The real southern Basin and Range: Mid- to late Cenozoic extension in Mexico

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ABSTRACT

Much of northern and central Mexico underwent east-northeast extension in the mid- to late Cenozoic; this area constitutes a major but little-recognized part of the Basin and Range province. The extended region is bounded on the east by the Laramide thrust front of the Sierra Madre Oriental. On the west, the relatively unfaulted Sierra Madre Occidental separates the extended area in central Mexico from that around the Gulf of California. Extension occurred as far south as what is now the Trans-Mexican volcanic belt, and in Oaxaca, south of the belt. The Basin and Range province in Mexico constitutes approximately half of the 19×10^5 km^2 of western North America that underwent mid- to late Cenozoic extension. North-northwest orientations of numerous epithermal vein systems indicate that east-northeast extension began as early as 30 Ma in areas north of the volcanic belt. Major episodes of faulting began at about 23 to 24 Ma and 12 to 13 Ma, both in Mexico and in the southwestern United States. Faulting was commonly accompanied by eruption of alkali basalts typical of intraplate rifting. Widespread Quaternary fault scarps and alkali basalts indicate that extension continues to the present in the region north of the Trans-Mexican volcanic belt. In contrast, the tectonics in and south of the belt are now probably related to subduction of the Rivera plate. Contemporaneity of the 12 Ma episode with early extension around the Gulf of California attributed to Pacific–North American plate boundary reorganization suggests that extension is related predominantly to plate boundary effects. The beginning of extension at ~30 Ma may be related to initial encroachment of the East Pacific Rise upon the trench that lay off western North America.

INTRODUCTION

The origin and characteristics of mid- to late Cenozoic extension in the Basin and Range province of western North America have long interested geologists. However, current models of extension are based solely on studies in the United States, which represents only half the area that underwent extension. Understanding the origin of extension requires knowing the total affected region and its characteristics. Unfortunately, lack of data in Mexico largely precludes incorporating this large region in models.

Most United States–based studies recognize that extension occurred in northernmost Mexico. For example, the Basin and Range province and core complex belt of southern California and Arizona continue into northern Sonora (Ruldan-Quintana, 1982; Wust, 1986). However, Stewart (1978) identified two belts of Cenozoic extension in Mexico: (1) a narrow belt bordering the Gulf of California (Stock and Hodges, 1989; Henry, 1989), and (2) a much wider area in northern Mexico. We show that mid- to late Cenozoic extension occurred throughout northern and central Mexico, at least to, and probably south of, the Trans-Mexican volcanic belt.

Even in the United States, comparison between parts of the extensional province is hampered by the variability in style, amount, and timing of extension and concurrent magmatism. For example, extension varied from metamorphic core complexes and/or detachment faults with up to several hundred percent extension to listric or domino faults to high-angle block faults with, at most, tens of percent extension (Zoback et al., 1981; Chamberlin, 1983; Henry and Price, 1986; Davis and Lister, 1988). What seems most characteristic is that the province underwent early east to northeast extension (Zoback et al., 1981; Wust, 1986) followed in most of the province by northwest extension, which continues to the present (Zoback et al., 1981; Aldrich et al., 1986). In addition, at least in Arizona, New Mexico, and Texas, east-northeast extension began at ~30 Ma (Chamberlin, 1983; Aldrich et al., 1986; Henry et al., 1991). Although extension may have begun earlier in northern Nevada and Idaho (Gans et al., 1989), we consider east-northeast extension, commonly in the Miocene but beginning as early as 30 Ma, to be an essential characteristic with which to evaluate adjacent areas.

MID- TO LATE CENOZOIC EXTENSION IN MEXICO

The region of extension in Mexico is continuous with that of the Basin and Range province of California, Arizona, New Mexico, and Texas (Fig. 1). This region continues at least to the Trans-Mexican volcanic belt and probably farther south into Oaxaca. Except where overprinted by the volcanic belt, the province consists of mostly north-northwest–elongate basins and ranges at an average elevation of nearly 2 km, similar to the province in the United States. We use examples from Durango, Guanajuato, the Trans-Mexican volcanic belt, and Oaxaca (Fig. 1) to illustrate the distribution, geometry, and history of extension in Mexico.

Durango Area

The earliest evidence for east-northeast extension comes from the orientation of open-space–filling veins, which typically form perpendicular to the least principal stress (Henry et al., 1991). Veins in the Santa Barbara mining district near the Durango-Chihuahua border (Figs. 1 and 2) strike slightly west of north and formed between 32 and 28 Ma (Grant and Ruiz, 1988). Paleomagnetic data suggest that the area underwent 10° to 15° of clockwise rotation, probably after vein formation (J. Urrutia-Fucugauchi, 1990, personal commun.). Therefore, extension may have been more east-northeast than east. Many other mining districts in northwestern Mexico have north-northwest–striking vein systems that formed between 31 and 26 Ma (Table 1).

Major normal faulting began by 23 Ma in north-central Durango (Figs. 1 and 3; Aguirre-Diaz and McDowell, 1988; our unpublished data). The north-northwest-striking Rodeo half graben is bounded on the east by a normal fault with at least 3 km of displacement that separates folded Cretaceous limestone from basin-fill sediments. Mid-Tertiary volcanic rocks dip as much as 35° eastward into the graben and are repeated by small displacement normal faults. The relatively small stratal tilt suggests that total extension is not great. Alkali basalts, dated at 23 Ma (Aguirre-Diaz and McDowell, 1988; our unpublished data), erupted along the eastern boundary fault and are interbedded with basin-fill sediments; thus, faulting began by at least 23 Ma. East-northeast extension is indicated by the orientation of the graben and individual faults, the direction of stratal tilt, and paleostress analysis from faults and slickenlines using the method of Angelier (1979).

The north-northwest-striking Rio Chico–Otinapa graben (Figs. 1 and 4) formed west of Durango City at ~12 Ma (McDowell and Keizer, 1977; our unpublshed data). Displacement at the south end is small, ~300 m, but increases

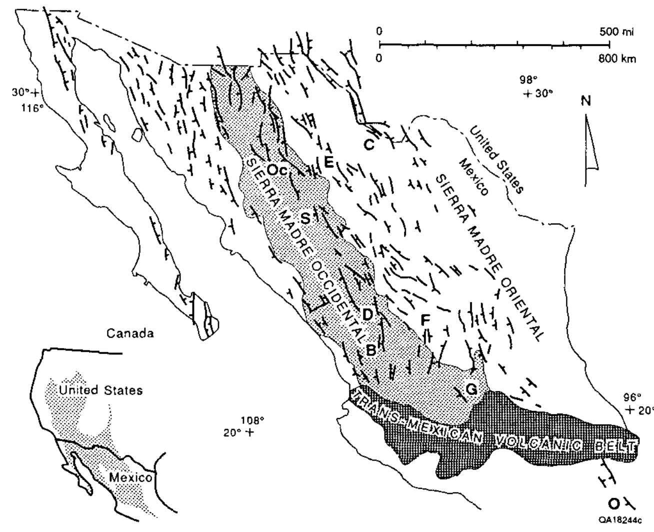

Figure 1. Generalized distribution of mid- to late Cenozoic extensional faults in Mexico. Faults without tick marks are from Stewart (1978); faults with tick marks were compiled from published sources, including 1:50,000 scale geologic maps of INEGI (Instituto Nacional de Estadistica Geografia e Informatica), Mexico, and from new mapping. Part of Trans-Mexican volcanic belt underwent late Cenozoic extension that is now overprinted by younger volcanic rocks. Sierra Madre Occidental is a relatively unextended block separating areas of major extension in northern and central Mexico from those around Gulf of California. Letters indicate locations discussed in text or in Table 1 (Oc = Ocampo; E = Santa Eulalia; C = San Carlos; S = Santa Barbara; D = Durango City; B = Bajio; F = Fresnillo; G = Guanajuato; O = Oaxaca). Inset map and calculations in text show that Mexico constitutes approximately half of area of extension in North America.

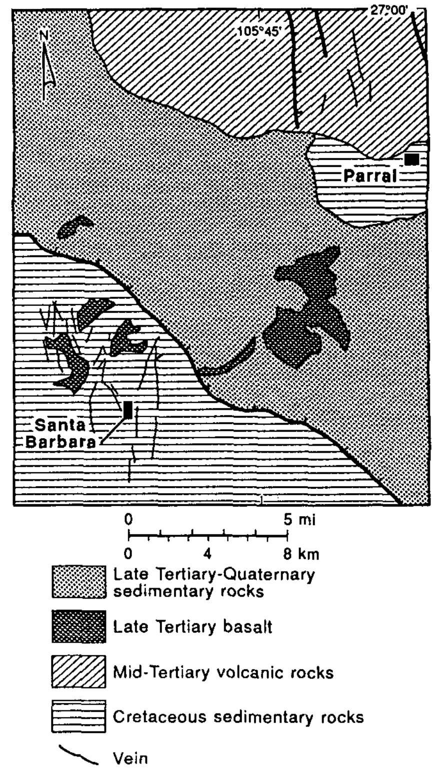

Figure 2. Simplified geologic map of Santa Barbara–Parral district of Chihuahua (location S in Fig. 1); modified from 1:50,000 Santa Barbara G13A57 geologic map, Detenal (now INEGI). Open-space filling veins dated at between 32 and 28 Ma (Grant and Ruiz, 1988) strike slightly west of north and indicate east to east-northeast extension.

to the north where the topographic scarp reaches 900 m. However, mid-Tertiary volcanic rocks are tilted no more than 12° around the graben; total extension was modest. Alkali basalts are interbedded with basin-fill sediments throughout the graben. K-Ar ages of 12 Ma on basalts at the south end (McDowell and Keizer, 1977) that overlie thin sequences (10–15 m) of basin-fill gravels indicate that faulting began only slightly earlier. Preliminary K-Ar ages on basalts to the north are 2 to 3 Ma; one dated flow crosses the eastern boundary fault, but is unfaulted (Fig. 4); faulting must have ended there before 2 Ma. As at Rodeo, graben, fault, and slickenline orientations indicate east-northeast extension. The Sierra Madre Occidental west of the Rio Chico–Otinapa graben is essentially unfaulted and unextended.

Faulting continues to the present northeast of Durango City, where abundant faults cut Quaternary alkali basalts. Individual faults are as much as 23 km long and have scarps up to 15 m high. The north-northwest strike of these faults suggests continued east-northeast extension. However, no kinematic indicators are available, and the north-northwest trend may simply be inherited from older faults.

Guanajuato–San Luis Potosi Area

Grabens in the Guanajuato–San Luis Potosi area strike northwest and northeast (Figs. 1 and 5; Aranda-Gomez et al., 1989). The major, northwest-striking Bajio fault separates the high area of Guanajuato from the lower country of Leon. On the upthrown side of this fault, veins of the Guanajuato mining district occupy north-northwest–striking normal faults with as much as 1400 m displacement (Gross, 1975). K-Ar ages of host rocks and vein adularia indicate that faulting began between 32 and 28 Ma (Gross, 1975). Intraplate, alkali basalts erupted at 11–13 Ma and in the Quaternary near San Luis Potosi (Aranda-Gomez et al., 1989; Luhr et al., 1989, 1991), suggesting episodes of extension at these times. The significance and relative age of the northeast-striking grabens are unclear (Aranda-Gomez et al., 1989). A northeast-striking graben terminates against the Bajio fault north of Guanajuato, suggesting that northwest extension is younger than northeast extension. In contrast, several small northwest-striking grabens terminate against northeast-striking faults south of San Luis Potosi.

Trans-Mexican Volcanic Belt

East-northeast extension occurred between 15 and 5 Ma south of Guanajuato in what is now the central part of the Trans-Mexican volcanic belt (Pasquare et al., 1988). Pasquare et al. (1988) interpreted this area to be a "Southern protraction of the Basin and Range Province of the western United States." This Miocene extension was preceded by east-west shortening and was followed by Pliocene strike-slip faulting that may be related to Rivera–North American plate convergence. Therefore, the volcanic belt is no longer part of the extensional province.

Oaxaca

Late Cenozoic extension has occurred in Oaxaca, south of the Trans-Mexican volcanic belt. North-northwest–striking grabens up to 75 × 20 km developed in the Miocene in central Oaxaca (Ferrusquia and McDowell, 1988; Centeno-Garcia et al., 1990). Although some basin boundary faults may be reactivated from older faults (Centeno-Garcia et al., 1990), paleontologic and K-Ar data demonstrate that the basins formed between 19 and 12 Ma (Ferrusquia and McDowell, 1988). The grabens have as much as 1700 m of displacement and are filled by upper Cenozoic volcanic rocks and continental sediments.

As with the Trans-Mexican volcanic belt, Oaxaca is no longer part of the extensional province. Neotectonic activity in the grabens may be related to Rivera–North American plate convergence (F. Ortega-Gutierrez, 1990, personal commun.). Continuation of the Basin and Range province south of the volcanic belt is speculative. Nevertheless, the geometry and history of grabens in Oaxaca make the area indistinguishable from parts of the Basin and Range province in the United States.

Margins of the Region

Much of northern and central Mexico has clearly undergone Cenozoic extension. The boundaries of the extended region vary from well established to uncertain, as, for example, the southern limit. An irregular western boundary follows the relatively unextended Sierra

TABLE 1. VEIN SYSTEMS THAT INDICATE EARLY EAST-NORTHEAST EXTENSION IN MEXICO

Mining district	Vein orientation	Age (Ma)	Reference
Ocampo, Chihuahua	N30°W	29–28	Knowling (1976)
San Carlos, Chihuahua	N27°W	31	Henry et al. (1991)
Santa Eulalia, Chihuahua	N10°W	27	Maldonado-Espinosa and Megaw (1983)
Santa Barbara, Chihuahua	N10°W	32–28	Grant and Ruiz (1988)
Fresnillo, Zacatecas	N10°–45°W	31?	Lang et al. (1988)
Guanajuato, Guanajuato	N35°W	32–28	Gross (1975)

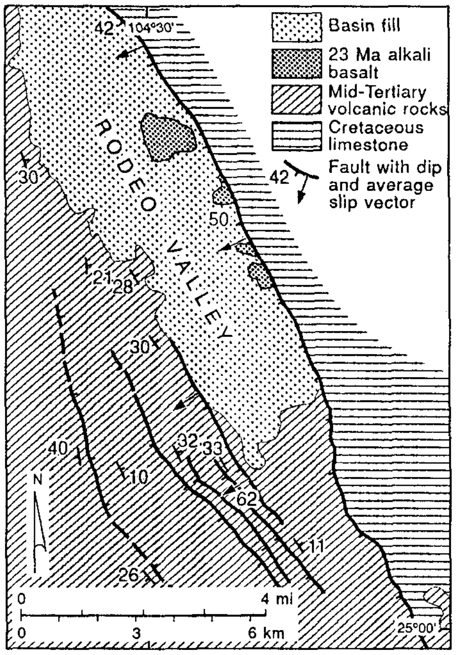

Figure 3. Simplified geologic map of Rodeo half graben, Durango (just north of D in Fig. 1). Mid-Tertiary volcanic rocks are faulted down against folded Cretaceous limestone. Alkali basalts, dated at 23 Ma (Aguirre-Diaz and McDowell, 1988; our unpublished data), erupted along eastern boundary fault and are interbedded with basin-fill sediments. Graben, fault, and slickenline orientations indicate east-northeast extension at 23 Ma.

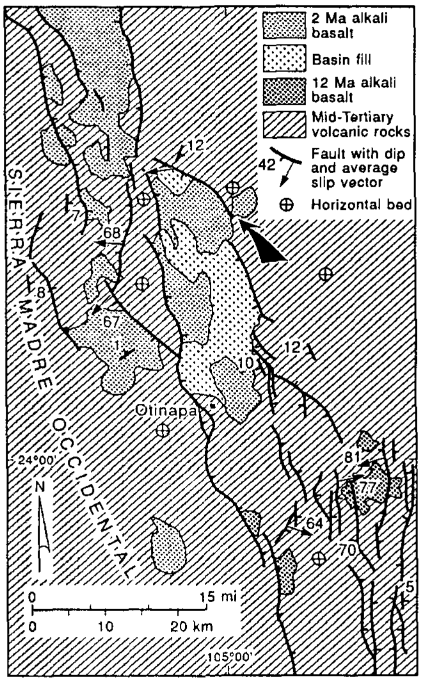

Figure 4. Simplified geologic map of Rio Chico-Otinapa graben, Durango (just west of D in Fig. 1). Alkali basalts in south, dated at 12 Ma (McDowell and Keizer, 1977), overlie thin sequences of basin fill and are themselves faulted; therefore, faulting began at ~12 Ma. Basalts to north have preliminary K-Ar ages of 2 to 3 Ma. One such flow crosses eastern boundary fault (arrow) and is unfaulted; therefore, faulting ended before 2 Ma. Graben, fault, and slickenline orientations indicate east-northeast extension.

Madre Occidental. For much of its length, the Sierra Madre Occidental is a high plateau of predominantly flat-lying, mid-Cenozoic, rhyolitic ignimbrites (McDowell and Keizer, 1977); deformation of any kind has been negligible. However, Miocene east-northeast extension occurred west of the Sierra Madre Occidental, around what is now the Gulf of California (Stock and Hodges, 1989; Henry, 1989). Thus, the Sierra Madre Occidental is an ~800-km-long block of varying width surrounded by regions of major extension.

The regions of extension around the Gulf and in central Mexico join across northern Sonora and Chihuahua and at the southern end of the Sierra Madre Occidental (Fig. 1). In contrast, faulting in Jalisco south of the Sierra Madre Occidental at the western end of the Trans-Mexican volcanic belt began in the Pliocene and created a graben triple junction (Allan, 1986), distinctly unlike Basin and Range extension.

The eastern limit of extension approximately follows the Laramide fold belt of the Sierra Madre Oriental. However, distinguishing basins and ranges formed by extension from those formed by folding is hampered by the lack of detailed mapping in much of the Sierra Madre Oriental. Mapping at the eastern margin of the Laramide belt in southeastern San Luis Potosi indicates that extension did not reach that far east (Suter, 1984).

DISCUSSION

Although data on the history, geometry, and causes of extension in Mexico are sparse, several features are clear. East-northeast extension began as early as 30 Ma in Mexico north of the Trans-Mexican volcanic belt. Earlier, at least to ~40 Ma, the maximum principal stress was probably east-northeast, reflecting Farallon–North American plate convergence (Henry et al., 1991). Stress orientations are unknown between 40 and 30 Ma. However, the many examples of east-northeast extension at ~30 Ma suggest that extension may have begun then.

The best-defined episodes of extension in Mexico, beginning about 23 and 12 Ma, appear to be part of regionally extensive episodes in the southern and central Basin and Range province. The earlier episode includes detachment faulting in Arizona (Spencer and Reynolds, 1989) and high-angle normal faulting in the Salton Trough (Kerr and Kidwell, 1991), Sonora (McDowell and Roldan-Quintana, 1991), and Texas (Stevens and Stevens, 1985; Henry and Price, 1986).

The episode that began about 12 to 13 Ma also occurred in southern Arizona (Eberly and Stanley, 1978), the Rio Grande rift (Morgan and Golombek, 1984), and Texas (Stevens and Stevens, 1985). In addition, pre–sea-floor-spreading extension around the Gulf of California began at the same time (Gastil et al., 1979; Stock and Hodges, 1989; Henry, 1989). The event around the Gulf of California probably resulted from a plate boundary reorganization when a transform margin replaced a subduction margin west of Baja California (Stock and Hodges, 1989). Stock and Hodges (1989) attributed extension around the gulf to partitioning of relative Pacific–North American plate motion between this extension and strike-slip motion along the transform margin. Continuity of the area of gulf extension with unequivocal parts of the Basin and Range province in Sonora and Arizona and contemporaneity of faulting at 12 Ma throughout much of the province suggest extrapolating this mechanism beyond the gulf.

Extension continues to the present in most of north and central Mexico, commonly accompanied by alkali basalts typically associated with intraplate rifting (Luhr et al., 1989). The Trans-Mexican volcanic belt and parts of Oaxaca may have undergone extension during the Miocene, but are now in a distinctly different tectonic province.

The Mexican part of the Basin and Range province constitutes about half the area and length of the province (Fig. 1). We estimate the total area of mid- to late Cenozoic extension in western North America to be $\sim 19 \times 10^5$ km^2. Of this, possibly 9.4×10^5 km^2 are in Mexico, including 8.8×10^5 km^2 in central and northwestern Mexico that unequivocally underwent mid- to late Cenozoic extension. An additional 0.6×10^5 km^2 in the Trans-Mexican volcanic belt and Oaxaca underwent Miocene extension, but are no longer part of the Basin and Range province. Approximately half of the 3000 km overall length of the province from Oregon to the volcanic belt is within Mexico. Arizona, commonly considered to be the southern part of the Basin and Range province, is really in the north-central part of the province.

Several facets of extension in Mexico suggest

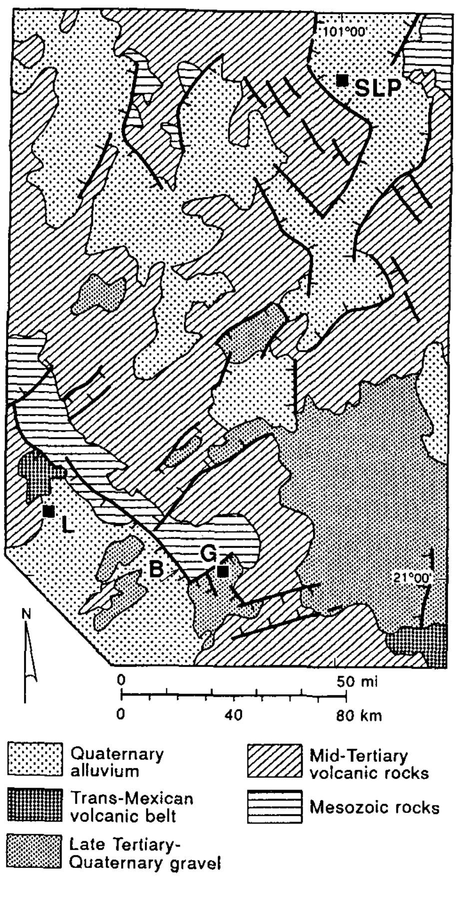

Figure 5. Geologic map of Guanajuato-San Luis Potosi area (location G in Fig. 1) adapted from Aranda-Gomez et al. (1989). G = Guanajuato; SLP = San Luis Potosi; L = Leon; B = Bajio fault. North-northwest-striking veins at Guanajuato formed between 32 and 28 Ma and indicate east-northeast extension at that time. Relative timing of northwest and northeast-striking faults and grabens is uncertain. Intraplate alkali basalts erupted near San Luis Potosi ~12 Ma and in Quaternary time.

an origin related to plate boundary effects. Correlation of the 12–13 Ma event with Pacific-North American plate reorganization may be the most striking. In addition, the occurrence and similarity in orientation of early extension throughout most of the Basin and Range province seem to require a plate boundary effect. Initial extension at ~30 Ma may be related to slowing and ultimate cessation of subduction off the west coast of North America. An origin of extension related to collapse of overthickened crust seems less likely, but is difficult to evaluate. The areas of extension and likely crustal thickening from Laramide shortening largely overlap in Mexico. However, precise correspondence of extension and Laramide deformation in the Sierra Madre Oriental needs to be tested. The Sierra Madre Occidental, the region of most likely crustal thickening related to magmatism, is the least extended; an extensive batholith that probably underlies the ignimbrite field may have acted as a buttress to resist extension.

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