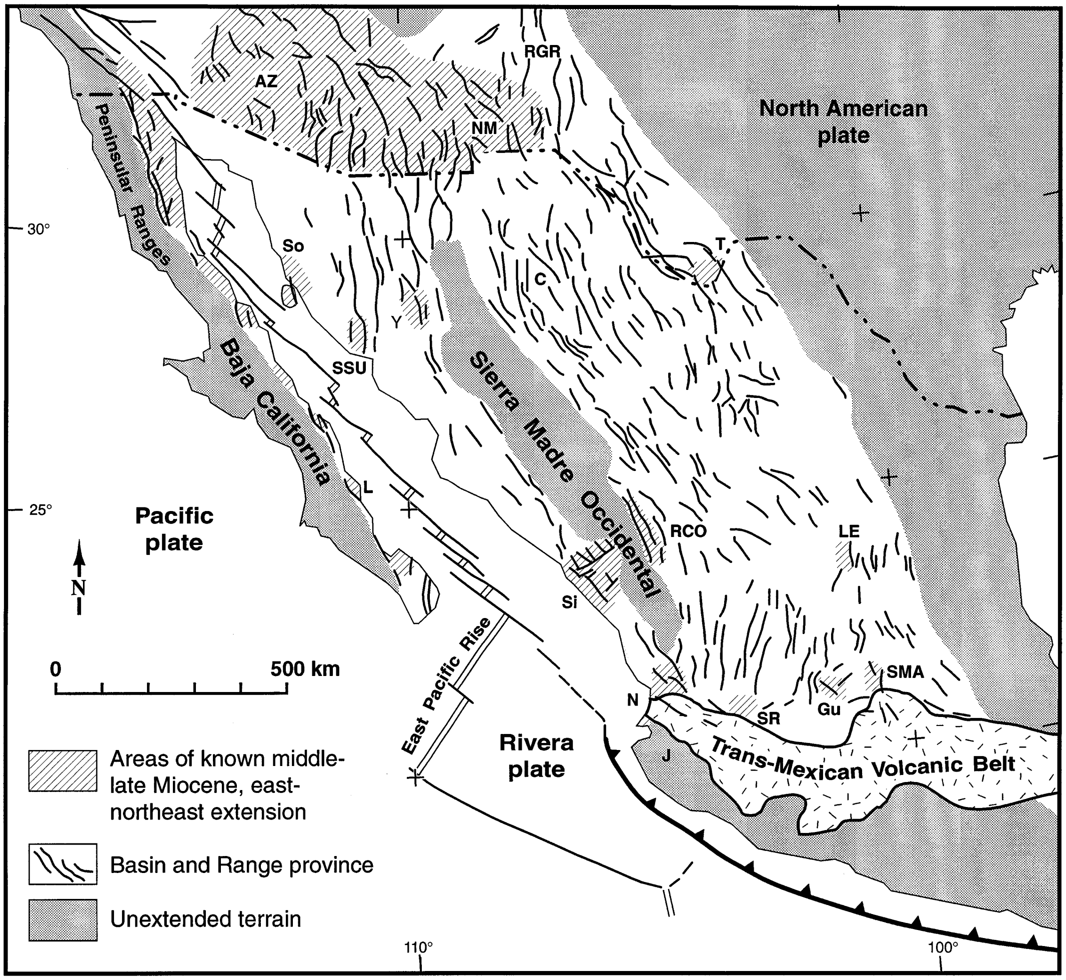

Fig. 1. The southern Basin and Range in southwestern US and northern Mexico, showing areas that are known to have undergone east to northeast extension in the middle to late Miocene (~13–5.5 Ma). The Gulf Extensional Province includes that part of the Basin and Range province that surrounds the Gulf of California. See text for discussion and references. AZ = Arizona; NM = New Mexico; RGR = Rio Grande rift; So = Sonora; SSU = Sierra Santa Ursula; Y = Rio Yaqui basin; C = Chihuahua; T = Trans-Pecos Texas; L = Loreto; Si = Sinaloa; RCO = Rio Chico–Otinapa graben; LE = Los Encinos volcanic field; N = Nayarit; SR = Santa Rosa; Gu = Guanajuato; SMA = San Miguel de Allende; J = Jalisco block.

1.2. Plate motion partitioning origin for the proto-Gulf of California

The part of the Basin and Range province that includes the Gulf of California is an excellent location to evaluate alternative origins for extension. Although initially considered to be 'back-arc' extension (Karig and Jensky, 1972), it is now more widely accepted that the middle–late Miocene proto-Gulf extension resulted from partitioning of Pacific–North American plate motion between strike–slip displacement along the plate margin west of Baja California and extension to the east, within the North American plate (Spencer and Normark, 1979; Hausback, 1984; Stock and Hodges, 1989; Lee et al., 1996). This mechanism was most comprehensively developed by Stock and Hodges (1989), who restored Baja California to a pre-seafloor spreading position (~5.5 Ma) and used global plate circuit reconstructions to determine plate configurations in the Miocene. The Pacific and North American plates first came into contact in the late Oligocene (Atwater, 1970), a strike–slip boundary developed between them, and triple junctions migrated both to the south (Rivera) and north (Mendocino). Subduction and arc volcanism ceased as the Rivera triple junction migrated southward along the southern California and Baja California coast. At 12.9 Ma, subduction was occurring along southern Baja California so the triple junction lay to the north. Little if any extension is recognized in the GEP concurrent with subduction (Stock and Hodges, 1989). Earlier extension within the GEP is known only from central Sonora, where late Oligocene–earliest Miocene extension including core-complex development was substantial (Nourse et al., 1994; Gans, 1997; McDowell et al., 1997). By 10.6 Ma, the triple junction had jumped relatively abruptly to the reconstructed position of the southern tip of Baja California, and subduction had ceased all along Baja California. The Pacific–North American plate margin had evolved into a 2100 km long strike–slip fault, which, off Baja California, consisted of the San Benito and Tosco–Abreojos faults (Spencer and Normark, 1979). However, displacement of the Pacific plate between about 10 and 5 Ma was distinctly oblique to these faults, which required a component of motion perpendicular to them as well as strike–slip along them. This perpendicular (east–northeast) motion was taken up by extension in the GEP, not by deformation along the plate margin. Hausback (1984) and Stock and Hodges (1989) suggested that extension was focused in the GEP because heating from the immediately preceding volcanic arc had weakened the crust.

This interpreted mechanism makes several testable predictions about extension in the GEP. First, extension should have started between about 12.9 and 10.6 Ma. Also, initiation of extension may have migrated southward with the migrating triple junction. Critically, plate reconstructions imply about 160 ± 80 km extension in the northern GEP and about 110 ± 80 km in the southern GEP (Stock and Hodges, 1989). Stock and Hodge's pre-seafloor spreading (pre ~ 5.5 Ma) reconstruction of Baja California indicates post-extensional widths of the GEP of 400 km in the north and 250 km in the south. They therefore calculated 66% extension in the northern part and 78% in the southern part of the Gulf.

We fully support the process of plate motion partitioning to generate proto-Gulf extension, but add that this mechanism applies equally well to a much larger area of the southern Basin and Range province in the southwestern US and northern Mexico (Fig. 1). Evidence for this assertion includes the fact that east–northeast to east extension affected an area at least from southern Arizona and New Mexico to the Trans-Mexican Volcanic Belt in the middle to late Miocene, contemporaneous, and in part contiguous, with the GEP. Moreover, the amount of middle–late Miocene extension in the GEP determined from field relations is generally between 10 and 20%, with a maximum of 50% (Henry, 1989; Lee et al., 1996), considerably less than the approximately 70% apparently required by plate reconstructions. Therefore, either much of the extension occurred outside the defined GEP (Henry and Aranda-Gomez, 1995) or the mechanism of plate margin deformation was very different from that proposed by Stock and Hodges (Gans, 1997). We propose that this 'missing' extension was taken up over the entire width of the southern Basin and Range.

2. $^{40}Ar/^{39}Ar$ dating

$^{40}Ar/^{39}Ar$ ages were determined on five samples from Sinaloa and Durango to constrain the timing of extension. Mineral and whole-rock separates were obtained by crushing, sieving, and magnetic and density separation. Plagioclase was leached with dilute HF to remove adhering matrix. Whole-rock samples consist of coarse (~ 1 mm) grains hand picked to remove any phenocrysts. Samples were irradiated at Texas A&M University for 6 h and analyzed at the New Mexico Geochronological Research Laboratory. Samples were heated in a resistance furnace, and released gas was purified using SAES getters. Samples were generally degassed at about 600°C and then heated in eight to ten 10 min increments between about 700°C and 1650°C. Fish Canyon sanidine (27.84 Ma,

Table 1
$^{40}Ar/^{39}Ar$ data of mafic rocks of Sinaloa and Durango

Unit	Sample	Material	N lat.; W long.	Plateau age (Ma ± 1σ)	% ^{39}Ar
Mafic dikes, southern Sinaloa					
	H96-3	Whole rock	23°13.2′, 106°10.5′	10.7 ± 0.2	75.1
	H96-4	Whole rock	23°13.6′, 106°09.1′	11.03 ± 0.16	97.6
Hawaiite lavas, Rio Chico–Otinapa graben, Durango					
	H96-6	Plagioclase	23°57.1′, 104°51.2′	11.60 ± 0.07	95.5
	H96-8	Hornblende/pyroxene	23°56.0′, 104°51.4′	11.9 ± 0.5	90.0
	H96-9	Hornblende	23°55.8′, 104°51.9′	11.59 ± 0.05	100

$\lambda_\beta = 4.963 \times 10^{-10}\ \mathrm{yr}^{-1}$; $\lambda\epsilon_{+}\epsilon_{\prime} = 0.581 \times 10^{-10}\ \mathrm{yr}^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$.

relative to an age of 520.4 Ma on hornblende MMhb-1; Cebula et al., 1986; Samson and Alexander, 1987) was used to monitor neutron fluence. Calculated ages are listed in Table 1, and spectra are shown in Fig. 2. All ages are reported as ±1σ.

All samples provided readily interpretable plateau ages (Fig. 2). The most precise ages come from samples H96-6 (plagioclase; 11.60 ± 0.07 Ma) and H96-9 (hornblende; 11.59 ± 0.05 Ma). These are from the stratigraphically lowest lavas on opposite sides of the Rio Chico–Otinapa graben in Durango. An impure hornblende separate, consisting dominantly of pyroxene, from a dike that appears to feed a stratigraphically higher lava gave a less precise age of 11.9 ± 0.5 Ma (H96-8). This age, nevertheless, is indistinguishable from the other two ages. Whole-rock ages of two mafic dikes (H96-3, 10.7 ± 0.2; H96-4, 11.03 ± 0.16 Ma) from southern Sinaloa agree within analytical uncertainty with each other and are slightly younger than the Durango rocks.

3. Areas of middle–late Miocene extension in Mexico and Southwestern US

Stock and Hodges (1989) and Lee et al. (1996) thoroughly summarize proto-Gulf extension around most of the Gulf, so we focus on new studies within the Gulf Extensional Province and evidence of extension outside the Gulf (Fig. 1). Specifically, we look at similarities in style, kinematics, and timing of extension across three transects from the GEP into unequivocal Basin and Range province. These transects are (1) from southern Sinaloa across the Sierra Madre Occidental into Durango, (2) from coastal Sonora into Arizona, and (3) from Nayarit, at the southeastern end of the Gulf, across the southern end of the Sierra Madre Occidental into central Mexico.

3.1. Southern Sinaloa–Durango

East–northeast extension occurred at approximately the same time on opposite sides of the unextended Sierra Madre Occidental. Extended terrain in southern Sinaloa is west of the Sierra Madre in an area long considered part of the GEP. Extended terrain in Durango is east of the Sierra Madre in the main Basin and Range province of north-central Mexico.

3.1.1. Southern Sinaloa

Faulting in southern Sinaloa is generally recognized to be part of proto-Gulf extension (Henry and Fredrikson, 1987; Henry, 1989; Stock and Hodges, 1989; Lee et al., 1996), but, until now, its timing was poorly constrained. Faulting occurred in a zone up to 120 km wide from the Pacific coast to the Sierra Madre Occidental (Fig. 3). Indeed, the eastern limit of faulting and of the GEP defines the western edge of the unextended Sierra Madre Occidental. Most faults strike north–northwest and dip 40 to 70° eastward. Middle Tertiary volcanic rocks are tilted mostly westward between 30 and 40°, but locally as much as 65°. A subsidiary set of east–northeast-striking faults is probably

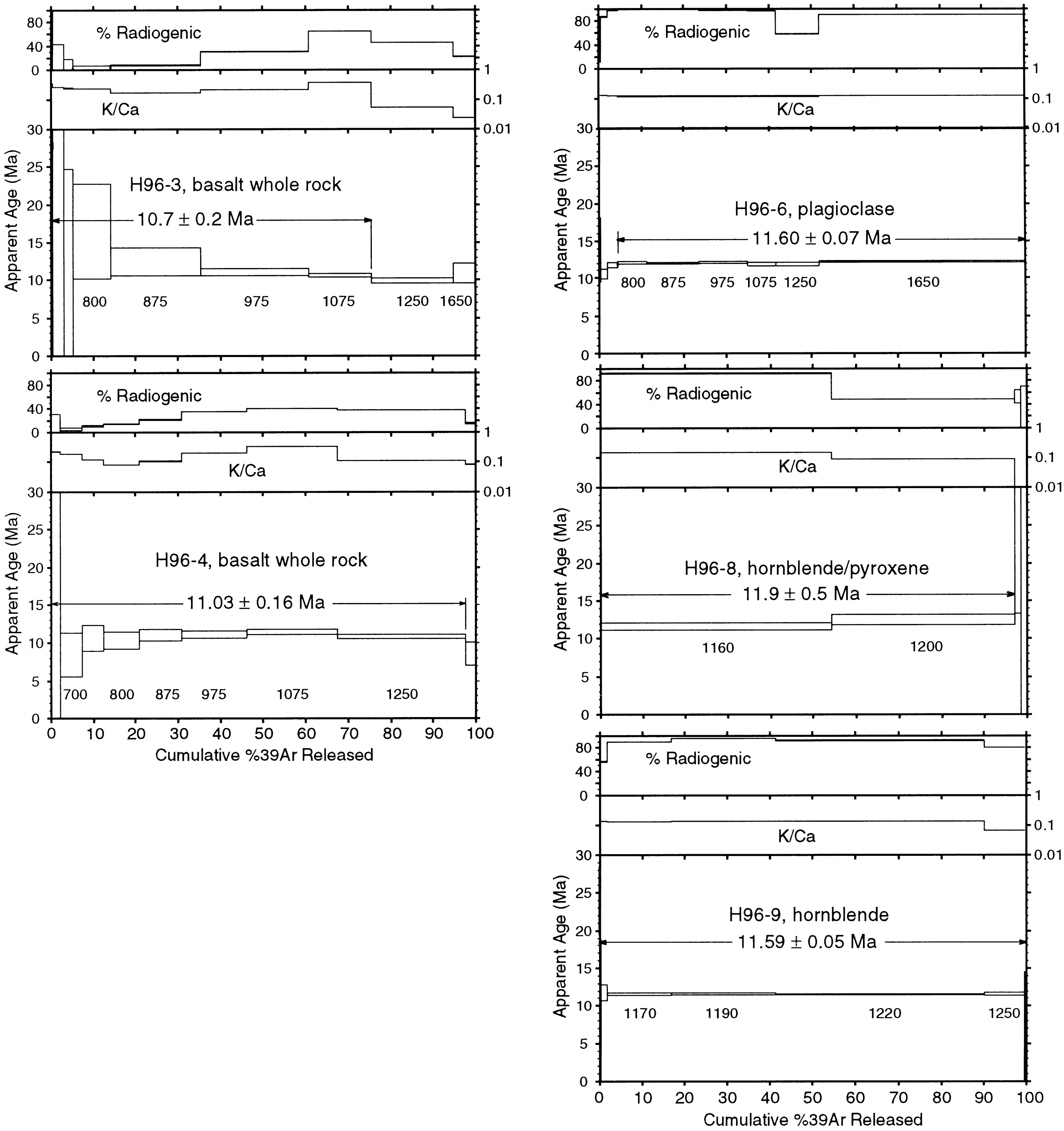

Fig. 2. $^{40}Ar/^{39}Ar$ incremental heating spectra for mafic whole rock, hornblende, and plagioclase samples from Sinaloa and Durango. Arrows show increments used in plateau. Numbers show selected extraction temperatures (°C).

transfer zones (terminology of Gibbs, 1984; Faulds and Varga, 1998) separating areas of differential extension or tilting. Fault orientation, stratal tilt, fault and slickenline data, and orientation of dikes indicate that extension was east–northeast (Henry, 1989). Total extension may range from 20 to 50%, dependent upon assumptions about subsurface geometry of the faults (Henry, 1989).

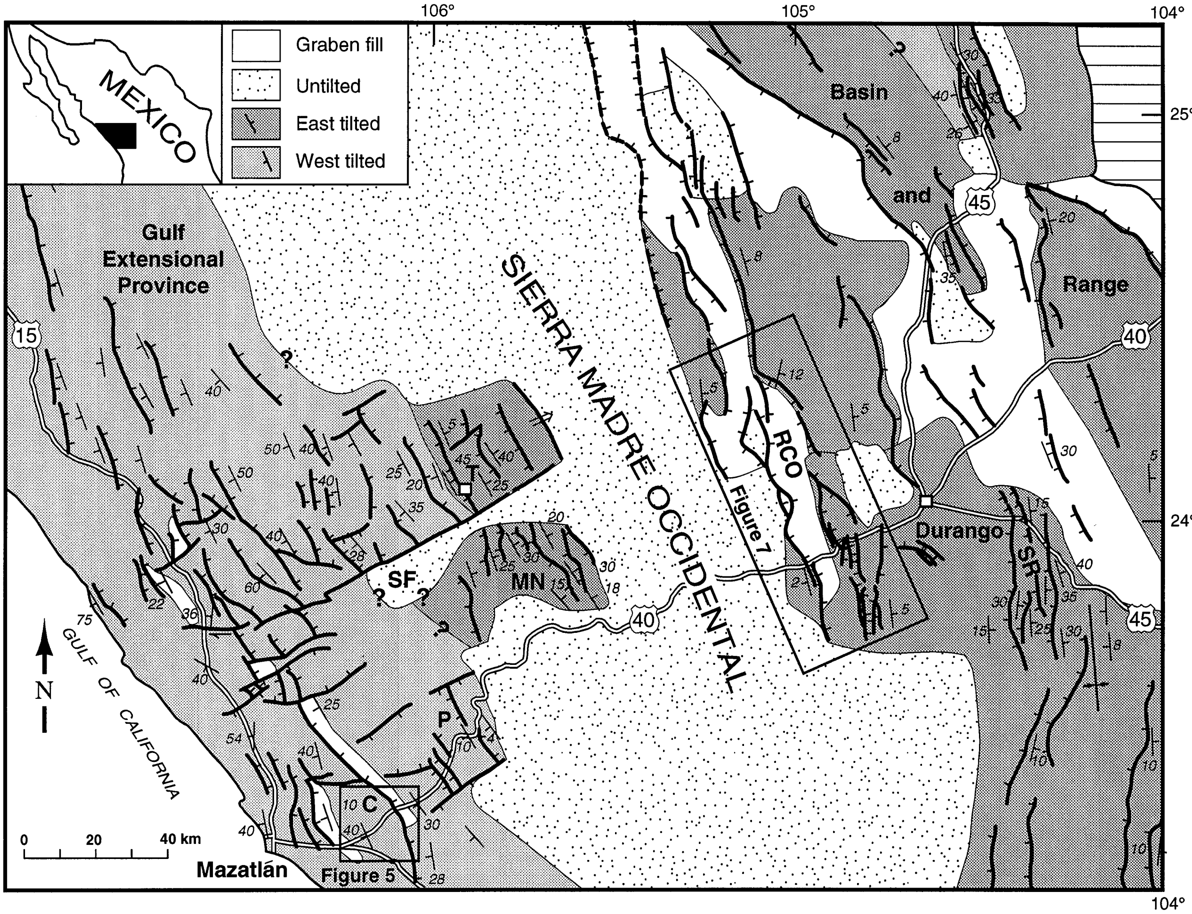

Fig. 3. Faults and tilt domains in a transect across the Gulf Extensional Province in southern Sinaloa, the unextended Sierra Madre Occidental, and the Basin and Range province of western Durango. Extension in Sinaloa and in the Rio Chico–Otinapa graben probably occurred entirely during the middle–late Miocene (~13–5.5 Ma), whereas the Basin and Range province of Durango underwent both older and younger episodes of extension. RCO = Rio Chico–Otinapa graben; SR = Sierra Registro; T = Tayoltita; SF = Sierra de los Frailes; MN = Mala Noche; P = Panuco; C = Concordia fault.

Faults in southern Sinaloa define several vergence domains, as have been recognized in Baja California (Axen, 1995; Umhoefer et al., 1997). The geometry of faulting is best illustrated by two east–northeast transects across the area. A northern transect through Tayoltita (Figs. 3 and 4) shows numerous north–northwest-striking normal faults spaced at irregular 3 to 10 km intervals. Faults across most of this zone dip 40 to 70° eastward, and upper volcanic rocks are tilted 30 to 60° westward. The faults are well marked by juxtaposition of west-dipping, mid-Tertiary volcanic rocks in the hangingwall against Cretaceous–Eocene granitic rocks in the footwall. Near Tayoltita, attitudes are reversed. Faults dip westward and volcanic rocks are tilted eastward. Near the center of the area of dip reversal, individual blocks are irregularly tilted; some are flat lying. Displacement on individual faults is at least several kilometers and is as much as 7 km, as determined by offset of the base of the mid-Tertiary volcanic rocks.

What we interpret to be a west-dipping master or breakaway fault forms the eastern boundary of this northern transect (Figs. 3 and 4). Volcanic rocks in the footwall of this master fault also dip

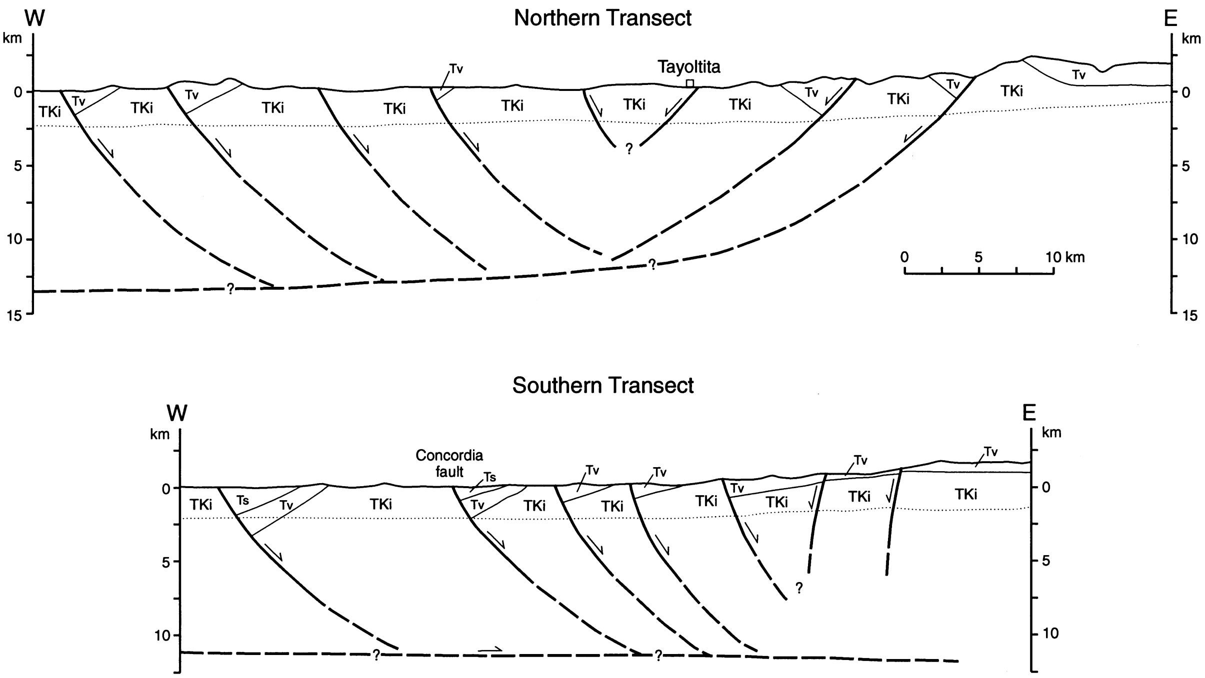

Fig. 4. Partly diagramatic cross-sections illustrating interpreted, oppositely dipping fault systems in the Gulf Extensional Province of southern Sinaloa, west of the Sierra Madre Occidental. Uppermost parts ($\sim$2 to 3 km, above dotted lines) of sections are based on geologic mapping in southern Sinaloa and are modified from Henry and Fredrikson (1987). Lower parts of sections diagramatically illustrate possible detachment faults that allowed west (northern transect) and east (southern transect) transport.

moderately eastward but flatten across a monoclinal hinge several kilometers east of the fault. Volcanic rocks in the Sierra Madre Occidental are flat lying and unfaulted from the hinge eastward approximately 50 km. This master fault may be listric; the entire faulted zone would then be an upper plate in its hangingwall. The dip reversal near the Sinaloa–Durango border would be a rollover anticline or anticlinal accommodation zone (terminology of Faulds and Varga, 1998). This geometry implies that the upper plate has pulled westward away from the Sierra Madre along a master fault that extends beneath the faulted area. The unextended core of the Sierra Madre Occidental is at its narrowest at this latitude.

A complex east–northeast-striking fault zone separates this northern tilted area from flat-lying volcanic rocks in a narrow tongue of the Sierra Madre Occidental on the south (Fig. 3). This is probably a transfer zone separating the Sierra Madre from the more extended area to the north and implies that motion along it should be dominantly left-lateral.

A transect across the southern zone, approximately through Concordia and Panuco, shows dominantly east-dipping, north–northwest-striking faults (Figs. 3 and 4). At the eastern end of the transect, volcanic rocks in the Sierra Madre are flat lying. Across a boundary that is one of the few west-dipping, down-to-the-west faults, upper volcanic rocks dip gently westward. The increase in dip across this fault suggests that the fault steepens downward, that is, it is antilistric. Dips increase progressively westward across northwest-striking normal faults that are conspicuous on aerial photographs but appear to have only modest displacement. Farther west, individual faults have generally greater displacement, culminating in the large half graben bounded by the Concordia fault (Figs. 3 and 5), which has as much as 7 km of displacement. Mid-Tertiary volcanic rocks east of the Concordia fault dip no more than about 10°,

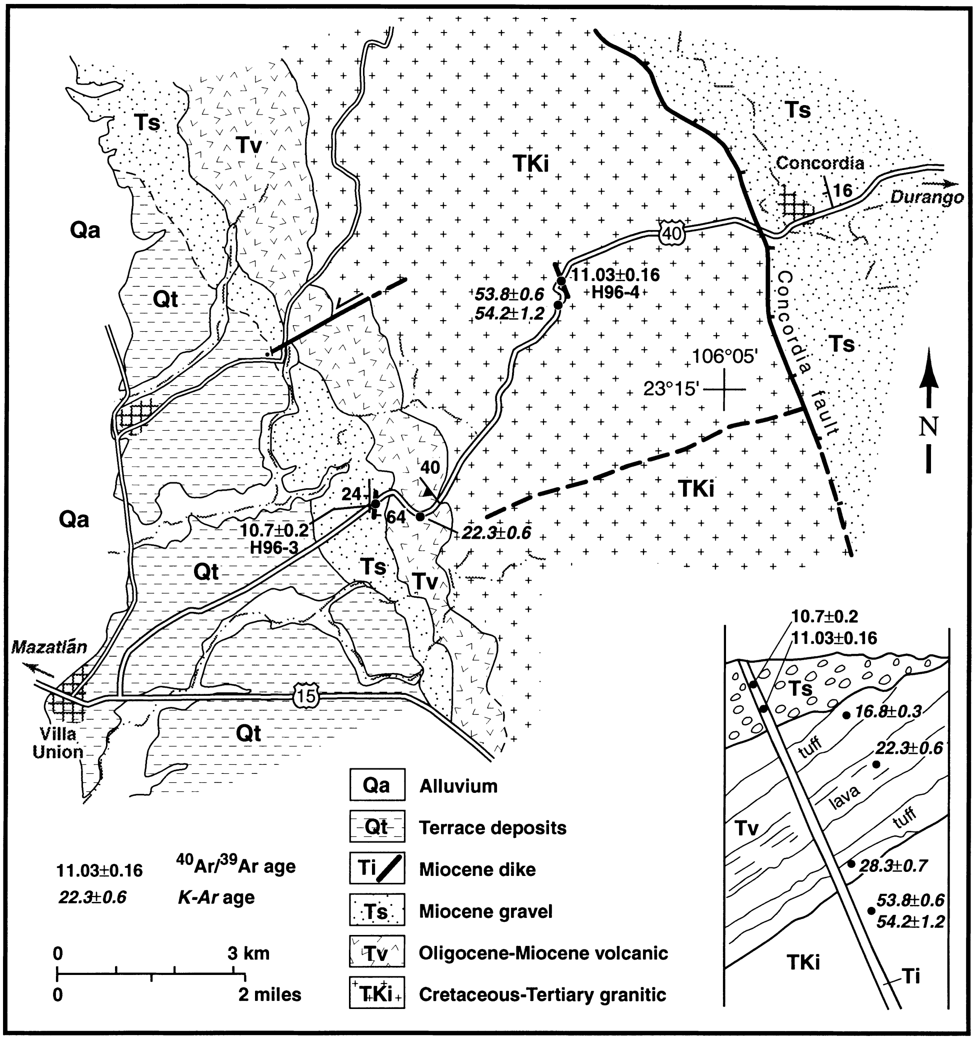

Fig. 5. Simplified geologic map of part of the west-tilted domain in southern Sinaloa, east of Mazatlan (see Fig. 3 for location). Another major, north–northwest-striking normal fault probably underlies Quaternary alluvium just west of the map. New $^{40}Ar/^{39}Ar$ ages on mafic dikes that were emplaced during early part of extension indicate extension began shortly before 11 Ma. K–Ar ages from Henry (1975) and Henry and Fredrikson (1987). The 16.8 and 28.3 Ma ages are from Oligocene–Miocene volcanic sections approximately 50 km to the northwest.

except within about 5 km of the fault, where dip increases over a few kilometers to as much as 30°. From the Concordia fault west, the geometry is similar to that to the north. Faults dip 40 to 70° eastward, and beds are tilted westward up to 40°. Some minor faults dip as shallowly as 22°. A possible implication of this geometry is that an east-dipping master fault, developed to the west, underlies the faulted area, i.e. the reverse of the pattern to the north. The breakaway zone for this east-dipping fault would lie in Baja California in the vicinity of Loreto (Axen, 1995; Umhoefer et al., 1997). Another probable transfer zone separates the gently dipping, eastern part from an unextended(?) area to the south.

Our current understanding of the geometry of faulting in Sinaloa allows as many as four vergence domains across a zone only 100 km long (Fig. 3).

The apparent narrowness of domains contrasts with the much longer domains, individually 50 to 150 km, recognized in Baja California (Axen, 1995; Umhoefer et al., 1997). It is unlikely that the four domains are underlain by oppositely dipping listric faults, because they are so much narrower than typically observed in the Basin and Range province (Axen, 1995; Faulds and Varga, 1998; Stewart et al., 1998). Possibly a single transition separates the northern and southern transects; the Sierra de los Frailes and Mala Noche areas may be complexities within this transition zone. Nevertheless, Umhoefer et al. (1997) recognized similar narrow domains near Loreto in Baja California, which restores approximately opposite southern Sinaloa before seafloor spreading.

The timing of faulting in Sinaloa was previously constrained only between 17 and 3 Ma ago (Henry and Fredrikson, 1987; Henry, 1989). Volcanic rocks as young as 17 Ma are as steeply tilted as older rocks and are overlain by flat-lying 3.2 Ma basalt along the coast (Aranda-Gomez et al., 1997).

New data from the southern transect (Figs. 3 and 5) indicate that faulting started probably no more than a few million years before 11 Ma. In an area approximately 25 km east of Mazatlan, north–northwest-striking, east-dipping normal faults bound a series of half graben. West-tilted Oligocene–Miocene volcanic rocks overlie an eroded surface on Eocene granodiorite, and both are repeated by these faults. Minor east–northeast-striking faults appear to have some strike–slip motion. The volcanic rocks consist of moderately welded ash-flow tuff and dacitic lava, which has a biotite K–Ar date of 22.3 ± 0.6 Ma (Henry and Fredrikson, 1987). Planar flow bands near the base of the lava dip 40° westward, which is probably a maximum for tectonic tilt.

Coarse, poorly sorted, and poorly to moderately bedded gravel overlies the volcanic rocks, strikes north, and dips 24° to the west. In a roadcut along Highway 40, this gravel is cut by numerous, north–northwest-striking, mostly east-dipping, small-displacement normal faults and by a basaltic dike. The dike strikes north and dips 64° to the east, approximately perpendicular to bedding in the gravel. The dike gives a whole rock $^{40}Ar/^{39}Ar$ age of 10.7 ± 0.2 Ma (Fig. 2; Table 1). Lava flows that may have been fed by the dike have not been recognized, but exposure in the semi-tropical area is poor. A second, north–northwest-striking basaltic dike cuts Eocene granodiorite farther east and gives an age of 11.03 ± 0.16 Ma.

We interpret these relations to indicate that the gravel fills a half graben bound on the west by a major, east-dipping normal fault (Figs. 3 and 4). The presence of granitic rocks as clasts in the gravel requires substantial tilting to expose them, which is consistent with the $\leq 40°$ tilt of underlying volcanic rocks. The apparent lesser dip of gravel suggests that they accumulated after initial faulting and tilting. The basaltic dike was emplaced after some faulting but probably before faulting and tilting ended. Continued faulting tilted both the gravel and the dike. Therefore, extension began before 11 Ma and was ongoing at that time. How long before 11 Ma is unknown, but we argue that the geologic relations suggest it was no more than a few million years. Coupled with our previous constraint that faulting began after 17 Ma, this is consistent with the timing of proto-Gulf extension throughout the Gulf (Stock and Hodges, 1989; Henry, 1989; Lee et al., 1996) and confirms that extension in Sinaloa is part of the proto-Gulf episode.

The basaltic dikes are geochemically similar to the early-rift tholeiite suite of Sawlan (1991), which erupted at about the same time in Baja California and coastal Nayarit (Table 2; Fig. 6). Sawlan attributed this suite to preferential melting of clinopyroxenite veins in relatively refractory mantle and noted a similarity to oceanic island and continental tholeiites. This origin may apply to the Sinaloa dikes. Despite their intraplate rift setting, the dikes are distinctly unlike intraplate basalts, such as erupted in Durango at the same time (Table 2; Fig. 6).

3.1.2. Rio Chico–Otinapa graben, western Durango

The Rio Chico–Otinapa graben is a large, north–northwest-striking, slightly asymmetric graben immediately across the Sierra Madre Occidental from the area of extension in southern Sinaloa (Figs. 3 and 7). The graben marks both

Table 2
Chemical analyses of mafic rocks, Sinaloa and Durango

	Dikes, Sinaloa		Hawaiites, Rio Chico–Otinapa graben			
	H96-3	H96-4	H96-6	H96-7	H96-9	H90-8
W long.	106° 10.5′	106° 09.1′	104° 51.2′	104° 51.4′	104° 51.9′	104° 49.5′
N lat.	23° 13.2′	23° 13.6′	23° 57.1′	23° 56.0′	23° 55.8′	23° 55.5′
SiO_2	50.48	50.42	48.65	46.89	47.36	50.04
TiO_2	1.93	2.22	3.05	3.63	3.38	2.74
Al_2O_3	15.93	15.48	17.08	15.95	16.15	17.35
FeO[a]	10.28	11.51	11.17	11.63	11.73	10.69
MnO	0.17	0.26	0.17	0.16	0.16	0.16
MgO	7.08	4.28	4.79	6.39	6.13	3.87
CaO	9.46	11.74	6.73	7.93	7.69	6.60
Na_2O	3.47	2.93	4.28	3.55	3.99	4.71
K_2O	0.86	0.63	2.86	2.80	2.33	2.95
P_2O_5	0.32	0.51	1.18	0.99	1.03	0.90
Total[b]	98.38	95.88	98.09	97.92	97.76	98.54
Sc	35	36	13	19	22	13
V	253	291	165	224	211	127
Cr	191	105	28	95	82	14
Ni	85	15	21	81	63	12
Cu	39	47	15	29	25	15
Zn	86	102	104	111	102	91
Ga	21	23	22	25	20	20
Rb	19	7	57	50	45	49
Sr	376	476	1145	1029	1159	1136
Y	30	35	27	28	27	29
Zr	165	179	338	337	293	352
Nb	9.9	11.2	62.8	58.3	54.9	70
Ba	313	379	736	653	706	760
La	10	22	52	48	54	39
Ce	20	47	88	98	91	99
Pb	4	4	0	3	0	5
Th	4	3	7	4	7	4

All analyses by XRF at Washington State University.
[a] Total Fe as FeO.
[b] Total before normalization to 100% anhydrous.

the western edge of the Basin and Range province and the eastern edge of the Sierra Madre. It is at least 175 km long and 15 to 25 km wide and is defined by a complex array of anastomosing, somewhat en echelon faults. The graben makes a notable left step about 30 km north of Highway 40, where a horst separates two en echelon graben segments. Although faults bound both sides, the eastern boundary fault has greater displacement, and Oligocene volcanic rocks are tilted gently eastward. Greatest displacement is in the middle of the graben where the eastern topographic scarp is as much as 900 m high. At the southern end near Highway 40, net displacement across boundary faults is about 300 m. Displacement dies out about 25 km south of the highway. Dips on faults range from 45° to near vertical. Faults exposed in road cuts along Highway 40 mostly dip 75 to 85°. Oligocene volcanic rocks are tilted at most 12° eastward. All these data indicate that total extension is small. Graben and fault orientation, tilt direction, and fault and slickenline data from 39 faults indicate east–northeast extension (Fig. 8).

Mid-Tertiary ash-flow tuffs, dated at between

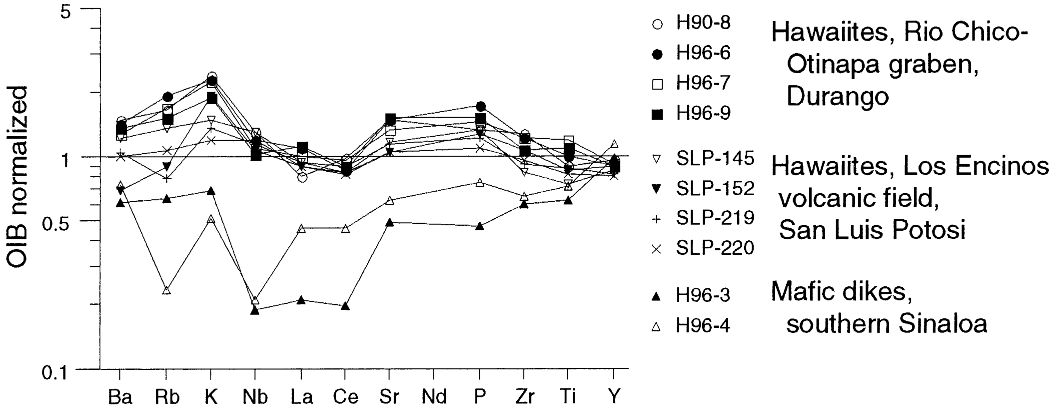

Fig. 6. Spider diagrams normalized to average oceanic island (intraplate) basalt (Fitton et al., 1991). The ~12 Ma hawaiites of the Rio Chico–Otinapa graben (Durango) are similar in age and composition to hawaiites of the Los Encinos volcanic field (San Luis Potosi; Luhr et al., 1995); both have intraplate characteristics. Mafic rocks of the same age in southern Sinaloa are similar to the early-rift tholeiite suite of Sawlan (1991) and distinctly unlike intraplate basalts.

32 and 29 Ma at the south end near Highway 40 (McDowell and Keizer, 1977), crop out on both sides of the graben and form the floor of the graben near the highway. These are overlain by thin gravel and hawaiitic lavas (McDowell and Keizer, 1977; Swanson et al., 1978) in the southern part of the graben. Northward, younger basaltic flows, with K–Ar dates of 2.3 to 2.5 Ma (Aranda-Gomez et al., 1997), are interbedded with sandstone and fine gravel.

Geologic relations in the southern part of the Rio Chico–Otinapa graben show that faulting began at 12 to 13 Ma. In the structurally lowest part of the graben, hawaiite lavas overlie thin sequences (10–15 m) of basin-fill deposits. A basal conglomerate about 1 m thick contains well-rounded clasts of various rhyolitic rocks. Upward, lenses of conglomerate are interbedded with massive sandstone that contains scattered rhyolite cobbles. The lowest hawaiite flow is at least 20 m thick and contains sparse megacrysts of plagioclase and kaersutite to about 2 cm. Dates on amphibole of 12.7 ± 0.4 Ma (K–Ar; McDowell and Keizer, 1977) and plagioclase of 11.60 ± 0.07 Ma ($^{40}Ar/^{39}Ar$; Table 1) have been obtained on this lowest flow.

Hawaiite lava rests directly upon a 29.3 Ma rhyolite lava dome (McDowell and Keizer, 1977) just west of the structurally lowest part of the graben (Fig. 7). The lowest flow there contains abundant plagioclase and kaersutite megacrysts up to about 3 cm long. Dates on amphibole are 12.0 ± 0.3 Ma (K–Ar; McDowell and Keizer, 1977) and 11.59 ± 0.05 Ma ($^{40}Ar/^{39}Ar$; Table 1). The lack of gravel may indicate that the rhyolite formed a paleohigh or that, at least initially, sedimentary material accumulated only within the lowest part of the graben. Additional ages include a less precise $^{40}Ar/^{39}Ar$ date of 11.9 ± 0.4 Ma on a dike that feeds a stratigraphically higher lava (Table 1) and a whole rock K–Ar date of 12.9 ± 1.2 Ma on hawaiite lava from the downthrown side of the western boundary fault of the graben (McDowell and Keizer, 1977).

These stratigraphic and structural relations indicate that graben development preceded eruption of the oldest lavas by a brief time. Therefore, east–northeast extension began between about 13 and 12 Ma in the Rio Chico–Otinapa graben. Although the Basin and Range province in Durango underwent earlier episodes of faulting (Henry and Aranda-Gomez, 1992; Aranda-Gomez et al., 1997), these had not affected the Rio Chico–Otinapa area. Therefore, the Basin and Range province expanded westward into the Sierra Madre Occidental at that time.

Geochemically, the hawaiite lavas and dikes have intraplate characteristics (high alkalies, Nb, Ti, and P) typical of mafic magmas erupted during

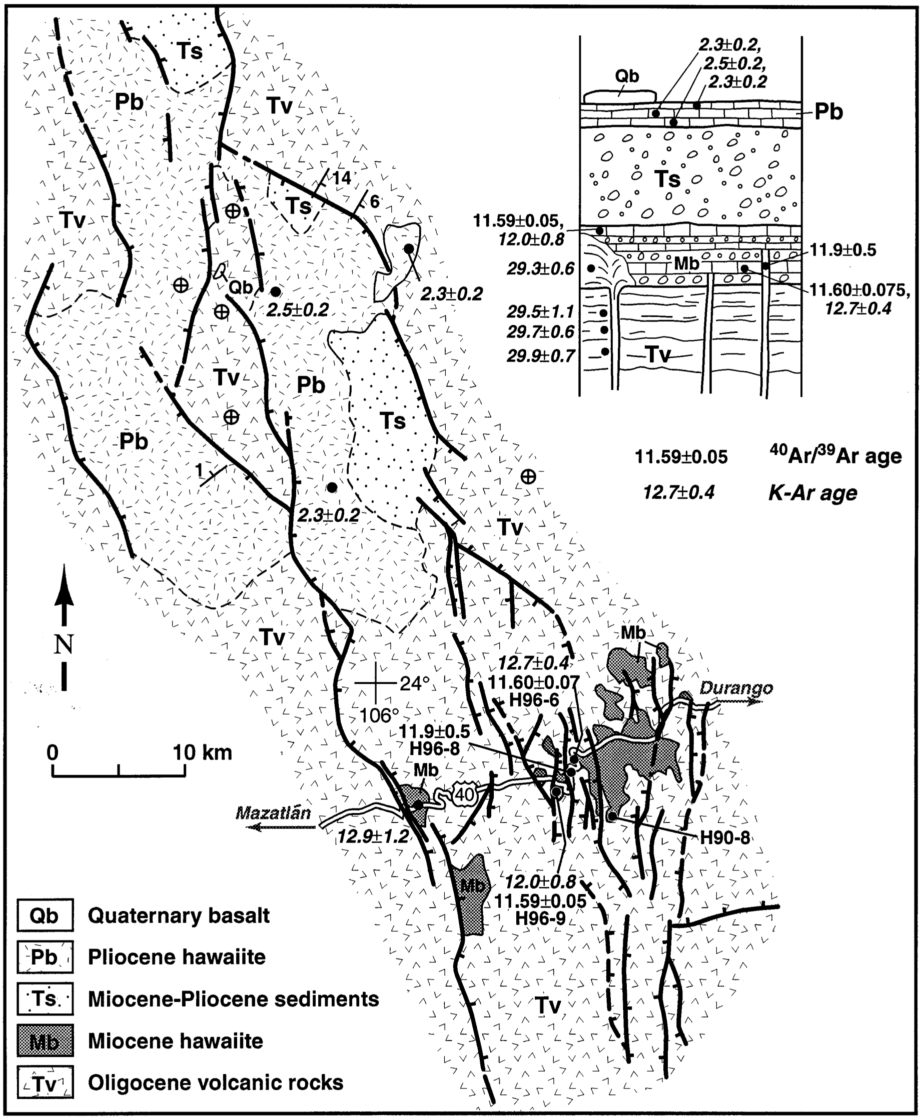

Fig. 7. Simplified geologic map of the Rio Chico–Otinapa graben, western Durango. Although fault-bounded on both east and west sides, the graben is asymmetric, with greater displacement along the eastern boundary fault system. Mid-Tertiary volcanic rocks are flat lying to gently east tilted. Miocene hawaiites in the southern part of the graben along Highway 40 are interbedded with the stratigraphically lowest graben fill. K–Ar (McDowell and Keizer, 1977; Aranda-Gomez et al., 1997) and ^{40}Ar/^{39}Ar ages (this study) indicate that extension began at about 12 to 13 Ma.

continental extension (Table 2; Fig. 6). This rock type is found throughout the Basin and Range province of northern Mexico associated with episodes of extension at ~24, 12, and 2–0 Ma (Luhr et al., 1989, 1995, 1997; Aguirre-Diaz and McDowell, 1993; Aranda-Gomez et al., 1997). Hawaiites of the Rio Chico–Otinapa graben are particularly similar to other Miocene hawaiites in Mexico and Texas in whole-rock composition, common presence of megacrysts, and lack of peridotitic mantle xenoliths (Luhr et al., 1995; Aranda-Gomez et al., 1997).

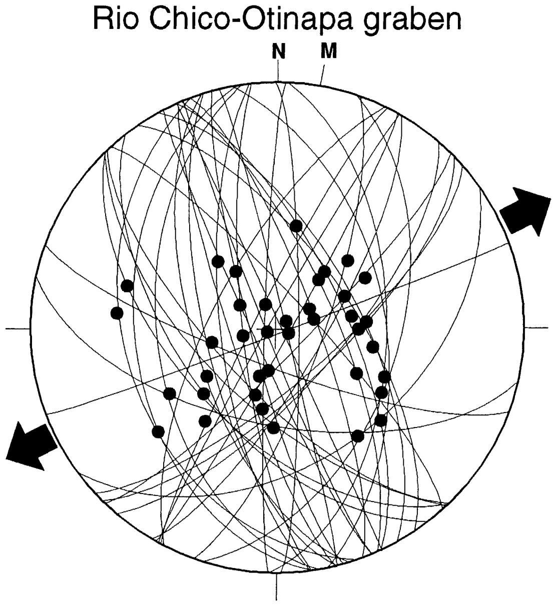

Fig. 8. Stereonet plots of faults and slickenlines (lower hemisphere projection) from the Rio Chico–Otinapa graben. East–northeast least principal stress (solid arrows; σ_3) calculated using method of Angelier (1979).

3.2. *Sonora–southern Arizona*

Late Miocene extension in Sonora and southern Arizona provides a critical tie between the GEP and unequivocal Basin and Range (Fig. 1). Previous compilations provided data only for coastal Sonora and noted that a boundary between the two provinces is uncertain (Stock and Hodges, 1989; Lee et al., 1996). We suggest that the uncertainty stems from the fact that there is no boundary. Areas of extension in Sonora and southern Arizona are physically contiguous and underwent similar extension at the same time.

3.2.1. *Sonora*

Late Miocene (proto-Gulf) extension has long been recognized in coastal Sonora (Gastil, 1974; Gastil and Krummenacher, 1977; Neuhaus et al., 1988; Lee et al., 1996). Two recent studies demonstrate the same episode affected central Sonora (Fig. 1). Throughout central Sonora, volcanic rocks with ages around 12 to 10 Ma are tilted as much as 35° (McDowell et al., 1997; Mora-Alvarez and McDowell, 1999). In the Sierra Santa Ursula, volcanic rocks were tilted eastward 15 to 35° between 11.4 and 10.3 Ma (Mora-Alvarez and McDowell, 1999). Volcanic rocks as young as 8.5 Ma are tilted 5°, indicating additional later faulting. In the Rio Yaqui basin of eastern Sonora, clastic rocks that overlie 12.5 Ma ignimbrite are tilted eastward; dip decreases upsection from about 25 to 6° (McDowell et al., 1997). These data indicate an episode of faulting probably shortly after 12.5 Ma. No kinematic data are available, but fault and tilt orientations indicate approximately east extension. The Rio Yaqui basin formed initially during an earlier period of extension beginning between 27 and 20 Ma (McDowell et al., 1997), and central and northern Sonora underwent large magnitude extension including core-complex development at that time (Nourse et al., 1994; Gans, 1997). This extension is probably part of a regional episode that affected much of western Mexico, mostly outside the GEP, in the late Oligocene and early Miocene (Henry and Aranda-Gomez, 1992; Stewart and Roldan-Quintana, 1994; Aranda-Gomez et al., 1997; Ferrari et al., 1997; Nieto-Samaniego et al., 1999). Total extension in Sonora during the late Miocene was probably no more than 20%.

3.2.2. *Southern Arizona*

The extended area in southern Arizona is outside but physically contiguous with areas in Sonora that are generally considered part of the GEP (Fig. 1) (Stock and Hodges, 1989; Lee et al., 1996). A late Miocene episode of extension, probably along moderately to steeply dipping normal faults, generated large graben and half graben throughout most of Arizona outside the Colorado Plateau (Eberly and Stanley, 1978; Menges and Pearthree, 1989). Onset of extension is generally given as ~13 Ma because 13 to 10 Ma basalt flows are locally interbedded with the lowermost basin fill (Eberly and Stanley, 1978; Nations et al., 1982). Tectonism may have begun locally as early as 15 Ma and propagated rapidly northeastward across southern Arizona into the Rio Grande rift of southern New Mexico between about 13 and 9 Ma (Seager et al., 1984; Menges and Pearthree, 1989). Menges and Pearthree (1989) estimate 5 to

20% total horizontal extension for this episode and distinguish it from preceding (late Oligocene–early Miocene), higher magnitude extension (Spencer et al., 1995). Faults, graben, and half graben generated during this episode strike dominantly northwest to north–northeast (Eberly and Stanley, 1978), and Menges and Pearthree (1989) suggested that the direction of extension rotated from east–northeast to west–northwest in the late Miocene. Late Miocene stress reorientation appears to be a common feature of the Basin and Range province (Zoback et al., 1981; Minor, 1995).

3.3. Nayarit–Southern Sierra Madre Occidental

Middle–late Miocene extension in Nayarit at the southeastern end of the Gulf of California and into central Mexico provides another critical link between the GEP and Basin and Range, in this case across the southern end of the Sierra Madre Occidental (Fig. 1). Extensional faulting began in the GEP part of Nayarit about 12 Ma (Jensky, 1974; Gastil et al., 1978, 1979; Damon et al., 1979; Nieto-Samaniego et al., 1999). In central Nayarit, volcanic rocks of the Sierra Madre Occidental as young as 14 Ma are tilted 20 to 30° to the northeast and overlain unconformably by 11 to 9 Ma alkali basalts (Gastil et al., 1978, 1979; Nieto-Samaniego et al., 1999). North- to northwest-striking, 12–11 Ma mafic dikes are inferred to mark the onset of rifting (Damon et al., 1979; Nieto-Samaniego et al., 1999). Extension was oriented ~N66°E (Ferrari, 1995; Nieto-Samaniego et al., 1999). In coastal southern Nayarit, 11 Ma tuffs that dip 36° eastward are overlain by clastic sedimentary rocks that shallow upward to 18°; both are overlain by gently east-dipping, 10 Ma basalt (Jensky, 1974). All data are consistent with initial rifting about 12 Ma and continuing to at least 10 Ma. The amount of extension appears to vary between different areas but is generally less than 20%.

More recently, Ferrari (1995), Ferrari and Rosas-Elguera (1999), and Nieto-Samaniego et al. (1999) demonstrate that extension also occurred well to the east, away from the present Gulf. Probable east-oriented extension occurred near Santa Rosa northwest of Guadalajara between about 11 and 9 Ma (Moore et al., 1994; Ferrari, 1995). This area of extension is kinematically connected to the proto-Gulf by right-lateral transtension along the west–northwest-striking north edge of the Jalisco block (Fig. 1) (Ferrari, 1995). Right-lateral motion along this boundary is consistent with east–northeast extension, and the boundary likely served to transfer extension around the Sierra Madre.

The easternmost areas of recognized, middle–late Miocene extension are near Guanajuato and San Miguel de Allende (Fig. 1). These areas underwent a major episode of extension in the Oligocene (~30–27 Ma), but additional phases occurred after 24 Ma and around 11 Ma (Nieto-Samaniego et al., 1999). Near Guanajuato, basaltic lavas dated at 13 to 11 Ma are displaced 200 to 600 m (Nieto-Samaniego et al., 1999). Nieto-Samaniego et al. estimated total extension of about 20% oriented 258°; only a small part occurred during the Miocene episode.

A north-striking, west-dipping zone of faults through San Miguel de Allende (Fig. 9) separates the highly faulted Mesa Central physiographic province (Raisz, 1964) on the west from the much less extended Sierra Madre Oriental on the east (Nieto-Samaniego et al., 1999). At San Miguel de Allende, this zone forms a moderately east-tilted half graben. The 11 Ma Allende andesite (Pérez-Venzor et al., 1996) is cut by the fault, interbedded with basin fill, and tilted to the east. Andesite lavas of the Palo Huérfano stratovolcano bury the San Miguel de Allende fault to the south. The Palo Huérfano volcano is imprecisely dated, but the best estimate of its age is also ~11 Ma (Pérez-Venzor et al., 1996). These data indicate an episode of ~east-oriented extension centered around 11 Ma. A younger set of east–northeast-striking normal faults that cut Palo Huérfano andesites (Fig. 9) are probably related to tectonics of the Trans-Mexican volcanic belt.

3.4. Eastern Basin and Range province

In addition to these areas contiguous with or close to the GEP, middle to late Miocene extension affected at least two areas at or near the eastern edge of the Basin and Range province (Fig. 1). These areas are in southern Trans-Pecos Texas and San Luis Potosi state, Mexico.

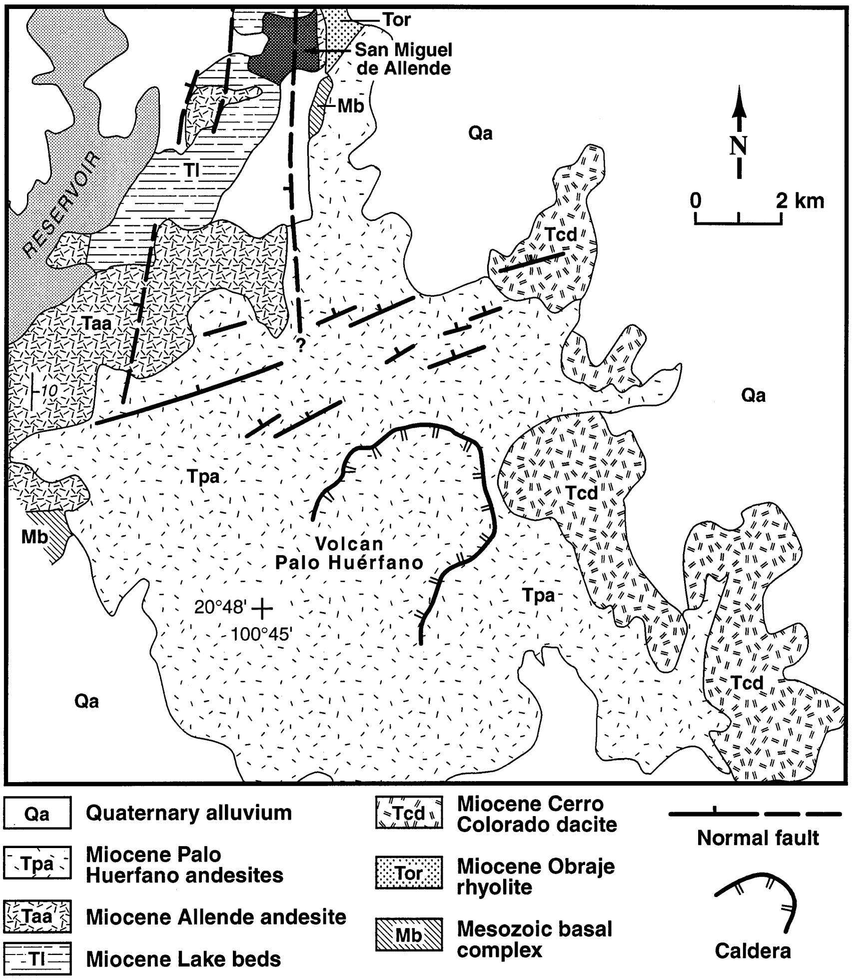

Fig. 9. Simplified geologic map of the San Miguel de Allende area; see Fig. 1 for location. The north-striking fault through San Miguel de Allende is part of a major zone of faults that separate the relatively more extended Mesa Central on the west from the less extended Sierra Madre Oriental. The gently east-tilted 11 Ma Allende andesite is interbedded with basin fill in a half graben in the hangingwall. The fault is buried by the ~11 Ma Volcan Palo Huérfano, which demonstrates that extension occurred about 11 Ma.

3.4.1. *Trans-Pecos Texas*

Trans-Pecos Texas is an area of low-magnitude extension at the eastern edge of the Basin and Range Province (Fig. 1) (Henry and Price, 1986; Henry et al., 1991; Henry, 1998). Total extension across the province there is ≤10% and occurred in several episodes beginning at least as early as 24 Ma and, as evinced by abundant Quaternary fault scarps (Muehlberger et al., 1978; Collins and Raney, 1994), continuing today. Paleostress data indicate that early episodes of extension were oriented east–northeast. Stratigraphic and paleontologic data demonstrate an early Clarendonian (~11–9 Ma) episode of extension and basin filling in the Tornillo and possibly the Castolon graben of Big Bend National Park (Stevens and Stevens, 1990; Dickerson and Muehlberger, 1994). The basin-filling rocks are themselves faulted. Total amount of extension represented by this episode in Texas is unknown but must be still less than

10%. The Tornillo and Castolon graben strike north–northwest, which suggests that extension was east–northeast at ~11–9 Ma.

3.4.2. Los Encinos volcanic field, San Luis Potosi

Numerous volcanic necks and a few lava remnants of Miocene hawaiite are scattered over ~11,500 km^2 in the Los Encinos volcanic field (LEVF) in the northeastern part of the Mesa Central (Figs. 1 and 10). The necks form a generally northwest-striking band with a subsidiary N30°E trend (Fig. 10) (INEGI, 1979).

Evidence for the association of the LEVF with extension are the similarity of the hawaiites to rocks of the Rio Chico–Otinapa graben and their relation to regional Basin and Range structure. Los Encinos hawaiites are similar in age (~13–10 Ma), composition (Fig. 6), and megacryst assemblages to the hawaiite lavas of the Rio Chico–Otinapa graben (Luhr et al., 1995; Aranda-Gomez et al., 1997), which are clearly contemporaneous with extension.

Basin and Range faults around San Luis Potosi south of the LEVF form two distinct sets striking N50°W and N30°E (Labarthe-Hernandez et al., 1982; Tristan-Gonzalez, 1986; Aranda-Gomez et al., 1989), the same orientation as chains of volcanic necks. This rhombohedral fault pattern controls physiography throughout the Mesa Central (INEGI, 1982) and is interpreted to have formed in the Eocene during several pulses of northeast and northwest extension (Aranda-Gomez et al., 1989; Aranda-Gomez and McDowell, 1998). The faults were reactivated in the middle and late Cenozoic during ~east-oriented triaxial deformation (Nieto-Samaniego et al., 1997). Reconnaissance mapping indicates similar fault trends are present in the LEVF (Hart, 1979; Roush, 1981). We infer that the clusters of Miocene volcanic necks were emplaced along tensional fractures or faults during middle late Miocene extension.

4. Discussion

4.1. Plate-motion partitioning origin for Basin and Range extension

As noted by many, the proto-Gulf of California formed as a result of east to east–northeast extension beginning approximately 13 to 12 Ma (Karig and Jensky, 1972; Gastil et al., 1975; Dokka and Merriam, 1982; Hausback, 1984; Stock and Hodges, 1989; Henry, 1989; Sawlan, 1991; Lee et al., 1996). The data presented here indicate that this same episode of extension affected a much wider area, probably from southern Arizona and New Mexico southward to the northern edge of the Trans-Mexican Volcanic Belt and eastward to the eastern edge of the Basin and Range province (Fig. 1). Uncertainty in the distribution of this extensional episode reflects the lack of timing constraints in much of northern Mexico east of the Sierra Madre Occidental. On one hand, extension is only known to postdate mid-Tertiary (27.5 Ma) volcanic rocks in Chihuahua (McDowell and Mauger, 1994). On the other hand, several parts of northern Mexico (Guanajuato, Durango, and Sonora) have undergone multiple episodes of extension beginning as early as the late Oligocene (Henry and Aranda-Gomez, 1992; Aguirre-Diaz and McDowell, 1993; Aranda-Gomez et al., 1997; Ferrari et al., 1997; Gans, 1997; Jansma and Lang, 1997; Nieto-Samaniego et al., 1999). Although the middle–late Miocene episode is recognized only in scattered locations in north–central Mexico, we suggest that it affected most of the southern Basin and Range.

The critical implication of this recognition is that the mechanism of plate-motion partitioning to generate proto-Gulf extension (Spencer and Normark, 1979; Hausback, 1984; Stock and Hodges, 1989; Lee et al., 1996) applies equally well to this episode of extension over a vast area of the southern Basin and Range province. The Basin and Range province has undergone a long history of extension, but at least this episode in this large region appears to be a result of plate interactions.

4.2. The ‘missing’ extension of the Gulf Extensional Province

Allowing extension to occur over the entire width of the GEP and Basin and Range province resolves the discrepancy between the amount of extension in the GEP calculated from plate recon-

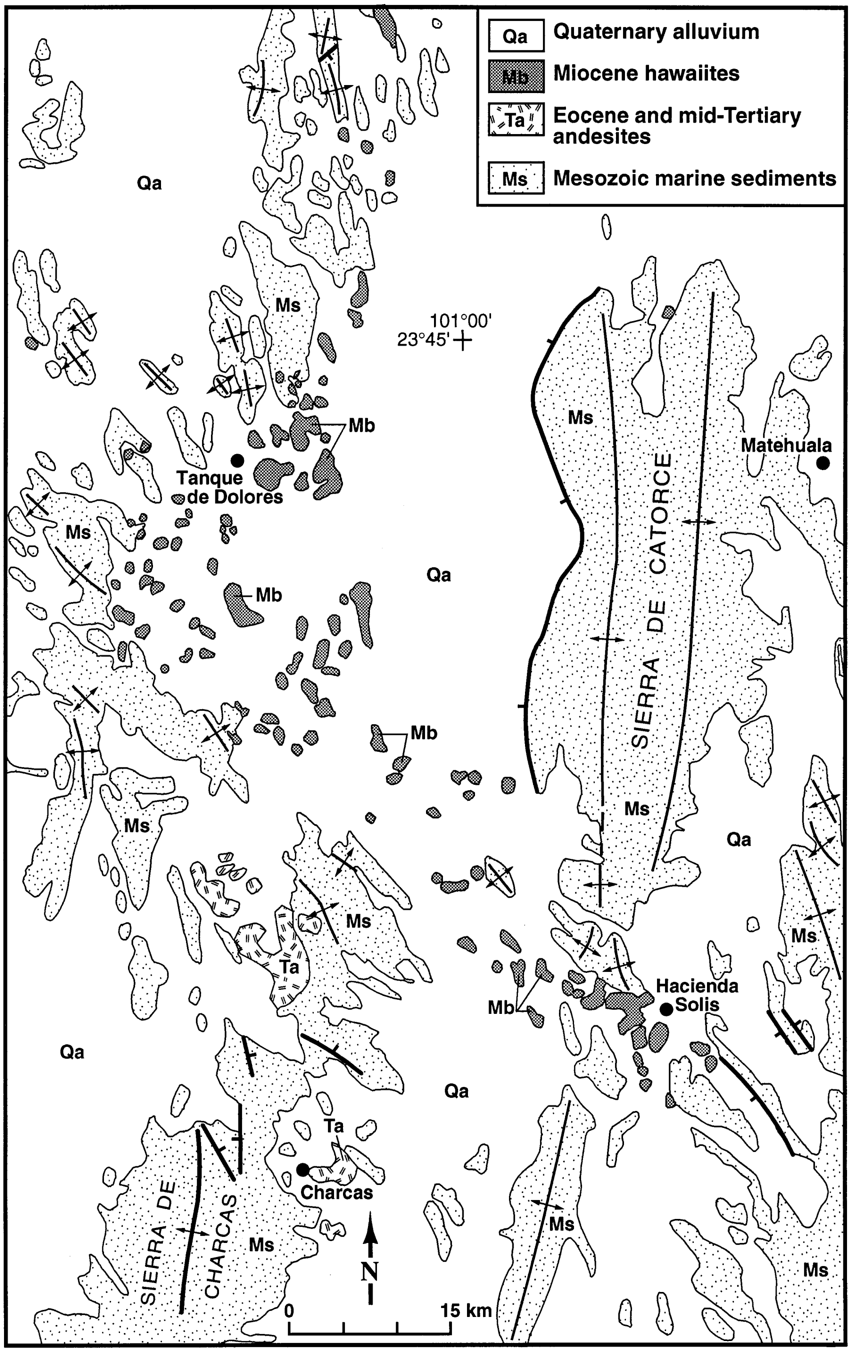

Fig. 10. Simplified geologic map of Los Encinos area; see Fig. 1 for location. Numerous Miocene (13–10 Ma) hawaiite necks form a N50°W band with a subsidiary N30°E trend. Similarity of the hawaiites to lavas of the Rio Chico–Otinapa graben (Figs. 6 and 7) and alignment with regional Basin and Range faults indicate they were emplaced during extension.

structions and observed in the field. As noted in Section 1.2, observed extension in the Gulf is at most about 50% and probably averages 10 to 20% (Lee et al., 1996). Somewhat larger estimates of 32 to 39% near Loreto in Baja California are for Pliocene motion, unrelated to proto-Gulf extension (Umhoefer and Stone, 1996). Calculated total east–northeast extension resulting from oblique displacement of the Pacific plate is 160 ± 80 km in the northern Gulf and 110 ± 80 km in the southern Gulf (Stock and Hodges, 1989). Restricting this motion entirely within the GEP requires 66% extension in the northern Gulf and 78% extension in the southern Gulf (Fig. 11) (Stock and Hodges, 1989). Henry and Aranda-Gomez (1995) and Gans (1997) pointed out that such large magnitudes have not been observed. Allowing total displacement to be taken up partly within the main Basin and Range province greatly reduces calculated percentage extension. Adding a present-day width of 500 km of the province in Chihuahua and Texas to the 400 km width of the GEP at 5.5 Ma gives an overall width of 900 km. If 160 km of that width resulted from late Miocene extension, extension was 22% (160/740). Similarly, adding the present day width of ~500 km in the southern Basin and Range to the 250 km of 5.5 Ma southern GEP gives an overall width of 750 km. If 110 km resulted from late Miocene extension, total extension was approximately 17% (110/640).

These calculated values are much more consistent with observed extension both in the GEP and the main Basin and Range, for example, the 10 to 20% estimate for southern Arizona (Menges and Pearthree, 1989). An important point is that our calculated extension applies only to the episode between about 13 and 6 Ma, not to total extension from Oligocene to present. Total extension in the Basin and Range in Mexico is a result of several episodes beginning in the late Oligocene or early Miocene and continuing today (Henry and Aranda-Gomez, 1992; Aguirre-Diaz and McDowell, 1993; Aranda-Gomez et al., 1997; Ferrari et al., 1997; Gans, 1997; McDowell et al., 1997; Nieto-Samaniego et al., 1999). We also emphasize that our calculations give an average extension across the GEP and Basin and Range, and extension was not homogeneous. Extension in Texas at the eastern edge of the Basin and Range was probably less than 5%. The overall distribution of strain is poorly known. Nevertheless, our revision may resolve much of the objection of Gans (1997) to the plate-motion partitioning mechanism for extension.

The data of Stock and Hodges (1989) and our calculations also predict that the absolute amount and percentage of extension should decrease from north to south, which is also consistent with observation. First, the total width of the extended belt, both GEP and Basin and Range, decreases from north to south (Figs. 1 and 11). More importantly, the amount of extension as indicated by stratal tilt and other measures decreases from north to south. Tertiary volcanic rocks in Chihuahua and Durango are commonly tilted 30 to 40° (McDowell and Mauger, 1994; Aranda-Gomez et al., 1997; our observations). In contrast, tilts in the region north of the Trans-Mexican volcanic belt are generally less than 20° (Nieto-Samaniego et al., 1999; our observations). Nieto-Samaniego et al. (1999) estimated total extension for this region to be about 20%, most of which occurred in the late Oligocene or early Miocene.

4.3. *Partitioning of extension*

The distribution of extension into the GEP and main Basin and Range province, separated by the relatively unextended Sierra Madre Occidental, probably reflects several factors. Extension was partly focused within the GEP probably because the crust had been weakened by heating by the immediately preceding volcanic arc (Hausback, 1984; Stock and Hodges, 1989). Furthermore, extension was constrained between two stable batholith belts, the Mesozoic Peninsular Ranges batholith in the northern Gulf and the mid-Tertiary Sierra Madre Occidental along the entire eastern margin. The Sierra Madre Occidental is underlain by numerous calderas and their related plutons (Swanson and McDowell, 1984); the underlying crust is probably continuous batholith. Batholiths generally resist extension (Wernicke, 1992). For example, in the US the Cretaceous batholith belt of the Sierra Nevada marks the western edge of the Great Basin. However, extension in the central

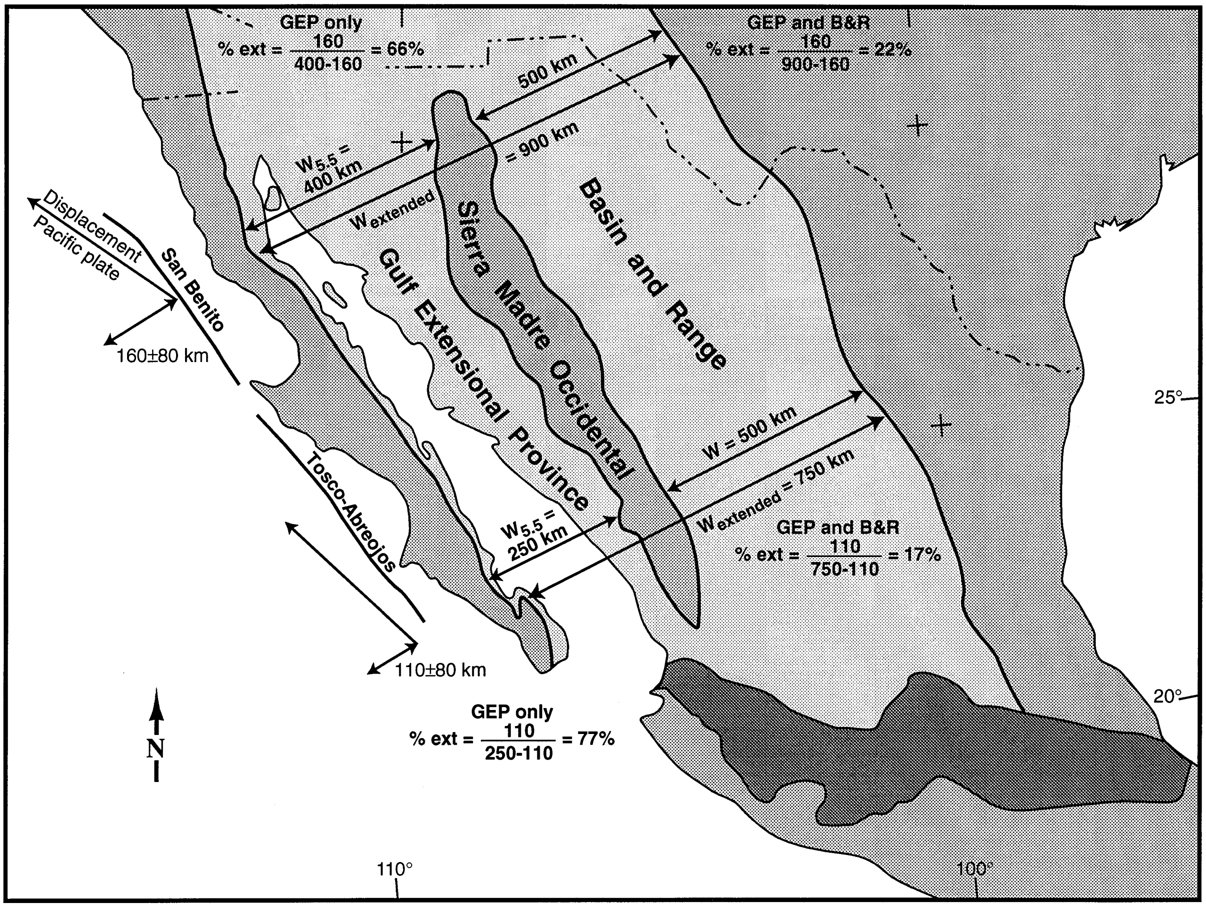

Fig. 11. Interpretation of 13–5.5 Ma extension episode in northern Mexico as a result of partitioning of oblique Pacific–North American plate motion into strike–slip along the plate margin (San Benito–Tosco–Abreojos faults) and perpendicular (east–northeast) extension within the North American plate; Baja California is restored to its position at 5.5 Ma (adapted from Stock and Hodges, 1989). If taken up solely within the Gulf Extensional Province (west of the Sierra Madre Occidental), perpendicular displacement of 160 km (north) and 110 km (south) requires 66 and 77% extension within the Gulf. If displacement is spread over the entire width of the Basin and Range province, including GEP, only 22 and 17% extension is required, which is more consistent with observations. Width of Basin and Range is present day and assumes east–northeast extension since 5.5 Ma can be neglected. See text for further discussion.

Gulf cut directly across the older Cretaceous–early Tertiary batholith belt. Basement of the extended terrain in southern Sinaloa is almost entirely 100–45 Ma batholiths (Henry and Fredrikson, 1987; Henry, 1989). Presumably thermal weakening resulting from Miocene arc volcanism was able to overcome the tendency of batholiths to resist extension.

Occurrence of extension in the main Basin and Range province east of the Sierra Madre Occidental cannot be explained by thermal weakening. Arc volcanism extinguished in most of the area near the end of the Oligocene, and contemporaneous extension and eruption of intraplate basalts at ~ 12 Ma suggests the crust was relatively brittle. Nevertheless, the Basin and Range province was probably weak relative to the strong caldera–batholith belt of the Sierra Madre Occidental. For example, the transition between stable Sierra Madre Occidental and Basin and Range in

Chihuahua lies at a change from overlapping calderas, and probably continuous batholith, in the Sierra Madre Occidental to scattered calderas in the Basin and Range (Swanson and McDowell, 1984; our observations). In this sense, the Sierra Madre Occidental is simply an unextended island surrounded by extended terrain. The inferred Tahue–Tepehuano terrane boundary, which underlies the Sierra Madre (Sedlock et al., 1993), does not appear to have been reactivated by extension or to have affected its distribution.

Thermal weakening related to arc magmatism does not appear capable of explaining the distribution of some earlier extension. A late Oligocene–early Miocene (~24 Ma) episode of extension affected much of western Mexico (Henry and Aranda-Gomez, 1992; Aguirre-Diaz and McDowell, 1993; Aranda-Gomez et al., 1997; Ferrari et al., 1997; Gans, 1997; McDowell et al., 1997; Nieto-Samaniego et al., 1999). In Durango, this episode affected only the area east of the Sierra Madre Occidental, where arc magmatism had probably ceased by ~30 Ma, despite the fact that magmatism continued at the same time in the western Sierra Madre (McDowell and Keizer, 1977; Aranda-Gomez et al., 1997). This indicates that thermal weakening is not the only factor in guiding extension.

4.4. Application of plate-motion partitioning to pre-middle Miocene extension

Although earlier ('pre-Basin and Range' of Zoback et al., 1981) extension is interpreted by some to have formed by fundamentally different processes and in different tectonic environments (Burchfiel et al., 1992), the plate-motion partitioning mechanism may apply to earlier episodes of extension (Bohannon and Parsons, 1995; Dokka and Ross, 1995; Stock and Atwater, 1997; Atwater and Stock, 1998). Atwater and Stock (1998) found that motion of the Pacific plate was similarly oblique to the North American plate beginning as early as 33 Ma; the plate boundary was in transtension since inception to about 8 Ma, when Pacific motion became more northerly and more nearly parallel to their boundary. This suggests that east–northeast extension, perpendicular to the boundary, should have begun much earlier than 12 Ma. Atwater and Stock (1998) found that calculated displacements from plate circuit reconstructions agree closely with estimated coast-perpendicular (N60°E) extension in a transect across the Rio Grande rift, Colorado Plateau, and central California from 24 Ma to the present. Therefore, plate-motion partitioning was probably critical to extension at least as early as 24 Ma. Atwater and Stock cite large-magnitude extension in the Mojave desert in the earliest Miocene as an example.

We add that east–northeast extension was also occurring in the latest Oligocene and early Miocene through a large part of the southern Basin and Range province from Arizona and Sonora to, and even south of, the Trans-Mexican volcanic belt (Henry and Aranda-Gomez, 1992; Aguirre-Diaz and McDowell, 1993; Aranda-Gomez et al., 1997; Ferrari et al., 1997; Gans, 1997; McDowell et al., 1997; Jansma and Lang, 1997; Nieto-Samaniego et al., 1999). Only Arizona and Sonora in the northermost part of this region may have been immediately inboard from the transtensional boundary; the rest of the region lay behind a subduction margin. Nevertheless, as with the ~12 Ma episode, extension immediately behind both the transtensional and subduction margins appears to be contemporaneous, physically contiguous, and kinematically similar. It is beyond the scope of this paper to examine these implications fully, but the possibility that earlier episodes of extension in the southern Basin and Range may also have been controlled by plate interactions needs further consideration.

The role of gravitational collapse of overthickened crust in generating extension in northern Mexico, both in the middle to late Miocene and earlier, is more problematic. The Sierra Madre is currently the topographically highest region of the area, it is underlain by a thick batholith, and gravity data indicate that it has the thickest crust of the region (~50 km; Schellhorn et al., 1991). Thick crust probably resulted from Oligocene magmatism, so these characteristics may have existed since then. The gravitational collapse mechanism would suggest that extension should have been concentrated in the Sierra Madre, which is just the opposite of what happened. Gravitational collapse may contribute to extension, but release of the boundary by transtensional motion along the plate margin seems necessary for such a process to act (Bohannon and Parsons, 1995; Dokka and Ross, 1995; Atwater and Stock, 1998).

5. Conclusions

An episode of predominantly east–northeast oriented, middle to late Miocene (~12–6 Ma) extension affected most of the southern Basin and Range province from southern Arizona and New Mexico to the Trans-Mexican volcanic belt. This episode has long been recognized in the Gulf Extensional Province as the 'proto-Gulf' rifting event that preceded seafloor spreading and opening of the present Gulf of California (Karig and Jensky, 1972; Gastil et al., 1975; Hausback, 1984; Stock and Hodges, 1989; Lee et al., 1996). The difficulty of placing a boundary between the proto-Gulf and the Basin and Range is resolved because there is no boundary. The Gulf Extensional Province is a part of the Basin and Range province, partly separated by the unextended Sierra Madre Occidental but connected across Sonora and Arizona to the north and across Nayarit to the south.

Extension within the GEP is reasonably interpreted as resulting from partitioning of 12–6 Ma Pacific–North American plate motion into strike–slip displacement along the plate margin and east–northeast extension within the North American plate (Spencer and Normark, 1979; Hausback, 1984; Stock and Hodges, 1989; Lee et al., 1996). This mechanism applies equally well to the 'main' Basin and Range province of north–central Mexico, and at least this part of the extension in the Basin and Range appears to be controlled by plate interactions.

Distribution of extensional strain into the GEP and the main Basin and Range of north–central Mexico, east of the Sierra Madre Occidental, probably reflects two major factors. Extension was resisted by the major batholith belts of the Mesozoic Peninsular Range, which forms the western edge of extension, and of the mid-Tertiary Sierra Madre Occidental, which separates the two parts of the extended terrain. As suggested by many, thermal weakening of the Gulf region by arc magmatism that ended ~12 Ma was probably an additional and significant factor in localizing extension there. However, thermal weakening cannot account for extension in the main Basin and Range because arc magmatism had generally ceased there by about 30 Ma.

Because recent work indicates the Pacific–North American plate margin was in transtension even before 12 Ma (Stock and Atwater, 1997; Atwater and Stock, 1998), plate-motion partitioning may also apply to earlier episodes of extension in the Basin and Range province.

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