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Regional characteristics, tilt domains, and extensional history of the late Cenozoic Basin and Range province, western North America

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ABSTRACT

The Basin and Range province covers a large region of western North America and contains diverse late Cenozoic extensional structures, including metamorphic core complexes, detachment faults, strike-slip faults, and basin and range fault blocks. The central region of the Basin and Range province, extending from the northern Rocky Mountains in the western United States to Sonora, Mexico, contains local or regional areas characterized by moderate- to large-magnitude extension overprinted by basin and range faults that have produced major elongate mountain horsts or tilted blocks and intervening valleys underlain by grabens, half grabens, or down-tilted blocks. In southeast Oregon and most the Mexican part of the Basin and Range province east of the Sierra Madre Occidental, the province is only slightly or moderately extended, and structures consist mainly of basin and range blocks produced by widely spaced high-angle normal faults. Strike-slip faults are most common in the western part of the Basin and Range province in the Walker Lane belt of Nevada and California, the Eastern Mojave shear zone of the Mojave Desert region, and parts of the Gulf of California region.

Tilt domains in which the dip of stratified rocks and the tilt of mountains blocks are consistently, or fairly consistently, in one direction are characteristic of the Basin and Range province. These domains are commonly 50–200 km or more across in a direction perpendicular to the strike of stratified rocks and the trend of elongate mountain ranges and as much as 1,000 km across parallel to this direction. Tilt-domain boundaries (accommodation zones) consist of either (1) anticlinal boundaries where the strike of stratified rock and the trend of structural fault blocks is parallel to, and the dips or tilts are away from, the boundary; (2) synclinal boundaries where the strike of stratified rock and the trend of structural fault blocks is parallel to, and the dips or tilts are toward, the boundary; or (3) transverse boundaries at a high angle to the strike of stratified rocks and structural fault blocks. These transverse boundaries (transverse accommodation zones) mark areas across which the strike direction of Tertiary rocks and of mountain ranges remains essentially the same, but the dip or tilt direction reverses. Tilt-domain boundaries (accommodation zones) may correspond to areas of abrupt change in dip directions at individual faults or folds, or may be broad areas of structural change that are several kilometers to 20 km across.

Large-magnitude extension was initiated in the northern United States and southern Canada in the Eocene, and perhaps the Paleocene, and spread to the south

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and southwest. In much of the Basin and Range province, the age of large-magnitude extension decreases toward the west or southwest in the direction toward the western or southwestern margin of the Basin and Range province. Large-magnitude extension is as young as 10 Ma or younger (late Miocene) in the western part of the Basin and Range province, from Mexico to the western United States. Characteristically, basin and range block faulting follows and overprints structures related to large-magnitude extension. This block faulting began as early as 20 Ma in eastern parts of the province, is younger to the west, and younger than 10 Ma in some areas in the western part of the province. Large-magnitude extension is generally accompanied by large stratal rotation that occurs in a relatively short time in a high-strain regime, whereas basin and range block faulting involves relatively little tilting and perhaps develops over a longer time and in a lower strain regime.

Anticlinal and synclinal tilt-domain boundaries developed parallel to, but inland of, the convergent plate-tectonic margins of western North America. The domain boundaries can be viewed as extension-related structures in a back-arc setting associated with movement and extension of large segments of western North America away from a stable interior and toward a convergent margin. In the middle Cenozoic, the anticlinal and synclinal tilt-domain boundaries had a northwest trend parallel to a northwest-trending convergent margin along much of western North America. In the late Cenozoic, as the magmatic arc and subduction zone gave way to the developing San Andreas transform system, extension in Nevada, Utah, Oregon, and Idaho was to the northwest toward a convergent margin in the Pacific Ocean off northern California, Oregon, and Washington. In southern Mexico, latest Cenozoic extension was to the south-southwest toward a convergent margin in Pacific Ocean off southwestern Mexico. In contrast to extension in areas inland of convergent margins, little late Cenozoic basin and range block faulting has occurred in Sonora, Arizona, and the Mojave Desert region of California inland of where the San Andreas transform fault initially developed. This spatial relation of little extension inland of the oldest segment of the San Andreas transform system suggests that with time the transform system inhibits inland basin and range extension.

INTRODUCTION

The Basin and Range province of western North America is the product of late Cenozoic extension that has produced alternating block-faulted elongate valleys and mountain ranges. The province covers a vast region that extends 3,700 km from near the United States–Canada border on the north to southern Mexico on the south. The province in many places is 800 km wide and extends as much as 1,500 km inland from the late Cenozoic plate-tectonic boundary of western North America. The province has an irregular distribution, and it curves around, or partly around, two major unextended plateau areas—the Colorado Plateau of the western United States and the Sierra Madre Occidental of Mexico.

The province is moderately diverse structurally. Structures vary in style, scale, and timing from region to region, although major basin and range fault blocks characterize most of the province. The province is also segmented into regional tilt domains characterized by a consistent, or fairly consistent, direction of dip of stratified rocks and tilts of mountain ranges (Rehrig and Heidrick, 1976; Stewart and Johannesen, 1979; Stewart, 1980; Spencer and Reynolds, 1989; Faulds et al., 1990; Stewart and Roldán-Quintana, 1994; Chapin and Cather, 1994). Tilt domains cover broad areas, commonly 50 to 200 km across and several hundred kilometers to 1,000 km long. The distribution and character of these tilt domains provides information on the nature of fragmentation of western North America during late Cenozoic extension.

The purpose of this report is to describe the regional characteristics of the Basin and Range province and, in particular, the tilt domains and other structures that segment the province. The discussion incorporates results from a new map of tilt domains in western North America (Stewart et al., this volume). The report also interprets these regional structures in terms of the history of development of the Basin and Range province and of the late Cenozoic plate-tectonic setting of western North America.

In this report I use the term Basin and Range province to describe all parts of western North America characterized by extension-related mountains and valleys. The term Basin and Range province has its origin in the term Basin Range System proposed by Gilbert (1875) to describe the system of "short ridges separated by trough-like valleys" in Utah, Nevada, and California. Powell (1895) later used the term "Basin Range Province" to refer to the area with this characteristic distribution of ranges and valleys. Fenneman (1928) changed the term to "Basin and Range Province." As I use the term here, the Basin and Range province includes some regions (e.g., parts of the northern Rocky Mountains region of the United States and the Central Mesa of Mexico) that traditionally have been included in other provinces.

I also use the terms "basin and range block faulting," "basin and range blocks," and "basin and range block structures" in this report for the processes or structures that form the typical fault-bounded mountains and valleys of the Basin and Range province. I use the term "block faulting" by itself as a general term that includes basin and range block faulting, as well as older block faulting that is not related, or not clearly related, to present-day basin and range topography.

REGIONAL CHARACTERISTICS OF THE BASIN AND RANGE PROVINCE

For the discussion presented here, the Basin and Range province and parts of adjacent provinces are divided into 11 regions (Fig. 1). The physiographic and structural characteristics of each of these regions varies somewhat from that of adjacent regions, although the boundaries between regions are indefinite and gradational and, in places, arbitrary. The physiographic and structural characteristics of each of these regions are summarized here.

Northern Rocky Mountains region

This region is a part of the Northern Rocky Mountains province of Fenneman (1931) and includes, in its southern half, the Rocky Mountains Basin and Range of Wernicke (1992). It consists of a large area of block-faulted basins and ranges (Pardee, 1950; Reynolds, 1979); mountain elevations commonly exceed 3,500 m in the southern part of the region and 2,000 m in the northwestern part. Valley elevations range from about 650 to 1,800 m. Major mountain ranges are linear to curvilinear and are spaced about 30 to 40 km apart.

The region has had a long and varied Cenozoic extensional history (Sears and Fritz, this volume) including moderate-magnitude (about 25%) to large-magnitude (100% or greater) extension (Fig. 2). Older events include Eocene detachment faulting in metamorphic core complexes (Wust, 1986; Armstrong and Ward, 1991; Hodges and Applegate, 1993) and local middle Eocene and Oligocene detachment faulting in east-central Idaho and southwest Montana (Hait, 1984; Janecke, 1991). Late-middle Eocene to Oligocene extension also produced major grabens that preserve as much as 2.6 km of clastic sedimentary rocks (Janecke, 1994). Younger extension has produced typical basin and range block-faulted mountains.

The region is divided into two subregions by the Lewis and Clark line, a northwest-trending, predominantly Cretaceous or early Tertiary system of right-lateral faults (Wallace et al., 1990). North of the Lewis and Clark line, block-faulted ranges have been related, in part, to a continuation of the Rocky Mountain trench of Canada (Powell and Williams, 1989) and are also a northward continuation of basin and range style deformation (Constenius, 1982; Powell and Williams, 1989). Synextensional sedimentary deposits suggest that north of the Lewis and Clark line, the block faulting occurred ca. 33 Ma (Constenius and Dyni, 1983; Powell and Williams, 1989). These sedimentary rocks, however, are mainly in fault contact with uptilted blocks, and some of the block faulting that produced the present-day topography could be younger than the sedimentary rocks.

South of the Lewis and Clark line, mountain ranges and valleys are clearly related to basin and range block faulting (Reynolds, 1979; Wernicke, 1992). Relief from the valleys to the crests of adjacent mountains is commonly 300 to 1,800 m (Reynolds, 1979), and many of the ranges are bordered by young or historic faults (Pardee, 1950; Stickney and Bartholomew, 1987). The block faulting is considered to be younger than 17 to 19 Ma (Barnosky et al., 1993) and in many places is younger than 6 Ma (Kreps et al., 1992). Reynolds (1979) related much of the basin and range block faulting south of the Lewis and Clark line to dip-slip movement on faults that splay southward from right-lateral faults of the Lewis and Clark line. This hypothesis depends on significant right-lateral movement on faults near or along the Lewis and Clark line. Wallace et al. (1990) proposed that much of the movement on the Lewis and Clark line is Cretaceous or early Tertiary in age. Nevertheless, they indicated that Cenozoic movement occurred on some faults along the Lewis and Clark line, and Sears and Fritz (this volume) summarize evidence of at least local middle Eocene to late Oligocene, middle Miocene, and late Miocene and younger movement on faults in the eastern part of the Lewis and Clark line.

Eastern Oregon and the Snake River Plain

This region is a large Miocene and younger uneven volcanic plateau or plain within which late Cenozoic extensional faulting is prominent only in southeastern Oregon. Southeastern Oregon is generally considered part of the Basin and Range province, but the rest of the region was placed in the Columbia Plateau province by Fenneman (1931).

Southeastern Oregon contains well-defined grabens, half grabens, and tilted blocks (Russell, 1928; Fuller and Waters, 1929; Walker, 1973; Walker and Macleod, 1991). Major grabens or half grabens are either spaced 40 to 50 km apart or are present as isolated features within a broad plateau-like area. Tilting of stratified rocks is generally low, in most areas less than 15°. Upland areas have elevations of about 1,200 to 1,500 m. Relief on faulted margins of mountain ranges is 600 to 1,500 m in the southern part of the area, but the high relief dies out northward into a relatively undeformed plateau. The northern boundary of the major basins and ranges in Oregon is the Brothers fault zone (Lawrence, 1976), a zone of northwest-trending closely spaced faults, probably including some strike-slip displacement, that appears to have accommodated movement between an extended area to the south and a relatively unextended area to the north.

In most places in southeast Oregon, faults bounding major basin and range blocks cut rocks ranging in age from 16 to 13 Ma, and basin and range structures are clearly younger than this. Younger rocks (4 to 7 Ma) away from major basin and range

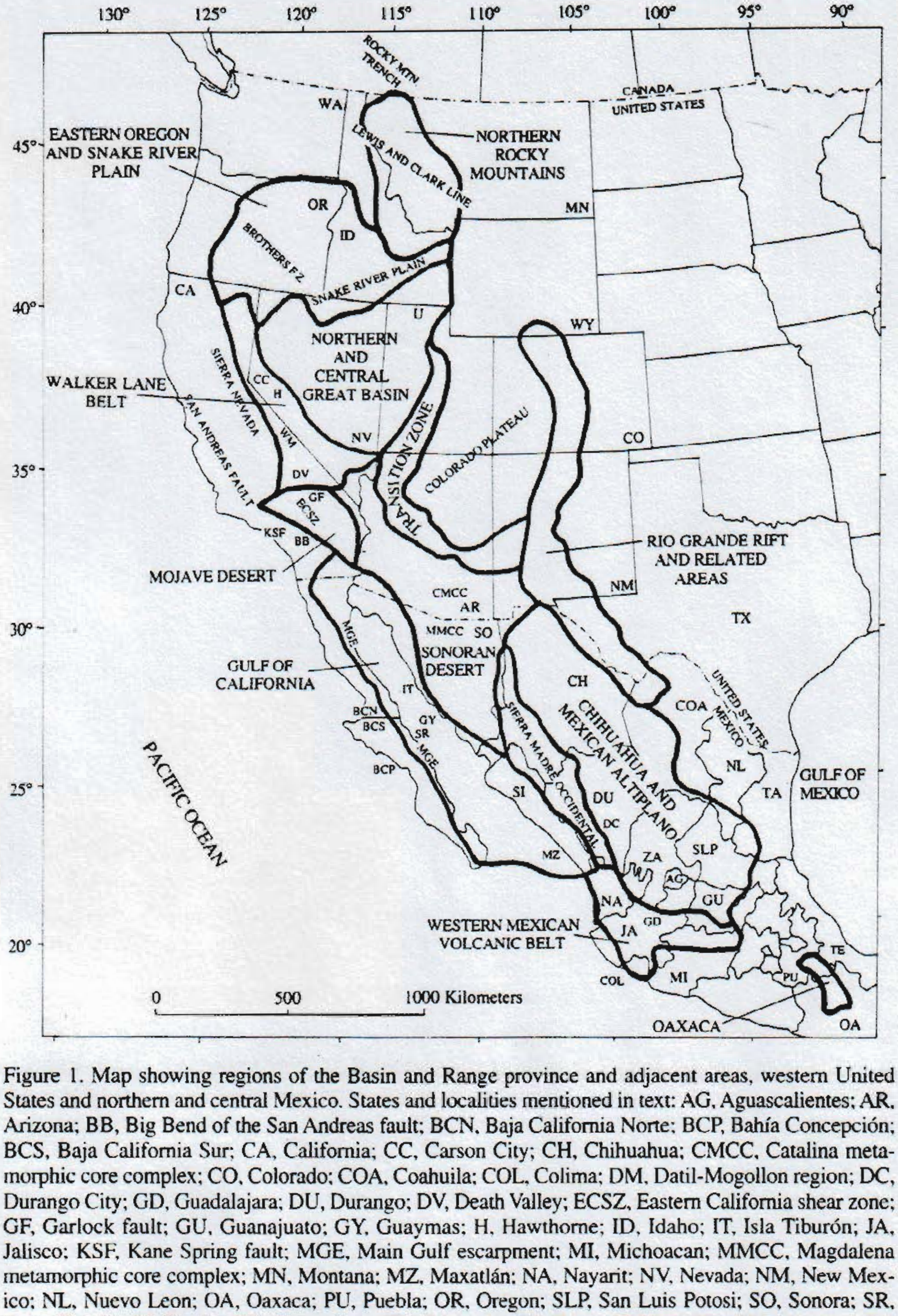


Figure 1. Map showing regions of the Basin and Range province and adjacent areas, western United States and northern and central Mexico. States and localities mentioned in text: AG, Aguascalientes; AR, Arizona; BB, Big Bend of the San Andreas fault; BCN, Baja California Norte; BCP, Bahía Concepción; BCS, Baja California Sur; CA, California; CC, Carson City; CH, Chihuahua; CMCC, Catalina metamorphic core complex; CO, Colorado; COA, Coahuila; COL, Colima; DM, Datil-Mogollon region; DC, Durango City; GD, Guadalajara; DU, Durango; DV, Death Valley; ECSZ, Eastern California shear zone; GF, Garlock fault; GU, Guanajuato; GY, Guaymas; H, Hawthorne; ID, Idaho; IT, Isla Tiburón; JA, Jalisco; KSF, Kane Spring fault; MGE, Main Gulf escarpment; MI, Michoacan; MMCC, Magdalena metamorphic core complex; MN, Montana; MZ, Maxatlán; NA, Nayarit; NV, Nevada; NM, New Mexico; NL, Nuevo Leon; OA, Oaxaca; PU, Puebla; OR, Oregon; SLP, San Luis Potosi; SO, Sonora; SR, Santa Rosalía; SI, Sinaloa; TA, Tamaulipas; TE, Tehuacán; TX, Texas; U, Utah; WA, Washington; WM, White Mountains; WY, Wyoming; ZA, Zacatecas.

structures are also highly faulted locally, indicating that some, perhaps all, significant faulting is younger than 4 to 7 Ma.

Basin and range structures in southeastern Oregon are relatively simple, slightly tilted grabens or half grabens. In this respect, the structures resemble grabens, half grabens, and tilted blocks in the Chihuahua and Mexican Altiplano region of the Basin and Range province in Mexico and, to a lesser extent, in west Texas. These structures appear to form in areas of little extension and seem to be the initial structure in areas undergoing basin and range block faulting.

Basin and range structures of southeast Oregon die out eastward into the Snake River Plain, which was formed by northeastward-migrating Miocene to Quaternary volcanism (Christiansen and Yeats, 1992). The lack of faulting in the Snake River Plain

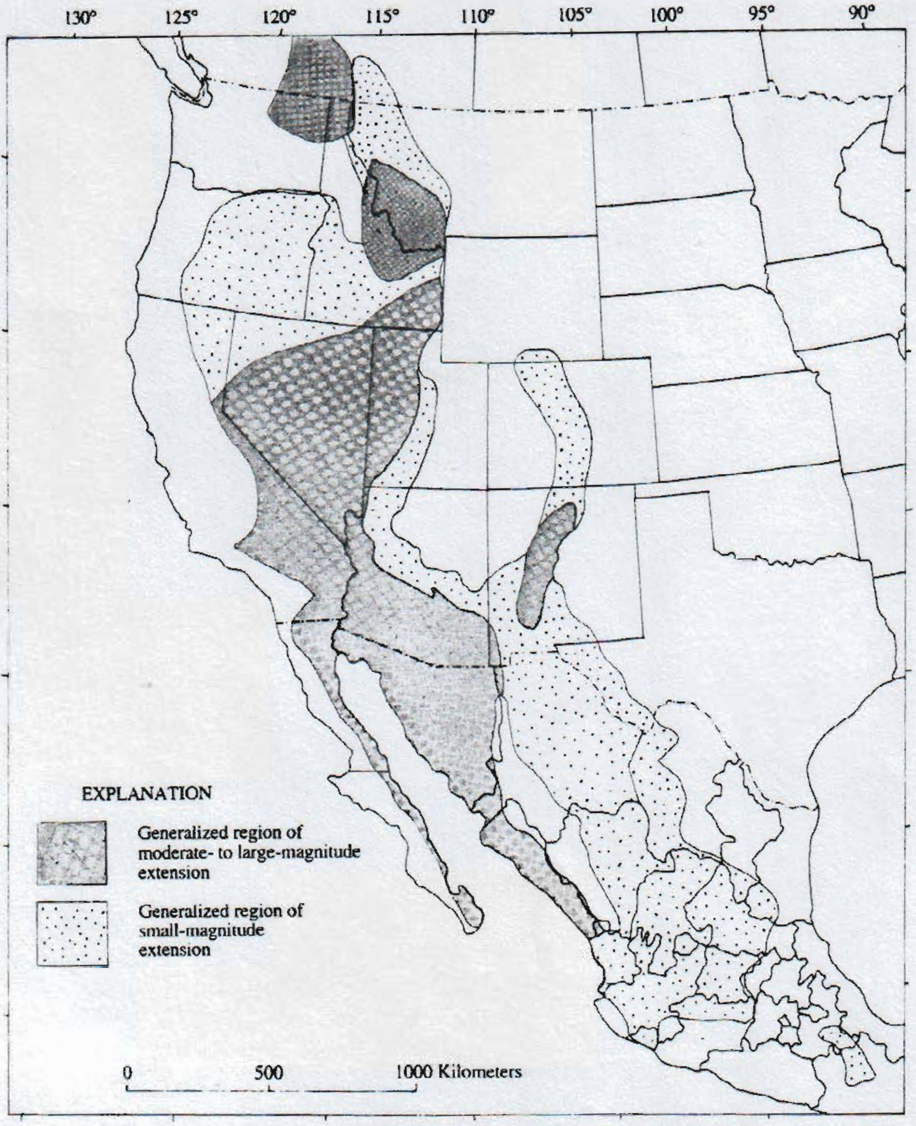


Figure 2. Areas of major and minor Cenozoic extension in western North America. Extension in Canada, Washington, northern Idaho, and Montana are primarily of Eocene age, whereas extension in other areas of western North America is locally as old as Eocene, but is predominantly late Oligocene or younger.

was interpreted by Parsons and Thompson (1991) to be due to magma overpressure that has suppressed normal faulting.

Northern and central Great Basin

The Great Basin is a large area of predominantly internal drainage in Utah, Nevada, and California. As generally defined (Fenneman, 1928), it includes western Nevada, parts of southeastern California, and adjacent areas that are described separately in this report (Walker Lane belt). The northern and central Great Basin contains structures first called "basin-range" (Gilbert, 1875) and is the most typical region of the Basin and Range province. Present-day topography is characterized by rnating elongate mountains and valleys trending north or north-northeast. The spacing between adjacent mountains, or valleys, averages about 30 km (Fletcher and Hallet, 1983). This pattern is clearly revealed by the spacing of the structurally lowest parts of late Cenozoic basins in Nevada based on interpretations of gravity data (Fig. 3). Elevations in valleys generally range from about 1,200 to 2,000 m and along mountain crests range from 1,500 to nearly 4,000 m. The flanks of mountains are commonly steep and marked by young, or historic, faults that form the boundaries between the mountains and valleys (Dohrenwend et al., 1996).

The Great Basin has had a long history of Cenozoic extension (Gans et al., 1989; Seedorff, 1991; Axen et al., 1993; Wernicke, 1990) that includes many areas of moderate-magnitude to large-magnitude extension (Fig. 2) that ranges in age from about 50 Ma

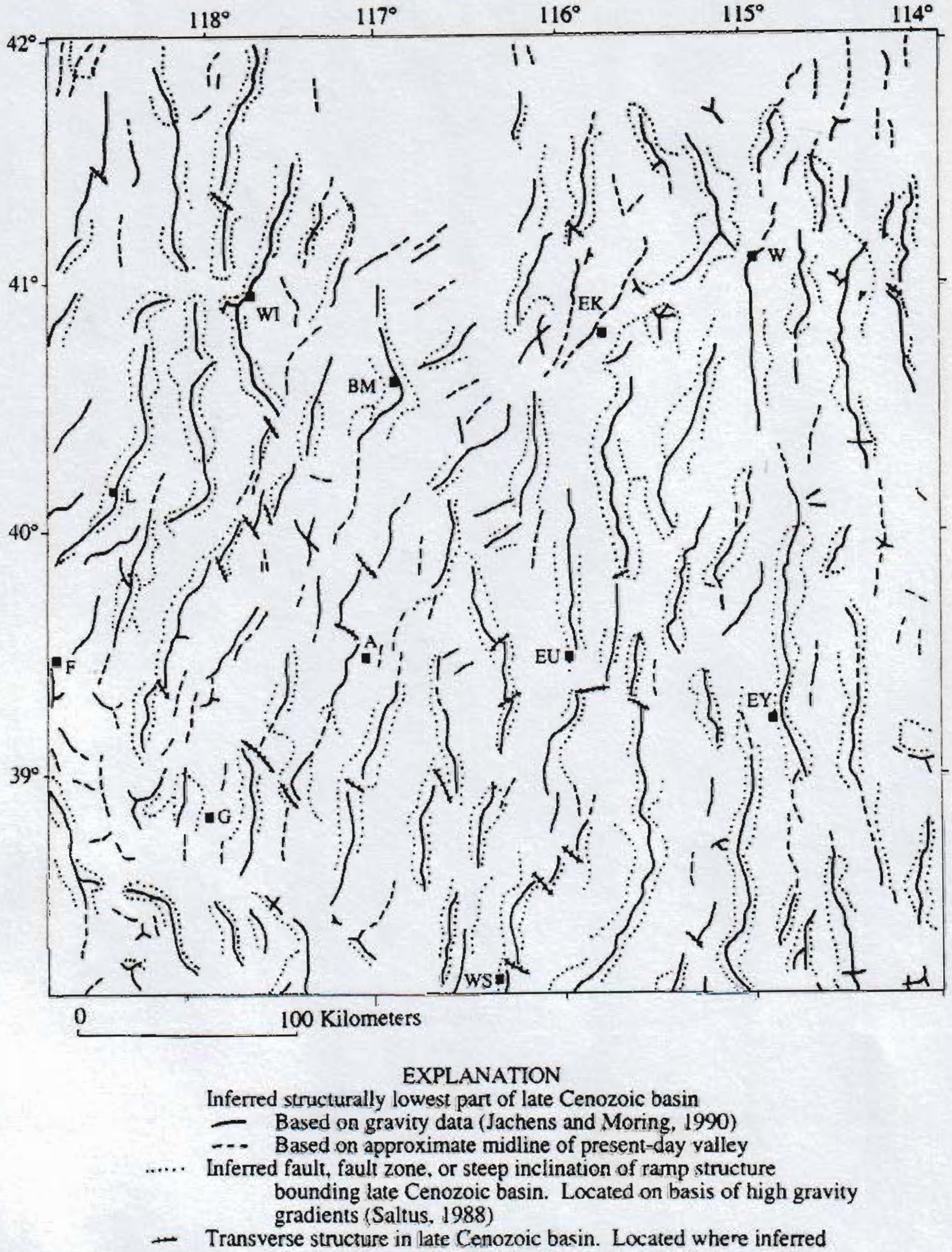


Figure 3. Map showing structurally lowest parts of basins and inferred bounding faults of northern and central Nevada based on gravity data (Saltus, 1988; Jachens and Moring, 1990). Localities: A, Austin; BM, Battle Mountain; EK, Elko; EY, Ely; EU, Eureka; F, Fallon; G, Gabbs; L, Lovelock; W, Wells; WI, Winnemucca; WS, Warm Springs.

to 10 Ma (Seedorff, 1991; Armstrong and Ward, 1991). Even younger large-magnitude extension took place in the Death Valley region, as described for the Walker Lane belt. Moderate- to large-magnitude extension includes detachment faulting in metamorphic core complexes and other areas, as well as extension in areas of steep stratal tilts where detachment faults are not present at the surface. In general, extension is associated with high stratal tilts (locally more than 90°) and closely spaced (about 1 to 2 km) faults.

Extension younger than about 10 Ma in the Great Basin is apparently of lesser magnitude (see discussion of tilting history) and is characterized mainly by basin and range block faulting along widely spaced (10 to 30 km) fault zones (Fig. 3). This style of faulting developed a well-defined system of complex valley grabens or half grabens and mountain horsts or tilted blocks that is reflected in the present-day physiography of the region. The valleys in Nevada are underlain by shallow to deep Cenozoic structural basins, many of which are characterized by observed or inferred faults on both sides (Fig. 3). These basins include grabens, half grabens that have steep down-faulted ramp structures on one side, or down-faulted parts of major tilted blocks (Anderson et al., 1983). Locally, basin axes are offset laterally along subsurface structures (Fig. 3), presumably faults or complex transfer zones.

Walker Lane belt

The Walker Lane belt is a northwest-trending belt of diverse topography in the western Great Basin characterized by basin and range block faulting, areas of moderate to extreme extension, and strike-slip faulting (Stewart, 1988; Hardyman and Oldow, 1991; Oldow, 1992). Strike-slip faults are distinctive characteristics of the region. The only other regions of the Basin and Range province having known common strike-slip faults are the Mojave Desert region and parts of the Gulf of California region.

The Walker Lane belt contains areas of extreme topographic relief, which is best illustrated in the Death Valley area, where elevations range from about 80 m below sea level in the valley to about 3,200 m above sea level in the adjoining mountains. In addition, Owens Valley along the western boundary of the Basin and Range province is at an elevation of about 1,100 to 1,200 m, and the adjacent Sierra Nevada on the west and the White Mountains on the east rise to more than 4,000 m. The impressive eastern escarpment of the Sierra Nevada is the western limit of the Basin and Range province.

Structurally the Walker Lane belt is diverse. It contains areas of moderate to extreme extension (Proffett, 1977; John et al., 1989; Wernicke et al., 1988), well-defined basin and range block faulting (Stewart, 1988), and a system of northwest-striking right-lateral faults and northeast-striking left-lateral faults (Stewart, 1988). Moderate- to extreme-magnitude extension is dated as about 24 to 14 Ma in age in the northern part of the Walker Lane belt (Seedorff, 1991; John et al., 1989; Dilles and Gans, 1995), between 14 to 4 Ma (or younger) in the Death Valley region (Wernicke et al., 1988), and from 13 to 8 Ma in southern Nevada (Duebendorfer and Simpson, 1994). In the west-central Nevada part of the Walker Lane belt, strike-slip faulting started about 22 to 24 m.y. ago and has continued, perhaps episodically, throughout the late Cenozoic (Ekren and Byers, 1984; Hardyman and Oldow, 1991; Dilles and Gans, 1995). Historic strike-slip rupture is recorded locally (Slemmons et al., 1979). In the Death Valley area, strike-slip movement is 14 Ma or younger in age, and locally some strike-slip faults exhibit Quaternary movement (Brogan et al., 1991). In the Lake Mead region of southern Nevada, strike-slip movement occurred about 13 to 8 m.y. ago (Duebendorfer and Simpson, 1994).

The strike-slip faults of the Walker Lane belt have been interpreted as transfer faults that accommodated relatively larger extension on one side of the fault than the other and are parallel or subparallel to the extension direction (Liggett and Childs, 1977; Guth, 1981; Wernicke et al., 1984). An alternative interpretation is the strike-slip faults are conjugate shear faults that developed at an oblique angle to the extension direction. The latter view is favored because (1) the present-day orientation of extension is oblique to the trend of most strike-slip faults in the Walker Lane belt; (2) the presence of both northwest-striking right-lateral faults and northeast-striking left-lateral faults is consistent with conjugate shear sets; (3) the presence of the two orientations of strike-slip faults (northwest and northeast striking) would require large changes in the orientation of the extension direction if both sets are related to extension; and (4) large-magnitude compressional drag features (oroflexual folds, Albers, 1967; Stewart, 1988) are associated with some strike-slip faults in the Walker Lane belt. However, in a complex zone of transtensional deformation and of partitioning of strike-slip and dip-slip deformation (Oldow, 1992), both styles of deformation may apply.

Mojave Desert

The Mojave Desert region is characterized by moderate elevations and relatively low relief. In the western part of the region, valley elevations are generally 650 to 850 m and crests of mountain ranges about 1,200 to 1,500 m. In the eastern part of the region, valleys are 450 m, or lower, and mountain crests about 850 to 1,200 m. Although many mountains are highly eroded and flanked by widespread pediments, a significant number have steep flanks and short, steep alluvial fans. Many steep-sided mountains are bounded by strike-slip faults.

The Mojave Desert region contains areas of moderate- to large-magnitude extension (Dokka, 1986, 1989; Glazner et al., 1989; Dokka et al., 1991; Bartley and Glazner, 1991) that are collectively referred to as the Mojave extensional belt (Dokka, 1989). This belt locally contains mylonitic metamorphic rocks considered by Bartley et al. (1990) to be a metamorphic core complex. The extended belt is of early Miocene age (about 23 to 18 Ma) and includes major detachment faults that are associated with areas of high stratal tilt and syntectonic sedimentary deposits.

The most distinctive structure of the Mojave Desert region is a system of strike-slip faults referred to as the Eastern California shear zone (Dokka, 1983; Dokka and Travis, 1990a, 1990b; Dokka et al., 1991). This fault system consists of northwest-striking right-lateral and east-striking left-lateral strike-slip faults. The right-lateral faults are predominant and form a distinctive pattern of subparallel faults spaced about 5 to 10 km apart. Cumulative displacement on the right-lateral faults is inferred to be about 65 km (Dokka, 1983; Dokka and Travis, 1990a, b; Dokka et al., 1991). The left-lateral Garlock fault that bounds the Mojave Desert region on the north has 48 to 64 km of cumulative left slip (Smith, 1962; Davis and Burchfiel, 1973), and other left-lateral faults in the region have a few kilometers to more than 10 km of slip (see summary by Stewart and Crowell, 1992). Most movement on faults in the Eastern California shear zone is no older than 20 Ma, and no younger than 6 Ma, according to Dokka et al. (1991), although significant movement younger than 3.5 Ma is evident locally (D. M. Miller, 1995, oral commun.). Quaternary offset has also taken place on the Garlock fault (Clark et al., 1984). In addition, right-lateral surface offset as great as 6 m took place during the 7.3 magnitude Landers earthquake in the western Mojave Desert in 1992 (Sieh et al., 1993). Extension and strike-slip faulting in the Mojave Desert region was accompanied by slight to moderate vertical-axis block rotation (Golombek and Brown, 1988; Ross et al., 1989; Wells and Hillhouse, 1989). Few, if any, simple block-faulted mountain ranges that are typical of the Basin and Range province are present in the Mojave Desert region.

Sonoran Desert

The Sonoran Desert region as described here includes most of southern Arizona, small areas in adjacent California and Nevada, and most of Sonora, Mexico. This region is near sea level or a few hundred meters above sea level in areas near the Gulf of California in Mexico and near the Colorado River in Arizona and California. In southwestern and southern Arizona, most valleys are near 150 to 450 m, and mountains are as much as 600 to 1,800 m high. Locally in some areas near the northern border of the region, mountain elevations range from 2,000 to 3,000 m. In most parts of the region, mountain ranges are low, highly dissected, and flanked by wide alluvial plains (the Sonoran buried ranges of Raisz, 1959). This dissected nature of the ranges contrasts with the ranges in the Great Basin, where range fronts are steep and range-valley boundaries are abrupt.

In the Sonoran Desert region, metamorphic core complexes and associated large-magnitude extension are recognized in areas of central Sonora (Anderson et al., 1980; Stewart and Roldán-Quintana, 1994), northern Sonora (Nourse, 1990; Nourse et al., 1994), and southern to western Arizona and easternmost California (Davis, 1980; Spencer and Reynolds, 1989, 1991; Frost and Martin, 1982; Howard and John, 1987; Davis and Lister, 1988). These metamorphic core complexes are scattered within a fairly narrow belt that trends north-northwest in Sonora, northwest in southern Arizona, and north-northwest in the Colorado River extensional corridor (Howard and John, 1987) near the Arizona-California border. Large-magnitude extension related to the metamorphic core complexes took place between 27 and 20 Ma (perhaps mostly 22 to 20 Ma) in northern Sonora (Aiken and Kistler, 1992; Miranda-Gasca and De Jong, 1992), about 28 to 17 Ma in southern Arizona (compilations by Glazner and Bartley, 1984; Armstrong and Ward, 1991), about 22 to 10 Ma (mostly 22 to 17 Ma) in southern California and western Arizona (compilations by Glazner and Bartley, 1984; Armstrong and Ward, 1991), and 16 to 11 Ma in southern Nevada and northwestern Arizona (Anderson et al., 1972; Faulds et al., 1995).

Beginning at about 15 to 10 Ma, extensional faulting in the Sonoran Desert region was characterized by basin and range block faulting (Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Scarborough et al., 1983; Spencer and Reynolds, 1986, 1989; Menges and Pearthree, 1989; Dickinson, 1991; Stewart and Roldán-Quintana, 1994). This faulting produced the pattern of elongate major mountains and valleys that characterize the present-day topography of southern Arizona. Seismic reflection profiles (Eberly and Stanley, 1978) and interpretations of gravity information (Scarborough and Peirce, 1978; Menges and Pearthree, 1989) indicate that individual valleys are commonly underlain by a graben or a half graben. Mountains are horsts or tilted blocks. In places, major high-angle normal faults associated with basin and range block faulting in the Sonoran Desert region clearly truncate structures of metamorphic core complexes (e.g., the Pirate fault on the west side of the Catalina metamorphic core complex, Dickinson, 1991, Fig. 1; and faults on the east side of the Magdalena metamorphic core complex, Nourse, 1990). Basin and range block faulting is considered to have been produced by relatively little extension (Spencer and Reynolds, 1989) compared to that associated with older detachment faulting.

Basin and Range–Colorado Plateau transition zone

A zone of transitional structures as wide as 150 km is present between the Colorado Plateau and the Basin and Range provinces. The transition zone contains structures characteristic of both provinces—gently tilted rocks comparable to those in the Colorado Plateau and high-angle normal faults and associated basins that are similar to, but on a wider spacing than, those in adjacent parts of the Basin and Range province. The transition zone is recognized in southwestern New Mexico; east-central, south-central, and northwestern Arizona; and southwestern to north-central Utah (Fig. 1). In New Mexico, it includes the Datil-Mogollon region characterized by large volcanic centers, high tablelands, broad structural basins, and scattered fault-block ranges (New Mexico Geological Society, 1982). In Arizona, the term "transition zone" as used here includes all of the "transition zone" as defined by Peirce (1984, 1985) as well as part of northwest Arizona that is included in the Colorado Plateau province but characterized by long, widely spaced, generally north- to north-northeast–striking, high-angle, normal faults (Best and Hamblin, 1978, and references therein). These major faults in northwest Arizona continue northward into the high plateaus region of Utah that is also included in the Colorado Plateau, but contains structures transitional between the plateau and the Basin and Range province (Anderson et al., 1975; Rowley et al., 1979; Blank and Kucks, 1989). Elevations in the transitional zone range from a low of about 450 m in Arizona to as much as 3,300 m in the high plateaus of Utah. Local relief is high in many places.

The transitional zone is characterized by widely spaced late Cenozoic high-angle normal faults and related sedimentary basins. Major faults in many places are parallel or subparallel to the margin of the Colorado Plateau and change trend from southeast in New Mexico, to northwest in central Arizona, to north-south or north-northeast in northwestern Arizona, and southwestern to north-central Utah (New Mexico Geological Society, 1982; Reynolds, 1988; Hintze, 1975). Tilt of stratified rocks is generally low. Late Cenozoic alkalic basaltic lavas are much more abundant in the transition zone relative to adjacent parts of the Colorado Plateau or Basin and Range province (Best and Brimhall, 1974).

Metamorphic core complexes and major low-angle detachment faults are absent at the surface, although such structures have been nferred to underlie part of the transition zone in Arizona (Foster et al., 1993; Reynolds and Spencer, 1985).

In Arizona, prior to middle Tertiary extension, what are now the Sonoran Desert region and the transitional zone were higher than the Colorado Plateau and shed detritus northeastward onto the Colorado Plateau (Peirce et al., 1979; Spencer and Reynolds, 1989). This paleogeography, according to Peirce et al. (1979), was disrupted by an Oligocene (?) base-level change and subsequent erosion that outlined the ancestral Colorado Plateau margin. During about the past 13 m.y. in Arizona, faulting has produced the present fault-related topography of the transition zone (Peirce et al., 1979; Spencer and Reynolds, 1989). In northwestern Arizona, eruption of the 18.5 Ma Peach Spring Tuff (e.g., Nielson et al., 1990) accompanied or immediately preceded most basin and range block faulting because only minor faulting along the boundary between the Basin and Range province and the Colorado Plateau is evident prior to 18.5 Ma (Young and Brennan, 1974). In southwestern Utah, the differentiation of the Colorado Plateau and the Basin and Range provinces is younger than 29 Ma, and significant topographic relief between the two provinces was evident by 24 Ma (Rowley et al., 1978). High-angle normal faulting and associated basin deposits related to the present-day topography of the high plateaus of Utah are mainly younger than 14 Ma (Rowley et al., 1978).

o Grande rift and its continuation into west Texas and jacent parts of Mexico

The Rio Grande rift is the only regionally coherent, laterally restricted rift system in the Basin and Range province. It is characterized by deep half grabens, a long history of extension, recent volcanism, and high heat flow (Seager and Morgan, 1979). The rift structures extend ~1,000 km from central Colorado to southern New Mexico (Tweto, 1979; Kelley, 1979; Chapin, 1979; Seager and Morgan, 1979; Baldridge et al., 1984; Chapin and Cather, 1994). For much of its length, the rift is between the unextended terrane of the Colorado Plateau on the west and continental interior on the east. To the south, the rift is commonly considered to extend into west Texas and closely adjacent parts of Chihuahua, Mexico (Seager and Morgan, 1979; Chapin and Cather, 1994), although the amount of extension in Texas and Chihuahua is far less than in the rift in New Mexico and Colorado. The rift appears to die out in northern Mexico, although dispersed late Cenozoic basin and range faulting extends farther south (Stewart et al., this volume). To the north, the rift continues at least as far as central Colorado. In addition, late Cenozoic extensional structures in northern Colorado, and even Wyoming, may be related to the rift (Tweto, 1979; Eaton, 1986, 1987). Along much of it length, the rift zone is the site of the Rio Grande, and elevations of the river range from about 500 m in west Texas in the southernmost part of the rift to about 0 m in southernmost Colorado. Adjacent mountain ranges are as much as 1,200 to 1,700 m above the Rio Grande or mid-rift valleys.

Structurally, the rift is characterized by a chain of half grabens containing sedimentary fill as thick as 5 to 6 km. The half grabens range in length from 80 to 240 km. In width, they range from 5 to 95 km, and average 50 km (Chapin and Cather, 1994). The symmetry of the half grabens reverses from basin to basin across transverse structural zones (accommodation and transfer zones), producing a distinct longitudinal segmentation of the rift (Chapin and Cather, 1994). In places, these accommodation zones correspond to mapped faults, but in other places the only recognizable feature is the change in dip direction of stratified rocks (Chapin and Cather, 1994).

Initial extension in the rift in New Mexico is as old as 35 to 36 Ma in central and southern New Mexico and about 32 Ma in west Texas, although significant extension and major basin development did not start in New Mexico and Colorado until about 25 to 29 Ma (Chapin and Cather, 1994), and major normal faulting in west Texas did not begin until about 24 to 23 Ma (Henry and Price, 1986; Henry et al., 1991). Early extension (about 29 to 10 Ma) in the rift in New Mexico and Colorado (Chapin and Seager, 1975; Baldridge et al., 1980; Chamberlin, 1983; Golombek et al., 1983; Morgan and Golombek, 1984; Seager et al., 1984; Morgan et al., 1986; de Voogd et al., 1988; Meyer and Foland, 1991) is characterized by the development of broad basins associated with areas of large-magnitude extension, large stratal rotations, and local detachment faulting, whereas late extension (about 10 to 5 Ma) is characterized by block faulting that produced narrow grabens associated with high-angle faults of large displacements (Baldridge et al., 1980; Morgan and Golombek, 1984; Seager et al., 1984; Morgan et al., 1986). In west Texas and adjacent parts of Chihuahua, Mexico, the rift is characterized by a concentration of high-angle normal faults that have produced horsts and grabens, but little stratal rotation, in a region of low-magnitude extension (Stevens and Stevens, 1985; Henry and Price, 1986; Henry et al., 1991).

Gulf of California

The Gulf of California is dominated by young (6 Ma or younger) submarine transform faults and associated short spreading centers (Lonsdale, 1989, 1991; Fenby and Gastil, 1991). Bordering these transform structures are onland areas of extensional, and locally strike-slip faults that partly predate and partly are coeval with the development of the transform system. The gulf is considered to have developed in two phases, an early proto-Gulf phase related to west-southwest extension and a younger phase that involved transform faulting (Karig and Jensky, 1972; Angelier et al., 1981; Colleta and Angelier, 1983; Dokka and Merriam, 1982; Stock and Hodges, 1989; Sawlan, 1991; Smith, 1991).

Baja California is mainly an unextended terrane. Extensional structures are evident only along the eastern margin of Baja California adjacent to the Gulf of California (Axen, 1995). In northernmost Baja California, the eastern margin of the unextended terrane is marked by a conspicuous escarpment (the Main Gulf escarpment) produced by a single normal fault or a system of closely spaced normal faults (Stock and Hodges, 1990; Axen, 1995). The Main Gulf escarpment is analogous, as described later, to the eastern escarpment of the Sierra Nevada in Nevada and California. Faulting related to the escarpment spreads out to the south near lat 30° 15'N. into a zone of numerous high-angle normal faults (Dokka and Merriam, 1982; Stock and Hodges, 1990; Stock et al., 1991; Stock, 1993). The tilting of strata and local detachment faulting in northernmost Baja California are middle and late Miocene or younger in age, and locally this tilting is dated as ca. 9 to 6 Ma (Stock and Hodges, 1989). A small metamorphic core complex is present in the northernmost part of Baja California, about 45 km south of the United States–Mexico border (Siem and Gastil, 1994). Father south in Baja California, near lat 27° 20'N, significant stratal tilt is seen in 10–20 Ma rocks below flat-lying uppermost Miocene and lower Pliocene strata (Sawlan and Smith, 1984; Stock and Hodges, 1989). In this area, the Main Gulf escarpment is younger than 10 Ma basalt. Near lat 26° 45'N, strata as young as 8 Ma locally dip as much as 45° (McFall, 1968).

On the eastern side of the Gulf of California region, extensional structures are evident west of extended Sonora Desert region as well as west of the unextended Sierra Madre Occidental. On Isla Tiburón, in the easternmost Gulf of California, tilting of stratified rocks was most rapid from 15 to 13 Ma, less so from 13 to 11 Ma, and has been slight since 11 Ma (Neuhaus et al., 1988). Near Guaymas, in the westernmost part of the Sonoran region described previously, tilting was mostly older than 10 Ma (Mora-Alvarez, 1992; Stewart and Roldán-Quintana, 1994). In southern Sinaloa, near Mazatlán, Cenozoic strata dip steeply, as much as 65°, and total extension may range from 20% to 50% (Henry and Fredriksen, 1987; Henry, 1989); in Nayarit tilted 21 to 13 Ma volcanic rocks are unconformably overlain by 10 to 8 Ma basalt (Gastil and Krumenacher, 1978; Gastil et al., 1979). In northernmost Sinaloa, a poorly studied area of metamorphic rock may be part of a metamorphic core complex (C. D. Henry, 1996, oral commun.). The metamorphic rocks in this area are the Francisco Gneiss of Mullan (1978) that has yielded a 220 Ma U-Pb zircon age (*in* Anderson and Schmidt, 1983, appendix) and K-Ar ages of ca. 65 Ma on hornblende, 22 Ma on muscovite, and 14 Ma on biotite (F. W. McDowell, 1996, written commun.).

Chihuahua and Mexican Altiplano

Chihuahua and the Mexican Altiplano (also called Mesa Central) region extend from near the United States–Mexico border south southeast for 1,100 km to the state of Guanajuato in Central Mexico. Valley elevations are generally about 1,600 to 2,000 m and mountain elevations about 2,500 to 3,000 m. Structures consist of grabens and half grabens, intervening horsts, and locally, tilted blocks (Duex, 1983; Henry et al., 1983; Córdoba and Silva-Mora, 1989; Aranda-Gómez et al., 1989; Aranda-Gómez, 1989; Bartolini, 1992; Henry and Aranda-Gómez, 1992). Dips of Cenozoic rocks are generally low, but moderate dips are noted in a few areas (Stimac and Wark, 1983; Henry and Aranda-Gómez, 1992; Aguirre-Díaz and McDowell, 1993). Individual grabens or half grabens are either about 10 to 15 km wide and spaced about 25 to 30 km apart or are present as isolated features developed in gently dipping middle Cenozoic tuffs. These structures are concentrated in a 150–200-km-wide belt along the east side of the Sierra Madre Occidental; they spread out in the southern part of the belt in the state of Guanajuato (Henry and Aranda-Gómez, 1992; Aranda-Gómez, 1989). To the west of the belt, they die out into the relatively undeformed plateau-like Sierra Madre Occidental, composed of middle Cenozoic tuffs. To the east they die out in Cretaceous rocks of the Laramide fold and thrust belt, where Cenozoic structures are difficult to recognize. Gries (1979) suggested that normal faulting is lacking in eastern Chihuahua because normal faults at depth do not propagate upward through mobile Jurassic evaporite strata that are widespread in the subsurface in this part of the region.

Extensional faulting in the Chihuahua and Mexican Altiplano region is considered to have started locally as early as 32 to 28 Ma because of the presence of dated extensional veins in the Santa Barbara mining district near the Durango-Chihuahua border (Henry and Aranda-Gómez, 1992). Tilting of as much as 35° took place at about 29 Ma in the Nazas area in the State of Durango (Aguirre Díaz and McDowell, 1993). Graben formation began in the north-central part of the state of Durango at about 23 Ma (Henry and Aranda-Gómez, 1992), is older than about 22 Ma at a locality 50 km north of Guadalajara (Moore et al., 1994), and formed at about 12 to 2 Ma west of Durango City (Henry and Aranda-Gómez, 1992). Quaternary faults are recognized northeast of Durango City (Henry and Aranda-Gómez, 1992), indicating that some extensional faulting is continuing. In the Guanajuato–San Luis Potosi area in the states of Guanajuato and San Luis Potosi, normal faults are as old as 32 and 28 Ma, but 11 to 13 Ma and Quaternary alkalic basalts suggest later extension (Henry and Aranda-Gómez, 1992).

Western part of Mexican volcanic belt

The Mexican volcanic belt that extends east-southeastward across central Mexico is a late Cenozoic magmatic arc related to subduction of the Cocos plate. The western part of this belt contains extensional structures that have been related to the Basin and Range province (Pasquarè et al., 1988; Moore et al., 1994; Suter et al., 1995; Henry and Aranda-Gómez, 1992).

Older structures within the eastern part of the western Mexican volcanic belt that have been related to basin and range extension consist of north- to north-northwest–striking normal faults of middle Miocene to early Pliocene age (about 15 to 5 Ma) (Pasquarè et al., 1988). Younger structures (mostly Quaternary in age) in this part of the belt consist of east-west–trending grabens (Pasquarè et al., 1988; Suter et al., 1992) related to normal faulting with a minor, but consistent left-lateral component of movement (Suter et al., 1992). In the western part of the belt, three intersecting grabens produce a rift-rift-rift triple junction (Allan, 1986; Moore et al., 1994) in rocks mostly younger than 5 Ma. These grabens are about 25 to 60 km across, have well-defined ounding faults (some have local Quaternary movement), and have relief on bounding escarpments of as much as 1,500 m. Structural blocks are either untilted or tilt gently away from the graben axis. The triple junction that these grabens form has been related to (1) an asthenospheric plume (Moore et al., 1994), (2) a reorganization of plates, perhaps accompanied by a plume, produced by an eastward jump of the spreading ridge (Luhr et al., 1985), or (3) some other process that allows part of Mexico to drift away from mainland Mexico in a manner analogous to the drift of Baja California away from mainland Mexico during the opening of the Gulf of California (Allan, 1986; Moore et al., 1994). The northwest-trending graben of this triple junction was reported by Allan (1986) to be characterized locally by strike-slip faults, and he considered the graben to be related to a continuation of the system of en echelon transform faults in the Gulf of California (Allan, 1986). Moore et al. (1994), however, indicated that this graben area probably is related to north-northeast extension that took place from <5.5 Ma to >1 Ma and was followed by strike-slip movement in the last 1 m.y.

Oaxaca region

A 75-km-long and 20-km-wide graben that formed between about 19 and 12 Ma is present in the state of Oaxaca, and extends north-northwest from Oaxaca to Tehuacán (Ferrusquia and Dowell, 1988; Centeno-Garcia et al., 1990; Henry and anda-Gómez, 1992). The graben has as much as 1,700 m of displacement on its bounding faults. Henry and Aranda-Gómez (1992) speculated that the graben is a continuation of the Miocene Basin and Range province. The graben is overprinted and separated from the present-day Basin and Range province of Mexico by the Mexican volcanic belt.

TILT DOMAINS AND THEIR BOUNDARIES

General characteristics and definitions

Tilt domains are areas of consistent, or fairly consistent, dip directions of middle and upper Cenozoic stratified rocks and tilted mountain blocks. Focus is on middle and upper Cenozoic rocks because older rocks may have been deformed by structural events unrelated to late Cenozoic extension. The tilt of individual mountain blocks is determined by a physiographic or geologic asymmetry of the range. In ranges where one side of the range is steep and fault bounded and the other side is a gentle slope (commonly a dip slope), tilt is toward the side having the gentle slope. Geologically, tilt of major mountains blocks is considered to be in the direction in which the stratified rocks, including Cenozoic rocks, become younger across the range. In general, geologic and physiographic information on the tilt of major mountain blocks is consistent, and it is also consistent with the dip of Cenozoic rocks e range. In most mountain ranges, the general dip direction of all ages of Cenozoic stratified rocks is the same. Rarely are dip directions of older rocks in a direction opposite, or at a significant angle to, the dip direction of younger rocks. Most tilt domains are broad areas, commonly 50 to 200 km or more wide, within which tilt directions are fairly consistent. However, relatively small areas of opposite tilt (local domains within the regional domains) are evident in most regions. In addition, the strikes of Cenozoic rocks and of mountain ranges are locally oblique to the dominant dip direction in a tilt domain. These areas of inconsistent strike are common in regions of strike-slip faulting or in areas where the extension direction has changed significantly during the Cenozoic.

Boundaries between tilt domains were referred to as accommodation zones by Bosworth (1985), Rosendahl (1987), and Faulds et al. (1990) (also see discussion of nomenclature in Faulds and Varga, this volume). These boundaries (accommodation zones) were classified by Stewart and Johannessen (1979), Stewart (1980), and Stewart and Roldán-Quintana (1994) as (1) antiformal (here called anticlinal) where the strike of stratified rock and the trend of structural fault blocks are parallel to, and the dips or tilts are away from, the boundary; (2) synclinal boundaries where strike of stratified rock and the trend of structural fault blocks are parallel to, and the dips or tilts are toward, the boundary; or (3) transverse boundaries at a high angle to the strike of stratified rocks and structural fault blocks. These transverse boundaries, or transverse accommodation zones, mark areas across which the strike directions of Tertiary rocks and of mountain ranges remain essentially the same, but the dip or tilt direction reverses. Accommodation zones may correspond to areas of abrupt change in dip directions at individual faults or folds, or they can be broad areas of structural change several to many kilometers across. Locally, the transverse boundaries between tilt domains are continuous with major structural discontinuities that segment regions of consistent tilt direction.

Regional description

In the northern Rocky Mountains region, tilt directions (Fig. 4) of Cenozoic stratified rocks and of mountain blocks are mainly to the northeast, east, and southeast (Reynolds, 1979; Powell and Williams, 1989; Sears and Fritz, this volume; J. W. Sears, W. J. Fritz, and S. U. Janecke, 1995, written commun.). This easterly tilt is fairly consistent in the region, as is common elsewhere along the eastern margin of the Basin and Range province. However, the spread in dip directions from northeast to southeast appears to be greater than in many other parts of the Basin and Range province (Sears and Fritz, this volume; S. U. Janecke, 1995, written commun.) and to be the result of interference among three generations of extensional fault systems (Sears and Fritz, this volume). The amount of dip of stratified Cenozoic rocks ranges from low (less than 25°) to high (greater than 25°). Dips of 50° or more are common in some areas. The tilt directions suggest westward to southwestward transport of blocks relative to an essentially stable cratonal area east of the Basin and Range province.

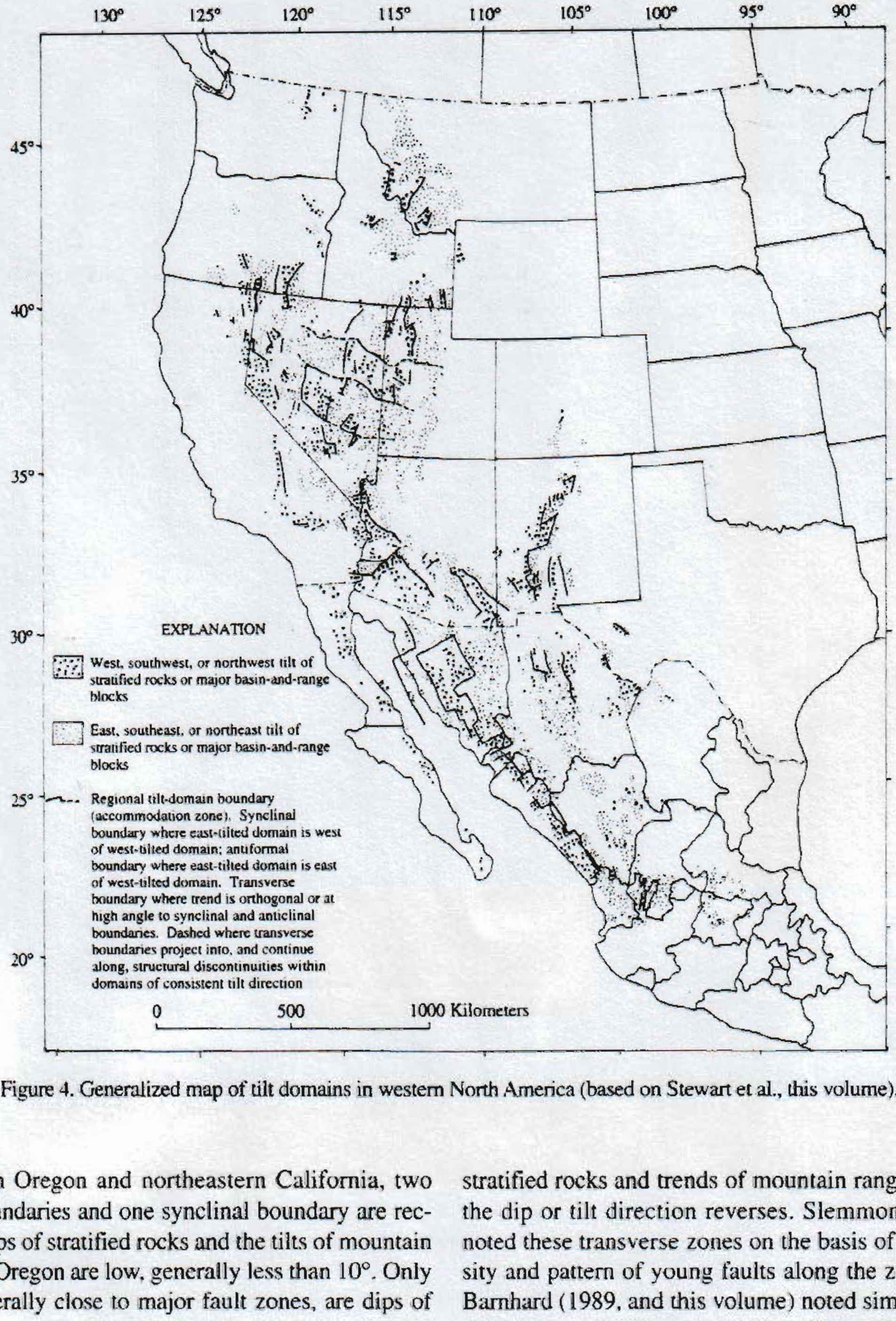


Figure 4. Generalized map of tilt domains in western North America (based on Stewart et al., this volume).

In southeastern Oregon and northeastern California, two major anticlinal boundaries and one synclinal boundary are recognized (Fig. 4). Dips of stratified rocks and the tilts of mountain ranges in southeast Oregon are low, generally less than 10°. Only in a few areas, generally close to major fault zones, are dips of 10° to 30° noted.

In the Great Basin, tilt domains (Fig. 4) are fairly well defined (Stewart and Johanneson, 1979; Stewart, 1980). They consist of areas about 50 to 200 km across in an east-southeast direction, perpendicular to the strike of Cenozoic strata and the trend of elongate mountain ranges, and 75 to 200 km long in a north-northeast direction, parallel to the strike of Cenozoic strata and the trend of mountain ranges. These domains are bounded by generally north- to north-northeast–trending anticlinal and synclinal boundaries and by west-northwest transverse zones (transverse accommodation zones) across which the strike of stratified rocks and trends of mountain ranges are the same, but the dip or tilt direction reverses. Slemmons (1967) originally noted these transverse zones on the basis of changes in the density and pattern of young faults along the zones. Thenhaus and Barnhard (1989, and this volume) noted similar changes, particularly in the distribution and abundance of late Quaternary and Holocene faults. Dips of Cenozoic rocks range from nearly horizontal to high (commonly 30° to 60°).

In the western part of the Walker Lane belt, along the western boundary of the Basin and Range province, tilt directions are generally to the west, a direction characteristic of the western margin of the province elsewhere. This pattern of westerly tilts is particularly evident in the Carson City to Hawthorne area of western Nevada (Stewart et al., this volume). However, patterns of tilting in the Walker Lane belt are complex, and locally the strike of stratified rocks and the trend of mountain ranges are at a high angle to those in typical parts of the Basin and Range province in the Great Basin region to the east. An area of consistent easterly dips is present in the southern part of the Walker Lane belt in the Death Valley area of easternmost California. Dips of Tertiary rocks are generally moderate to high in the Walker Lane belt.

In the Mojave Desert region, tilt domains (Fig. 4) are dominated by a conspicuous east-west–trending transverse accommodation zone, the Kane Springs fault (Dokka, 1986, 1989). North of this fault, dips are generally to the west, and to the south of the fault dips are generally to the east. Dips of Tertiary rocks are commonly 20 to 40°, and locally exceed 60°.

Northwest-trending tilt domains (Fig. 4) are well defined in the Sonoran Desert region of the southern United States and northern Mexico (Rehrig and Heidrick, 1976; Spencer and Reynolds, 1986, 1989; Stewart and Roldán-Quintana, 1994). These domains are 25 to 600 km across and a few hundred to many hundred kilometers long. One of the best-studied transverse accommodation zones (transverse boundaries) is present in the northernmost part of the Sonoran Desert region (Faulds et al., 1990). This transverse accommodation zone is characterized by a complex zone of extensional anticlines and synclines that accommodates different directions of tilting to the north and south (Faulds, 1994). A northern segment of the longest tilt-domain boundary recognized in western North America is present in the Sonoran Desert region. This boundary separates a domain of east tilts to the east from a domain of west tilts to the west and extends from northernmost Sonora southward into what is here described as the Gulf of California region. This boundary has a total length of about 1,000 km. Dips of Tertiary rocks in the Sonoran Desert region vary, and range from high dips in and near metamorphic core complexes to low dips in areas of relatively young Tertiary rocks.

Tilt domains in the Rio Grande rift consist of alternating areas of east and west tilt separated by complex transverse accommodation zones that mark the boundaries of major Cenozoic basins (Chapin and Cather, 1994). These basins are half grabens within which tilt directions shift from east to west (or vice versa) across the accommodation zones. The accommodation zones range in character from features that lack transverse faults and are invisible on geologic maps, except for a reversal in dip directions to distinct transverse faults with normal, reverse, and possible strike-slip displacement (Chapin, 1989; Chapin and Cather, 1994). The dip of Cenozoic rocks in the Rio Grande rift ranges from low to high. High dips are particularly characteristic of areas of domino-style faulting (Chamberlin, 1983). In west Texas, dips of Cenozoic rocks are low, and only a few areas of consistent tilt are recognized.

Tilts on the east side of Baja California in the Gulf of California region are dominantly to the west, as is characteristic of tilts in most areas along the western margin of the Basin and Range province. East of the Gulf of California, in coastal Sonora, dips are to the east, and east of coastal Sonora is a conspicuous belt of west-dipping rocks that approaches the Gulf of California southward. The anticlinal boundary along the eastern side of the belt of west-dipping rocks is a continuation of the 1,000-km-long anticlinal boundary mentioned in the description of the Sonoran Desert region. Tilts in the Gulf of California range from moderate to high. One of the small transverse boundaries shown on the tilt-domain map (Stewart et al., this volume) in Sinaloa corresponds to a major transverse high-angle fault mapped by Henry (1989) and indicated by him to have had a least some strike-slip movement. Other transverse boundaries shown on the map have not been studied, and their structure is not known.

Tilts in Chihuahua and the Mexican Altiplano east of the Sierra Madre Occidental are dominantly to the east, as is characteristic of most areas along the eastern side of the Basin and Range province. A few moderate-sized areas of west tilt are present in Chihuahua and, less commonly, in the Mexican Altiplano. Tilts are generally less than 20° in Chihuahua and the Mexican Altiplano.

STYLE OF TILTING AND EXTENSION

Tilting and extension in the Basin and Range province were produced by two seemingly contrasting styles of deformation. One style is associated with large-magnitude extension (commonly 50% to more than 100%) and is related to low-angle detachment faults or rotated normal faults (Anderson, 1971; Proffett, 1977; Davis and Lister, 1988; Gans et al., 1989). The spacing of major faults ranges from a few hundred meters to several kilometers, and stratal rotation is generally large, commonly ranging from 25° to more than 90°. This style is characteristic of extension above detachment faults in metamorphic core complexes (Davis, 1980; Armstrong and Ward, 1991) and in areas of domino-style rotation of normal faults and strata (Proffett, 1977; Chamberlain, 1983). The second style of extensional deformation produced the major basin and range linear blocks characteristic of the present-day topography (Spencer and Reynolds, 1986; Dickinson, 1991; Christiansen and Yeats, 1992). These blocks are grabens and half grabens that underlie valleys and are separated by mountain horsts or tilted blocks. The spacing of major block-bounding faults ranges from 10 km to locally as much as 50 km. Stratal rotation is generally small (a few degrees to 20°), and extension is only about 10% to 20%.

In parts of the Basin and Range province, the apparent change from the large-magnitude style of extension to basin and range block faulting is either preceded by, followed by, or overlaps in time with, the development of sedimentary basins significantly wider than the present-day basins (Seager et al., 1984; Chapin and Cather, 1994 ; Miller et al., 1993; Stewart and Diamond, 1990; Stewart, 1992b). These basins have been related either to (1) large-magnitude extension (Seager et al., 1984; Stewart and Diamond, 1990; Stewart, 1992b), (2) basin and range extension (Miller et al., 1993), or (3) a variety of structural settings (Stewart, 1992b). The tectonic significance of these widespread basins is poorly understood.

Geologists disagree in interpreting the origin and relation between the two different styles of extensional deformation (large-magnitude extension involving low-angle faults and large stratal rotation versus basin and range block faulting), as well as the validity of recognizing two styles. One view holds that the two structural styles are part of a continuum of related structures (Proffett, 1977; Gans et al., 1989; Wernicke, 1992) in which (1) basin and range block faulting is either the initial or final stage of extensional deformation that either precedes or follows, respectively, large-scale extension on low-angle faults or (2) basin and range faulting took place in one part of an extending allochthon while low-angle detachment faulting took place in another part, perhaps at a deeper structural level. In support of the view that low-angle faulting and basin and range block faulting are related, several geologists (Covington, 1983; Effimoff and Pinezich, 1986; Dickinson et al., 1987; Burchfiel et al., 1987; Johnson and Loy, 1992; Lund and Beard, 1992) described mountain ranges that appear topographically to be typical basin and range blocks, but are bounded, or are interpreted to be bounded, by relatively low-angle faults. However, surface or near-surface, high-angle, mountain-bounding faults characterize much of the Basin and Range province (e.g., see Gilluly, 1928; Okaya and Thompson, 1985; Zoback, 1989), and seismic and geodetic studies of earthquakes show that some major mountain-bounding faults extend at a relatively steep angle to a depth of at least 10 to 15 km (Romney, 1957; Witkind, 1964; Crone and Machette, 1984; Barrientos et al., 1987; Richins et al., 1987).

The concept of the existence of two styles of deformation (large-magnitude extension involving low-angle faults and large stratal rotation versus basin and range block faulting) is supported by the following. (1) The fault systems have obviously different scales and characters. (2) In most areas, structures intermediate in style between the two types do not exist. (3) In parts of the Basin and Range province the two styles of faulting do not occur in the same area (D. M. Miller, 1995, written commun.), as indicated by the presence of basin and range structure where there are no "precursor" metamorphic core complexes and the absence of basin and range faults overprinting the metamorphic core complexes in Washington, Canada, and northern Idaho. (4) Basin and range faults truncate major structures of the metamorphic core complexes in areas where metamorphic core complexes and basin and range faults are both present (Dickinson, 1991; Nourse, 1989). (5) The two modes have different ages (see discussion of Age of Extension). In addition, the initiation of basin-and-range block faulting generally corresponds to a change in the fundamental character of magmatism from compositionally diverse (andesite-rhyolite) to basaltic or bimodal basalt and rhyolite (Christiansen and Lipman, 1972; Dickinson, 1991; Christiansen and Yeats, 1992; Miller, 1993). This interpretation, however, is not accepted by all geologists. Seager et al. (1984), for example, suggested that the change to basin and range block faulting in the Rio Grande rift was coeval with the change from basaltic andesite to alkaline-olivine basalt, rather than a shift from andesite-rhyolite to basaltic andesite volcanism. In addition, Cameron et al. (1989) suggested that basaltic andesite in Mexico is related to extensional events prior to the development of basin and range topography. Nevertheless, the change from compositionally diverse or andesite-rhyolite volcanism to basaltic or bimodal basalt and rhyolite volcanism seems to mark the onset of basin and range block faulting in many areas (Dickinson, 1991; Christiansen and Yeats, 1992; Miller, 1993).

AGE OF EXTENSION

Large-magnitude extension involving low-angle faults and large stratal tilting was initiated in the northern United States and southern Canada (Armstrong and Ward, 1991) in the Eocene, or perhaps as early as the Paleocene (Fig. 5). This style of extension is generally described as younging to the south in the United States (Armstrong and Ward, 1991; Axen et al., 1993). However, the compilation presented here (Fig. 5), which includes times of strata rotation of greater than 25° as well as documented times of large-magnitude extension, suggests that the direction of decrease is generally to the southwest and that the apparent southward decrease (Armstrong and Ward, 1991; Axen et al., 1993) is only a component of the southwest-younging pattern. The west-northwest younging of low-angle faults described by Glazner and Bartley (1984) across southwestern Arizona, eastern California, and southern Nevada also appears to be an oblique component of the decrease in age to the southwest. The generalized age of large-magnitude extension or stratal rotation decreases to the southwest from values near 50 Ma in Washington, Idaho, Montana, and northeastern Nevada, to 20 to 30 Ma in central Nevada and parts of Arizona and New Mexico, to about 10 Ma in western Nevada, southeastern California, and western Mexico (Fig. 5). The relatively young age of extension near the Nevada, Idaho, and Utah boundary may be an exception to this general pattern, although Wells et al. (1994) indicated that middle to late Eocene, as well as younger, extension occurred in this region.

The age of basin and range block faulting is less-well known than that of large-magnitude extension; part of this uncertainty may result from the problem, discussed earlier, of whether basin and range structure is distinctly different from structures produced by large-magnitude extension. Structural and stratigraphic information indicates that major movements on basin and range block structures are mostly younger than 15 Ma (numbers without boxes in Fig. 6) and that older ages of major movement (as old as 23 Ma) are commonly in the eastern part of the Basin and Range province and younger ages (10 to 0 Ma) of major movement are in the western part. Also shown in Figure 6 (numbers within boxes) are the ages of the change from compositionally diverse (andesite-rhyolite) to basaltic or bimodal magmatism that, as discussed above, have been considered (Dickinson, 1991; Christiansen and Yeats, 1992; Miller, 1993) to generally correspond to the time of initiation of basin and range block faulting, although this concept was not accepted by Seager et al. (1984) and Cameron et al. (1989). The generalized isopleth lines shown in Figure 6 are based on the ages of this compositional change as well as the oldest ages of basin and range block structures. These isopleth lines are inferred to indicate the time of initiation of basin and range faulting. However, the lines are drawn on the basis of two types of information that may not precisely indicate

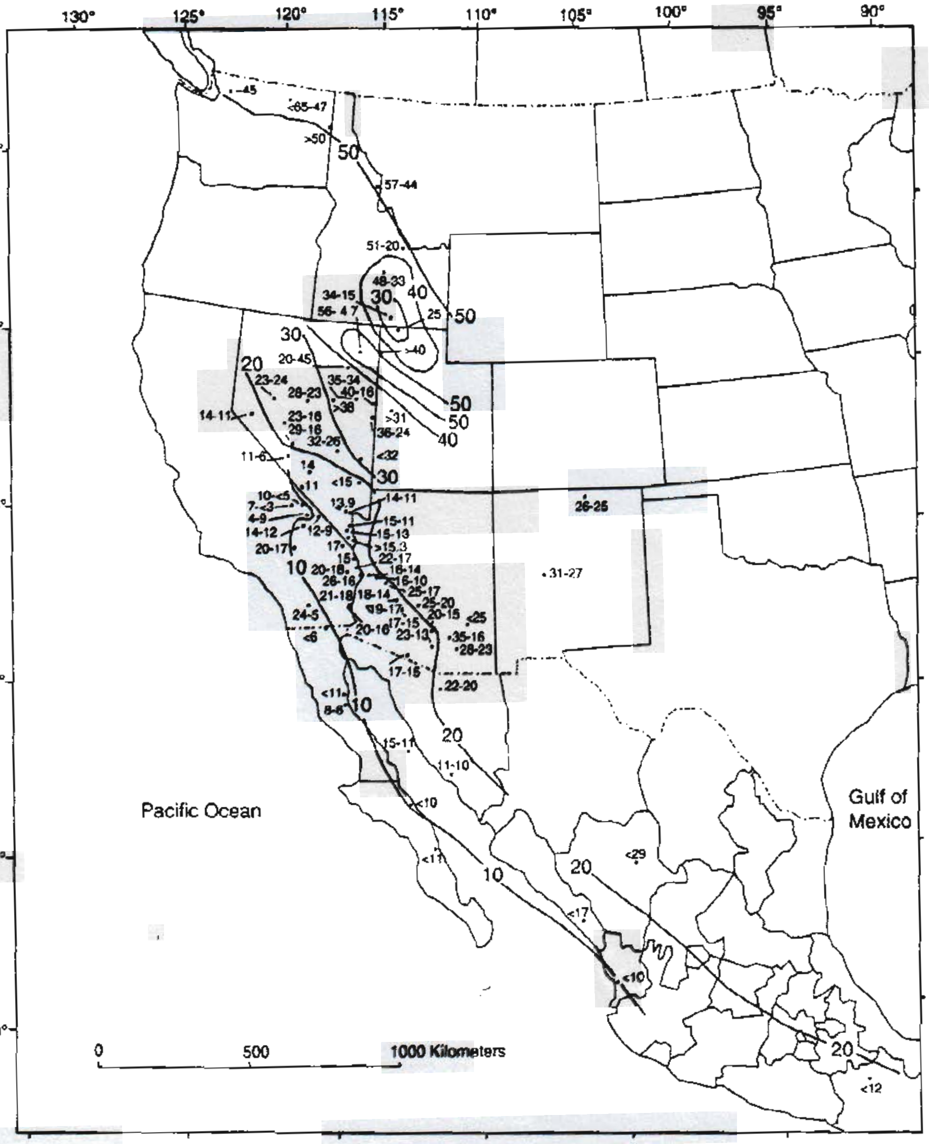
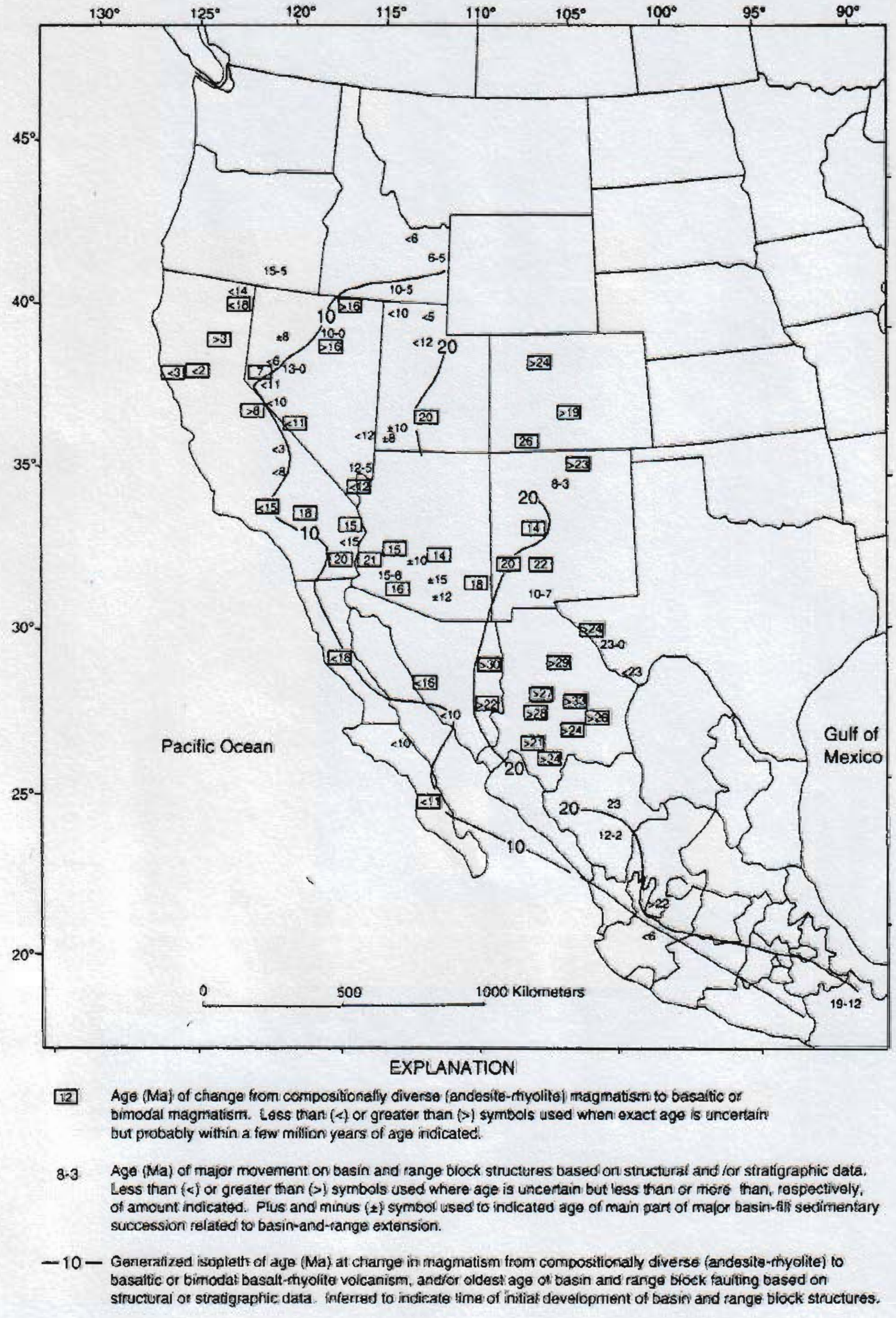


Figure 5. Ages (in Ma) of major extensional detachment faults and/or ages of stratal tilting (25° or more) of Cenozoic strata during extension. Range of age at any one point indicates either known or inferred time span of extension or, where dating is insufficient, the time frame within which extension is possible. Compiled from many sources including information contained or cited in the following: Shafiqullah et al. (1980); Chamberlin (1983); Glazner and Bartley (1984); Stevens and Stevens (1985); Taylor et al. (1989); Gans et al. (1989); Stock and Hodges (1989); Armstrong and Ward (1991); Seedorff (1991); Axen et al. (1993); Stewart and Roldán-Quintana (1994); Duebendorfer and Simpson (1994). Isopleths show generalized ages (in Ma) of major extensional detachment faults and/or ages of 25° or more of stratal tilting of Cenozoic strata.

the same structural event. The inferred ages of initiation of basin and range structure shown in Figure 6 range from older than 20 Ma in relatively interior parts of North America to younger than 10 Ma in western Nevada, eastern California, and western Mexico. The time of major movement on basin and range block structures, however, may be significantly younger locally than the time of initial movement. This relation is suggested by the younger age of some grabens in comparison to the inferred time of initial movement (Fig. 6). Basin and range block faulting largely ceased in the Sonoran Desert region of Arizona and Sonora and the Mojave Desert region of California in the latest Cenozoic (about 6 m.y. ago) (Dickinson, 1991; Stewart and Roldán-Quintana, 1994).

In general, the inferred time of development of initial basin and range block-fault structures in the eastern part of the Basin and Range province (Fig. 6) overlaps the time of development of large-magnitude extensional structures in the western part of the province (Fig. 5), although basin and range block faulting char-



EXPLANATION

12 Age (Ma) of change from compositionally diverse (andesite-rhyolite) magmatism to basaltic or bimodal magmatism. Less than (<) or greater than (>) symbols used when exact age is uncertain but probably within a few million years of age indicated.

8-3 Age (Ma) of major movement on basin and range block structures based on structural and /or stratigraphic data. Less than (<) or greater than (>) symbols used where age is uncertain but less than or more than, respectively, of amount indicated. Plus and minus (±) symbol used to indicated age of main part of major basin-fill sedimentary succession related to basin-and-range extension.

—10— Generalized isopleth of age (Ma) at change in magmatism from compositionally diverse (andesite-rhyolite) to basaltic or bimodal basalt-rhyolite volcanism, and/or oldest age of basin and range block faulting based on structural or stratigraphic data. Inferred to indicate time of initial development of basin and range block structures.

Figure 6. Ages (in Ma) of major movement on basin and range block structures and of the change from compositionally diverse (andesite-rhyolite) magmatism to basaltic or bimodal magmatism. Isopleths are inferred to indicate time of initiation of basin and range block faulting. See text for description of uncertainty of interpreting style and age of deformation. Compiled from many sources including information contained or cited in the following: Christiansen and Lipman (1972); Eberly and Stanley (1978); Scarborough and Peirce (1978); Anderson and Mehnert (1979); Shafiqullah et al. (1980); Seager et al. (1984); Henry and Price (1986); Cameron et al. (1989); Dickinson (1991); Walker and MacLeod (1991); Henry and Aranda-Gómez (1992); Christiansen and Yeats (1992); Rowley et al. (1992); Miller (1993); Moore et al. (1994); John et al. (1993, 1994).

acteristically follows large-magnitude extension in any one area. The diachronous character of both large-magnitude extension and basin and range block faulting suggests that, as large-magnitude extension progressed generally southwestward across western North America, it was replaced by basin and range block faulting, except in Washington, Canada, and northern Idaho. Structures produced by large-magnitude extension were overprinted by structures produced by lesser extension, suggesting a decrease in extension with time in any particular area.

The decrease in magnitude of extension through time is also suggested by the decrease in amount of tilting of stratified units with time (Fig. 7). In Figure 7, vertical lines indicate times of no stratal tilting, and horizontal, or slightly inclined lines, indicate times of rapid stratal rotation. Only areas of large stratal tilting are shown. Some areas relatively close to those shown may exhibit only minor stratal rotation. The diagrams illustrate that in most areas major stratal tilting occurs in a relatively short period of time, generally only a few million years, and that the time of major rotation varies from area to area. The times of significant tilting correspond to known or inferred times of moderate- to large-magnitude extension and are followed by a time of minor rotation and extension corresponding generally to the time of development of basin and range blocks.

Morgan et al. (1986) related high-strain rates to a high geotherm that resulted in a shallow crustal brittle-ductile transition, negligible mantle strength, and a decollement near the brittle-ductile transition zone. They related low-strain rates to lithospheric cooling, a deeper brittle-ductile transition, and relatively high mantle strength.

AGE OF TILT DOMAINS

The age of the tilt domains is difficult to date directly, but initial development is presumed to correspond to times of early extension in the southern part of the Basin and Range province and mostly to young extension in the northern part. The pattern of northwest-trending anticlinal and synclinal tilt-domain boundaries in Mexico, Arizona, eastern California, and locally in westernmost Nevada is considered to represent an older phase of tilt development because the tilt patterns can be related directly to extensional structures dated as 15 to 25 Ma. Extension directions during the older phase of tilt development are considered to be mainly west-southwest (Zoback et al., 1981; Henry et al., 1991; Henry and Aranda-Gómez, 1992). A younger age for the north-northeast trend of anticlinal and synclinal boundaries in Nevada, Utah, Oregon, and Idaho is inferred from the young age of many of the structures, such as tilted basin and range blocks that define the tilt pattern. These blocks are generally younger than 20 Ma and, commonly, younger than 10 Ma. The older northwest pattern of tilting may have originally characterized parts of the northern part the Basin and Range province, but this northwest pattern has been largely overprinted by the now-dominant north-northeast pattern (Stewart and Roldán-Quintana, 1994). Sparse northwest- or north-northwest–trending anticlinal and synclinal boundaries in western and southern Nevada (Stewart et al., this volume) may be remnants of this older pattern of tilt domains. The young age of the tilt patterns in Nevada is also indicated by a correlation between transverse tilt-domain boundaries and patterns of late Quaternary faulting (Thenhaus and Barnhard, this volume). A young age for the north-northeast–trending anticlinal and synclinal boundaries in the northern part of the Basin and Range province is compatible with evidence that the extension direction in this region changed about 10 m.y. ago from west-southwest to west-northwest (Zoback et al., 1981).

SCALE OF BASIN AND RANGE BLOCKS AND TILT DOMAINS

Basin and range blocks and extensional tilt domains form at distinctly different scales (Figs. 3 and 4). Basin and range blocks are generally about 30 km in width as measured from the crest of one mountain range to the crest of an adjacent mountain range (Fletcher and Hallet, 1983) or from the midline of a valley graben or half graben to the midline of the adjacent valley graben or half graben (Fig. 3). Tilt domains are not as regular in shape or as clearly defined as basin and range blocks. Individual tilt domains generally range in width from 50 to 200 km, but distances of twice those amounts result from measurements between boundaries of similar type (anticlinal to anticlinal, or synclinal to synclinal), a spacing analogous to measuring the distance between structures of similar type in basin and range blocks (the crest to crest spacing). The scale of basin and range blocks was considered by Fletcher and Hallet (1983), Froidevaux (1986), and Zuber et al. (1986) to be related to the scale of stretching boudinage or necking in the upper crust, whereas the scale of tilt domains is related to the scale of boudinage of a thick mantle lithospheric layer (Froidevaux, 1986) or a thick stratified mantle and crust that consists of a strong upper crust and mantle and a weak, lower crust (Zuber et al., 1986).

WESTERN MARGIN OF THE BASIN AND RANGE PROVINCE

The western margin of the Basin and Range province is an important structural and volcanic boundary in the western United States. It separates areas to the east, characterized by moderate to extreme extension and tilting, from areas to the west, characterized by the relatively untilted and unextended Mesozoic batholithic masses of the Sierra Nevada in eastern California and Peninsular California (southernmost California and Baja California, Mexico). The western margin is also the boundary toward which the ages of large-scale extension (Fig. 5) and of basin and range block faulting (Fig. 6) decrease. The youngest ages of both large-scale extension and basin and range structure are near the western margin of the Basin and Range province.

Topographically, the western margin of the Basin and Range province in western Nevada and eastern California is an impressive escarpment along the east side of the Sierra Nevada. The

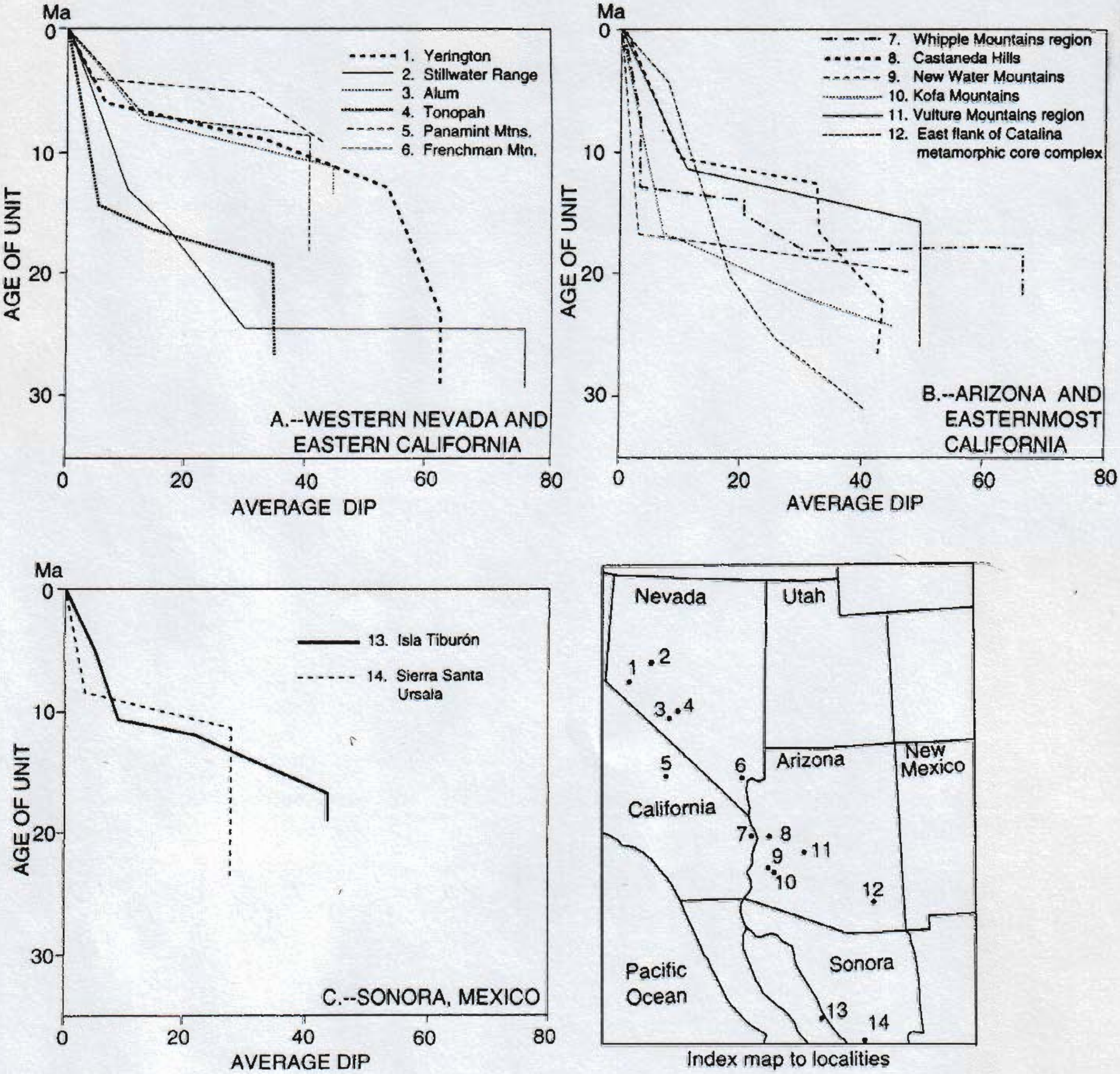


Figure 7. Tilt versus age diagram for (A) western Nevada and eastern California, (B) Arizona and easternmost California, and (C) Sonora, Mexico. Data for Yerington (1) are from Dilles and Gans (1993), for Stillwater Range (2) are from D. A. John (1994, oral commun.) and Dilles and Gans (1993), for Alum (3) are from Moiola (1969) and Stewart and Diamond (1990), for Tonopah (4) are from Bonham and Garside (1979), for Panamint Mountains (5) are from Hodges et al. (1990), for Frenchman Mountain (6) are from Duebendorfer and Simpson (1994), for Whipple Mountains region (7) are from Nielson and Beratan (1990), for Castaneda Hills (8) are from Lucchitta and Suneson (1993), for New Water Mountains (9) are from Shafiqullah et al. (1980) and Miller (1970), for Kofa Mountain (10) are from Shafiqullah et al. (1980), for Vulture Mountains (11) are from Rehrig et al. (1980), for east flank of Catalina metamorphic core complex (12) are from Dickinson (1991), for Isla Tiburón (13) are from Neuhaus et al. (1988), and for Sierra Santa Ursala (14) are from Mora-Alvarez (1992). Index map shows localities.

escarpment is locally as high as 3,000 m, and a quarter of the plift that produced this escarpment has occurred in the past 3 .y. (Huber, 1981). A remarkably similar escarpment (the Main Gulf escarpment) marks the western limit of extension along the eastern side of Peninsular California (southernmost California and Baja California) west of the transform system of the Gulf of California (Gastil et al., 1975; Stock et al., 1991). The boundary is less-well defined in southern California, where it has been disrupted by late Cenozoic strike-slip faulting. In places in southern California, the boundary corresponds with the trace of the San Andreas fault.

A zone of strike-slip faulting, associated in places with areas of greater than typical extension, parallels the western margin of the Basin and Range province (Fig. 8). In the Great Basin region of western Nevada and eastern California, this zone is the Walker Lane belt (Stewart, 1988, 1992a; Oldow, 1992), which is characterized by northwest-striking right-lateral faults and northeast-striking left-lateral faults. The oldest dated movement on these strike-slip faults is about 24 to 22 Ma (Ekren and Byers, 1984; Hardyman and Oldow, 1991; Dilles and Gans, 1995), and the youngest is historic (Gianella and Callaghan, 1934; Slemmons et al., 1979). In the Mojave Desert region, the strike-slip faulting forms the Eastern California shear zone, characterized by northwest-striking right-lateral faults and east- or northeast-striking left-lateral faults (Dokka, 1983; Dokka and Travis, 1990a, 1990b; Dokka et al., 1991). Movement on the Eastern California shear zone occurred mainly between 10 and 6 Ma (Dokka et al., 1991). The Eastern California shear zone is on line with the Walker Lane belt and with the transform faults of the Gulf of California. Transform faults in the Gulf of California postdate most of the strike-slip faulting elsewhere along the western margin of the Basin and Range province. However, the Gulf of California had an earlier history of extension that produced a proto-gulf in the Miocene, and strike-slip faulting is regarded as permissive during the devel-

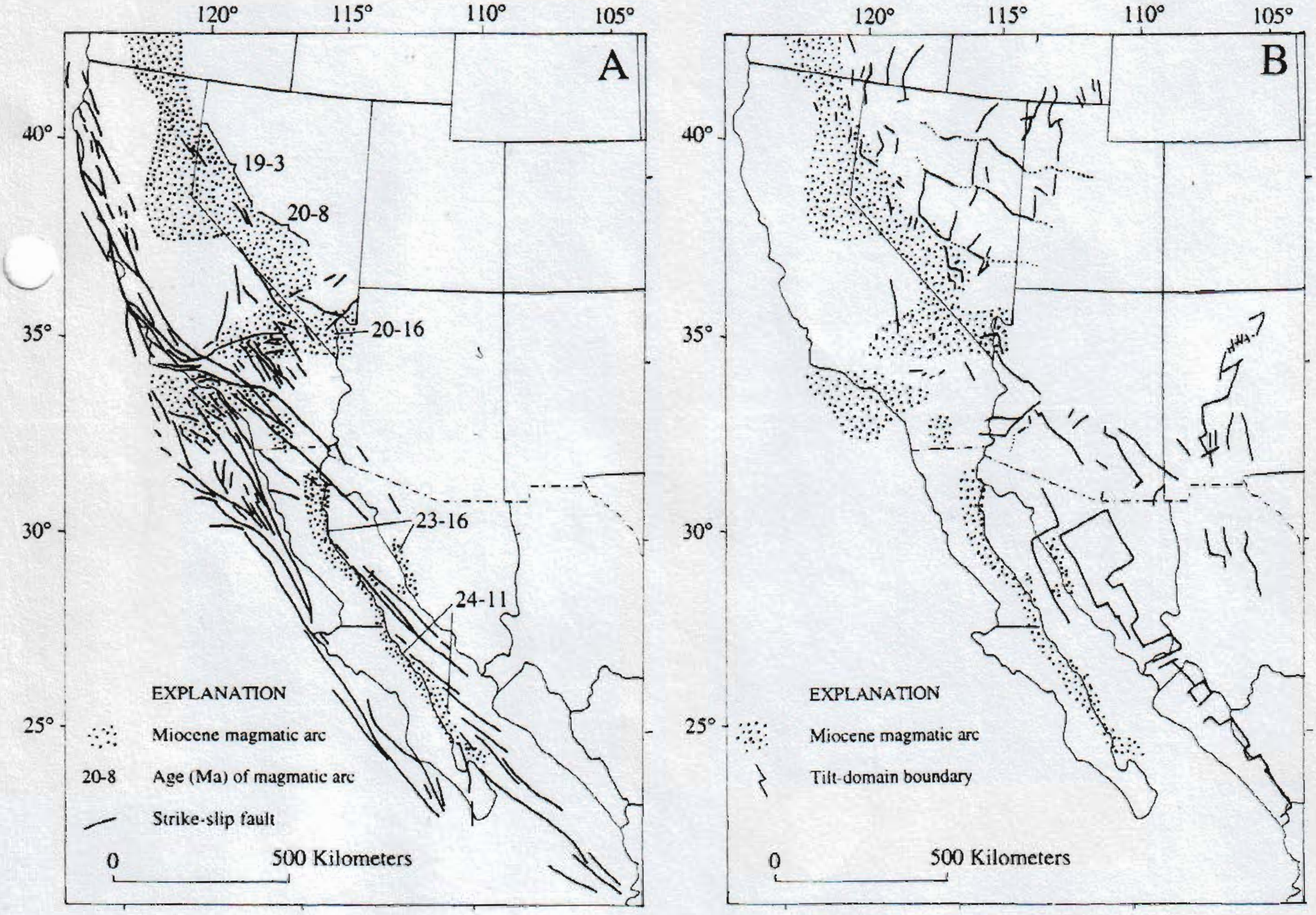


Figure 8. A: Relation of Miocene magmatic arc and strike-slip faults. Numbers are generalized ages of the arc (in Ma). B: Relation of Miocene magmatic arc to tilt-domain boundaries (accommodation zones). Distribution and generalized age of Miocene magmatic arc are after Christiansen and Yeats (1992) and Sawlan (1991).

opment of the proto-gulf, according to Stock and Hodges (1989). In addition, northwest-striking faults in western Sonora have been considered to be strike slip (Gastil and Krummenacher, 1978) and may have developed during the development of the proto-gulf.

The western boundary of the Basin and Range province is along or near the trace of a Miocene continental-margin magmatic arc (Fig. 8). This arc is delineated on the basis of generally thick, predominantly andesitic to dacitic calc-alkalic lavas, volcanic breccias (lahars), and small intrusive bodies formed predominantly in stratovolcanoes (Christiansen and Yeats, 1992; Sawlan, 1991). These rocks are related to continental margin subduction, whereas more inland volcanic rocks occur in settings that suggest other factors as dominant influences in their formation (e.g., intracratonic extension, Wernicke et al., 1987; Christiansen and Yeats, 1992). Lipman et al. (1972) and Lipman (1980), however, related these inland rocks to subduction. The Miocene continental margin arc is analogous to the present-day Cascade volcanic arc, which extends along the Pacific margin of North America from British Columbia to northern California inland of the convergent margin between the Juan de Fuca plate and the North American plate. The Miocene continental margin magmatic arc can be traced along the western margin of the Basin and Range province from Oregon to Baja California (Fig. 8) (Christiansen and Yeats, 1992; Sawlan, 1991). The arc initially developed from 24 to 20 Ma in response to the subduction of parts of the Farallon-Vancouver plate at the same time as the early development of the San Andreas transform system (Atwater, 1970; Engebretson et al., 1985; Severinghaus and Atwater, 1990). Prior to that time, a well-defined arc is recognizable in Washington, Oregon, and northern California, but farther south volcanism was spread out in broad magmatic belts without a distinct arc system. With the progressive change of the North American plate margin from a subduction zone to a transform margin, the arc died out over a zone that extended through time both to the north and south as the length of contact between the Pacific and North American plates increased (Snyder et al., 1976; Sawlan, 1991).

The Miocene magmatic arc overlapped in time with much of the extension and strike-slip faulting that occurred in the western part of the Basin and Range province. That extension can thus be interpreted as back-arc extension. The interrelation of the arc and the extension is evident from the parallelism of the arc and the inland anticlinal and synclinal tilt-domain boundaries in the southern part of the Basin and Range province (Fig. 8). The somewhat oblique trend of anticlinal and synclinal tilt-domain boundaries to the arc in the northern part of the Basin and Range province is probably due to a younger age of the tilt domains there. A correspondence of the area of the Miocene magmatic arc with strike-slip faulting is also evident. In the Basin and Range province, strike-slip faults are within, or a short distance east of, the Miocene magmatic arc. The strike-slip faulting can be related to a subduction zone that, as outlined by Engebretson et al. (1985), was obliquely convergent. Such oblique convergence commonly is associated with inland strike-slip faults along magmatic arcs (Fitch, 1972; Beck, 1983; Jarrard, 1986; McCaffrey, 1992).

Prior to the development of much of the San Andreas fault system, intra-arc or back-arc strike-slip faulting may have been continuous along the Walker Lane belt, the Eastern California shear zone, and the interpreted zone of strike-slip faulting in the proto-Gulf of California mentioned above. The younger transform faults in the Gulf of California and related faults of the San Andreas fault system, which resulted in part from an inland shift in the position of the transform boundary between the Pacific and North American plates, appear to follow this interpreted early zone of strike-slip faulting as far north as southern California, where the San Andreas fault system cuts across the arc in the area of the Big Bend of the San Andreas fault (Stewart, 1992a). The transform boundary might conceivably shift inland again, and the Walker Lane belt would then be the boundary between the Pacific and North American plates. Such a possible inland shift of movement is suggested by the distribution of earthquakes remotely triggered by the magnitude 7.3 Landers, California, earthquake (Hill et al., 1993). These earthquakes extend from near the San Andreas fault in southern California northward along the Walker Lane belt, following a path that might be expected if the transform boundary is establishing a new inland position.

DISCUSSION

The pattern of westward or southwestward younging of middle and late Cenozoic large-magnitude extension described here is crudely similar to the westward or southwestward sweep of middle and late Cenozoic igneous activity in the western United States and Mexico (Coney and Reynolds, 1977; Christiansen and Yeats, 1992; Burchfiel et al., 1992, Fig. 16). This westward or southwestward sweep in igneous activity was related by Coney and Reynolds (1977) to a progressive steepening of a subducting slab and the related westward migration of the accompanying igneous activity. Alternatively, Wernicke et al. (1987) related inland volcanism to intracratonic extension unrelated to plate-margin processes. In many areas, large-magnitude extension and, presumably, the initial development of some of the tilt domains overlaps in time, or shortly follows, major igneous activity (Gans et al., 1989) or possibly occurs during times of high heat flow, with or without surface igneous activity. Basin and range block faulting, as outlined previously, appears to follow development of structures related to large-magnitude extension and, thus, follows this time of major igneous activity or high heat flow. In this view, high strain rates are associated with the times of major igneous activity or high heat flow, and basin and range structure follows diachronously during times of lesser strain and generally lower igneous activity or heat flow. The actual geologic relations are clearly much more complex than this simplified time sequence because (1) time-space patterns of extension and igneous activity are complex, (2) times of extension and igneous activity may not correlate, (3) some areas of widespread igneous rocks are unextended, and (4) some extended areas are not associated with surface igneous activity.

The pattern of tilt-domain boundaries appears to be related to the plate-tectonic configuration of western North America, specifically to the positions of subduction zones and transform boundaries (Fig. 9, A and B). The tilt-domain boundaries can be viewed as extension-related structures in a back-arc setting associated with outward movement and extension of large segments of western North America away from the stable interior and toward a convergent margin. As a corollary to this interpretation, the location of the extended Basin and Range province inland of the approaching spreading centers that separated the Pacific and Farallon plates (Engebretson et al., 1985) may be related to the subduction of young hot crust beneath the Basin and Range. As outlined previously, the northwest-trending anticlinal and synclinal tilt-domain boundaries in Mexico and Arizona, and perhaps sparse northwest-trending boundaries in western Nevada, are probably older than the generally north-northeast trends of the boundaries in Nevada, Utah, Oregon, and Idaho. If so, the northwest-trending boundaries developed parallel to an older convergent margin along the western margin of North America (Fig. 9A), mostly south of the developing San Andreas transform boundary between the Pacific and North American plates, where young hot crust was being subducted. The northwest-trending boundaries, in the interpretation presented here, formed by the southwestward back-arc movement of a large region of Mexico and Arizona toward a convergent margin that was west of northern Mexico. The younger and contrasting north-northeast–trending boundaries in Nevada, Utah, Oregon, and Idaho are interpreted to be related to the west-northwest back-arc extension and movement of Nevada, Utah, Oregon, and Idaho away from a stable North America, and toward a convergent margin in northernmost California and areas farther north, where at that time young hot crust was being subducted (Fig. 9B). Extension in the Mexican volcanic belt is here related to a convergent margin that existed between the Cocos and North American plates (Fig. 9B). Young intra-arc extensional faulting inland of the convergent margin produced the Colima and Chapala grabens. These grabens form an orthogonal pattern interpreted by Allan (1986) to be a rift-rift-rift triple junction. Nevertheless, the west-northwest–trending Chapala graben and related extensional structures in the Mexican volcanic belt extend subparallel to the subduction

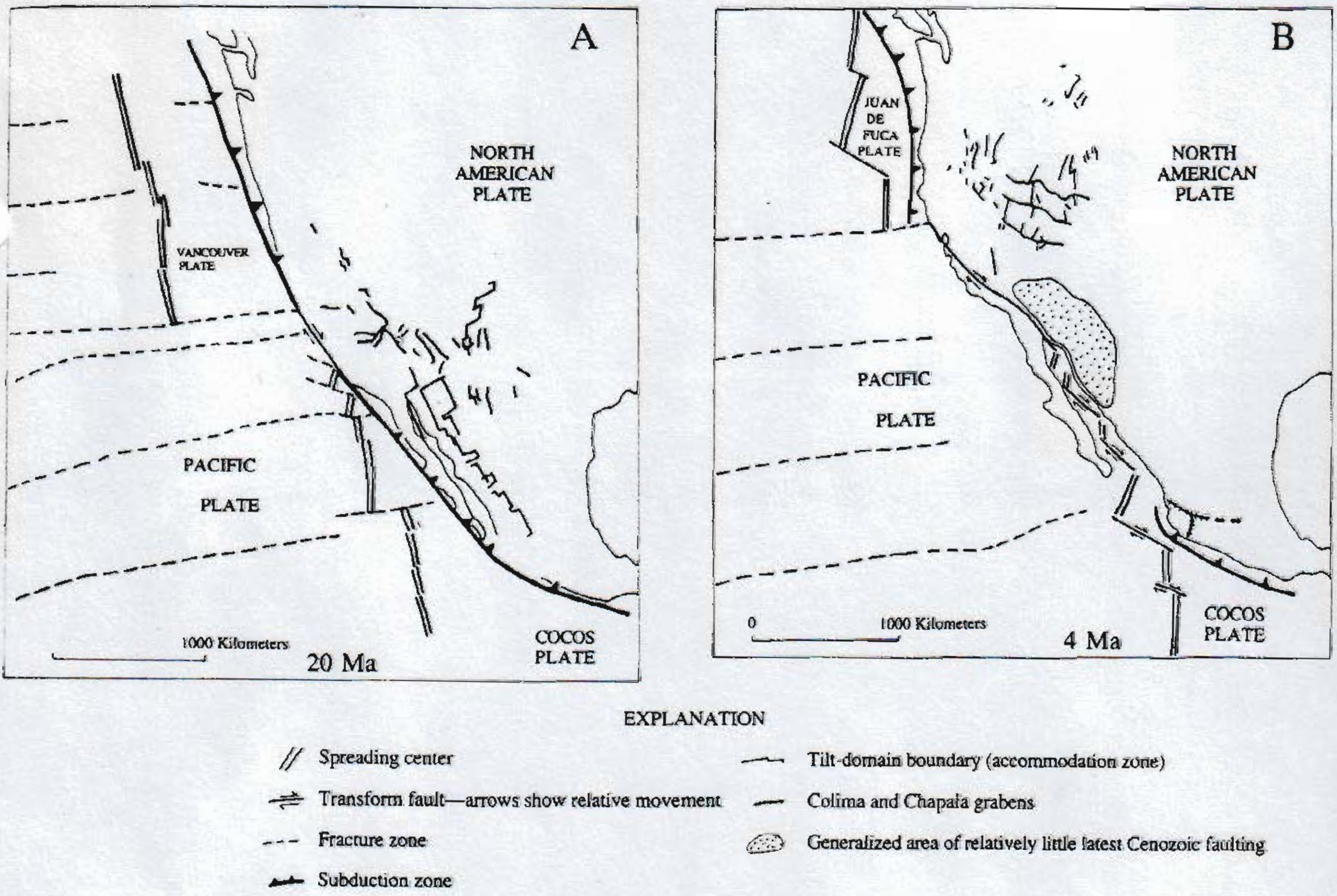


Figure 9. Relation of accommodation zones (tilt-domain boundaries) and major plate boundaries in the middle Cenozoic (A) and latest Cenozoic (B). Plate configuration for A is at 20 Ma and for B is at 4 Ma. The ages of the tilt-domain boundaries are not known exactly, and parts of them could be significantly older or younger than the ages of the plate boundaries shown. Plate boundaries are after Severinghaus and Atwater (1990) and Engebretson et al. (1985).

zone for about 500 km, supporting the view that the position of the convergent margin may be critical in localizing regions of extension in the western part of North America.

During latest Cenozoic time, little basin and range block faulting has occurred in the Sonoran Desert region of Sonora and Arizona and the Mojave Desert region of California. This spatial relation of little extension inland of the oldest segment of the San Andreas transform system suggests that with time the transform system inhibits inland basin and range extension.

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REFERENCES CITED

Aguirre-Díaz, G., and McDowell, F. W., 1993, Nature and timing of faulting and synextensional magmatism in the southern Basin and Range, central-eastern Durango, Mexico: Geological Society of America Bulletin, v. 105, p. 1435–1444.

Aiken, J. L., and Kistler, R. B., 1992, General geology of the Magdalena basin, Sonora, Mexico, *in* Clark, K. F., Roldán-Quintana, J., and Schmidt, R. H., eds., Geology and mineral resources of northern Sierra Madre Occidental, Mexico, Guidebook for the 1992 Field Conference: El Paso, Texas, El Paso Geological Society, p. 367–376.

Albers, J. P., 1967, Belt of sigmoidal bending and right-lateral faulting in the western Great Basin: Geological Society of America Bulletin, v. 78, p. 143–156.

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, J. J., Rowley, P. D., Fleck, R. J., and Nairn, A. E. M., 1975, Cenozoic geology of southwestern High Plateaus of Utah: Geological Society of America Special Paper 160, 88 p.

Anderson, R. E., 1971, Thin skin distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, p. 43–58.

Anderson, R. E., and Mehnert, H. H., 1979, Reinterpretation of the history of the Hurricane fault in Utah, *in* Newman, G. W., and Goode, H. D., eds., Basin and Range symposium and Great Basin field conference: Denver, Colorado, Rocky Mountain Association of Geologists and Utah Geological Association, p. 145–165.

Anderson, R. E., Longwell, C. R., Armstrong, R. L., and Marvin, R. F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, v. 83, p. 273–288.

Anderson, R. E., Zoback, M. L., and Thompson, G. A., 1983, Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range province: Geological Society of America Bulletin, v. 95, p. 1055–1072.

Anderson, T. H., and Schmidt, V. A., 1983, The evolution of middle America and the Gulf of Mexico–Caribbean Sea region during Mesozoic time: Geological Society of America Bulletin, v. 94, p. 941–966.

Anderson, T. H., Silver, L. T., and Salas, G. A., 1980, Distribution and U-Pb isotopic ages of some lineated plutons, northwestern Mexico, *in* Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 269–283.

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.

Aranda-Gómez, J. J., 1989, Geología preliminar del graben de Aguacalientes: Universidad Nacional Autónoma de México, Instituto de Geología Revista, v. 8, p. 22–32.

Aranda-Gómez, J. J., Aranda-Gómez, J. M., and Nieto-Samaniego, A. R., 1989, Consideraciones acerca de la evolución tectonica durante el Cenozoico de la Sierra de Guanajuato y la porción meridional de la Meseta Central, México: Universidad Nacional Autónoma de México, Instituto de Geología Revista, v. 8, p. 33–46.

Armstrong, R. L., and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, no. B8, p. 13201–13224.

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.

Axen, G., 1995, Extensional segmentation of the Main Gulf Escarpment, Mexico and United States: Geology, v. 23, p. 515–518.

Axen, G. J., Taylor, W. J., and Bartley, J. M., 1993, Space-time patterns and tectonic controls of Tertiary extension and magmatism in the Great Basin of the western United States: Geological Society of America Bulletin v. 105, p. 56–76.

Baldridge, W. S., Damon, P. E., Shafiqullah, M., and Bridwell, R. J., 1980, Evolution of the central Rio Grande rift, New Mexico—New potassium-argon ages: Earth and Planetary Science Letters, v. 51, p. 309–321.

Baldridge, W. S., Olsen, K. H., and Callender, J. F., 1984, Rio Grande rift—problems and perspectives, *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., eds., Rio Grande rift—northern New Mexico: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 1–12.

Barnosky, A. D., Schmidt, V. A., Zheng, J., and Nichols, R., 1993, Dating the onset of Miocene crustal extension in southwest Montana, northwest Wyoming, and adjacent Idaho: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 6.

Barrientos, S. E., Stein, R. S., and Ward, S. N., 1987, Comparison of the 1959 Hebgen Lake, Montana, and the 1983 Borah Peak, Idaho, earthquakes from geodetic observations: Seismological Society of America Bulletin, v. 77, p. 784–808 (errata, 1989, v. 77, p. 2018).

Bartley, J. M., and Glazner, A. F., 1991, En echelon Miocene rifting in the southwestern United States and model for vertical-axis rotation in continental extension: Geology, v. 19, p. 1165–1168.

Bartley, J. M., Fletcher, J. M., and Glazner, A. F., 1990, Tertiary extension and contraction of lower-plate rocks in the central Mojave metamorphic core complex, southern California: Tectonics, v. 9, p. 521–534.

Bartolini, J. R., 1992, Modified Basin and Range topography in the Bolson de Mapimi, Durango and Chihuahua, Mexico: Texas Journal of Science, v. 44, p. 295–300.

Beck, M. E., Jr., 1983, On the mechanism of tectonic transport of oblique subduction: Tectonophysics, v. 93, p.1–11.

Best, M. G., and Brimhall, W. H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, p. 1677–1690.

Best, M. G., and Hamblin, W. K., 1978, Origin of the northern Basin and Range province: Implications from the geology of its eastern boundary, *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. 313–340.

Blank, H. R., and Kucks, R. P., 1989, Preliminary aeromagnetic, gravity, and generalized geologic maps of the USGS Basin and Range–Colorado Plateau transition zone study area in southwestern Utah, southeastern Nevada, and northwestern Arizona (the "BARCO" project): U.S. Geological Survey Open-File Report 89-432, 26 p.

Bonham, H. F., Jr., and Garside, L. J., 1979, Geology of the Tonopah, Lone Mountain, Klondike, and northern Mud Lake quadrangles, Nevada: Nevada Bureau of Mines and Geology Bulletin 92, 136 p.

Bosworth, W., 1985, Geometry of propagating continental rifts: Nature, v. 316, p. 625–627.

Brogan, G. E., Kellogg, K. S., Slemmons, D. B., and Terhune, C. L., 1991, Late Quaternary faulting along the Death Valley–Furnace Creek fault system, California and Nevada: U.S. Geological Survey Bulletin 1991, 23 p.

Burchfiel, B. C., Hodges, K. V., and Royden, L. H., 1987, Geology of Panamint Valley–Saline Valley pull-apart system, California; palinspastic evidence for low-angle geometry of Neogene range-bounding fault: Journal of Geophysical Research, v. 92, p. 10422–10426.

Burchfiel, B. C., Cowan, D. S., and Davis, G. A., 1992, Tectonic overview of the Cordilleran orogen in the western United States, *in* Burchfiel, B. C., Lipman, P. W., and Zoback, M. L., eds., The Cordilleran orogen—Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 407–479.

Cameron, K. L., Nimz, G. J., and Kuentz, D., 1989, Southern Cordilleran basaltic andesite suite, southern Chihuahua, Mexico: A link between Tertiary continental arc and flood basalt magmatism in North America: Journal of Geophysical Research, v. 94, no. B6, p. 7817–7840.

Centeno-Garcia, E., Ortega-Gutierrez, F., and Corona-Esquivel, R., 1990, Oaxaca fault: Cenozoic reactivation of the suture between the Zapoteco and Cuicateco terranes, southern Mexico: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 13.

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

Chapin, C. E., 1979, Evolution of the Rio Grande rift—a summary, *in* Riecker, R. E., ed., The Rio Grande rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 1–5.

Chapin, C. E., 1989, Volcanism along the Socorro accommodation zone, Rio Grande rift, New Mexico, *in* Chapin, C. E., and Zidek, J., eds., Field Excursions to volcanic terranes in the western United States, southern Rocky Mountains region: New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 46–57.

pin, C. E., and Cather, S. M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G. R., and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 5–25.

Chapin, C. E., and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas, *in* Seager, W. R., Clemens, R. E., and Callender, J. F., eds., Guidebook of the Las Cruces country: New Mexico Geological Society, 26th Field Conference Guidebook, p. 297–321.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States; Part II, late Cenozoic: Royal Society of London Philosophical Transactions, ser. A, v. 271, p. 249–284.

Christiansen, R. L., and Yeats, R. S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B. C., Lipman, P. W., and Zoback, M. L., eds., The Cordilleran orogen—Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 261–406.

Clark, M. M., Harms, K. K., Lienkaemper, J. J., Harwood, D. S., Lajoie, K. R., Matti, J. C., Perkins, J. A., Rymer, M. J., Sarna-Wojcicki, A. M., Sharp, R. V., Sims, J. D., Tingsley, J. C., III, and Ziony, J. I., 1984, Preliminary slip-rate table and map of late Quaternary faults of California: U.S. Geological Survey Open-File Report OF 84-106, scale 1:1,000,000.

Colleta, B., and Angelier, J., 1983, Tectonique cassante du Nord-Ouest Mexicain et ouverture du Golfe de Californie (Fault tectonics in northwestern Mexico and opening of the Gulf of California): Bulletin du Centre de Recherches et exploration-production Elf-Aquitaine, v. 7, no. 1, p. 433–441.

Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406.

Constenius, K. N., 1982, Relationship between the Kishenehn basin, and the Flathead listric normal fault system and Lewis thrust salient, *in* Powers, R. B., ed., Geologic studies of the Cordilleran thrust belt, Volume 2: Denver, Colorado, Rocky Mountain Association of Geologists, p. 817–830.

Constenius, K. N., and Dyni, J. R., 1983, Lacustrine oil shales and stratigraphy of part of the Kishsenehn basin, northwestern Montana: Colorado School of Mines Mineral and Energy Resources Bulletin, v. 26, no. 4, p. 1–8.

Córdoba, D. A., and Silva-Mora, L., 1989, Marco geológico del área de Revolución-Puerta de Cabrera, Estado de Durango: Universidad Nacional Autónoma de México, Instituto de Geología Revista, v. 8, p. 111–122.

Covington, H. R., 1983, Structural evolution of the Raft River basin, Idaho, *in* Miller, D. M., Todd, V. R., and Howard, K. A., eds., Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 229–237.

Crone, A. J., and Machette, M. N., 1984, Surface faulting accompanying the Borah Peak earthquake, central Idaho: Geology, v. 121, p. 664–667.

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

Davis, G. A., and Lister, G. S., 1988, Detachment faulting in continental extension: Perspectives from the southwestern U.S. Cordillera, *in* Clark, S. P., Jr., ed., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 133–159.

Davis, G. H., 1980, Structural characteristics of metamorphic core complexes, southern Arizona, *in* Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 35–77.

de Voogd, B. D., Serpa, L., and Brown, L., 1988, Crustal extension and magmatic processes—COCORP profiles from Death Valley and the Rio Grande rift: Geological Society of America Bulletin, v. 100, p. 1550–1567.

Dickinson, W. R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America Special Paper 264, 106 p.

Dickinson, W. R., Goodlin, T. C., Grover, J. A., and Mark, R. A., 1987, Low-angle normal-fault system along the range front of the southwestern Galiuro Mountains in southeastern Arizona: Geology, v. 15, p. 727–730.

Dilles, J. H., and Gans, P. B., 1993, ^{40}Ar/^{39}Ar geochronology of Cenozoic magmatism and faulting, Yerington and northern Wassuk Range, Nevada: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 30.

Dilles, J. H., and Gans, P. B., 1995, The chronology of Cenozoic volcanism and deformation in the Yerington area, western Basin-and-Range and Walker Lane: Geological Society of America Bulletin, v. 107, p. 474–486.

Dohrenwend, J. C., Schell, B. A., Menges, C. M., Moring, B. C., and McKittrick, M. A., 1996, Reconnaissance photogeologic map of young (Quaternary and Late Tertiary) faults, *in* Singer, D. A., ed., An analysis of Nevada's metal-bearing mineral resources: Nevada Bureau of Mines and Geology Open-File Report 96-2, p. 9-1–9-12, plate 9-1, scale 1:1,000,000.

Dokka, R. K., 1983, Displacements on late Cenozoic strike-slip faults of the central Mojave Desert, California: Geology, v. 11, p. 305–308.

Dokka, R. K., 1986, Patterns and modes of early Miocene crustal extension, central Mojave Desert, California, *in* Mayer, L., ed., Extensional tectonics of the southwestern United States—a perspective on processes and kinematics: Geological Society of America Special Paper 208, p. 75–95.

Dokka, R. K., 1989, The Mojave extensional belt of southern California: Tectonics, v. 8, p. 363–390.

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.

Dokka, R. K., and Travis, C. J., 1990a, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, p. 311–340.

Dokka, R. K., and Travis, C. J., 1990b, Role of the eastern California shear zone in accommodating Pacific–North American plate motion: Geophysical Research Letters, v. 17, p. 1323–1326.

Dokka, R. K., Henry, D. J., Ross, T. M., Baksi, A. K., Lambert, J., Travis, C. J., Jones, S. M., Jacobson, C., McCurdy, M. M., Woodburne, M. O., and Ford, J. P., 1991, Aspects of the Mesozoic and Cenozoic geologic evolution of the Mojave Desert, *in* Walamender, M. J., and Hanan, B. B., eds., Geologic excursions in southern California and Mexico (Geological Society of America Annual Meeting Guidebook): San Diego, California, San Diego State University, Department of Geological Sciences, p. 1–43.

Duebendorfer, E. M., and Simpson, D. A., 1994, Kinematics and timing of Tertiary extension in the western Lake Mead region, Nevada: Geological Society of America Bulletin, v. 106, p. 1057–1073.

Duex, T. W., 1983, Geology, geochemistry, and geochronology of volcanic rocks between Cuauhtemoc and La Junta, central Chihuahua, Mexico [Ph.D. thesis]: Austin, University of Texas, 176 p.

Eaton, G. P., 1986, A tectonic redefinition of the southern Rocky Mountains: Tectonophysics, v. 132, p. 163–193.

Eaton, G. P., 1987, Topography and origin of the southern Rocky Mountains and Alvarado Ridge, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., 1987, Continental extensional tectonics: Geological Society of London Special Publication 28, p. 355–369.

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.

Effimoff, I., and Pinezich, A. R., 1986, Tertiary structural development of selected basins: Basin and Range province, northeastern Nevada, *in* Mayer, L., ed., Extensional tectonics of the southwestern United States: Geological Society of America Special Paper 208, p. 31–42.

Ekren, E. B., and Byers, F. M., Jr., 1984, The Gabbs Valley Range—A well exposed segment of the Walker Lane in west-central Nevada, *in* Lintz, J., Jr., Western geological excursions, Volume. 4: Reno, Nevada, Mackay School Mines, p. 203–315.

Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates of the Pacific Basin: Geological Society of America Special Paper 206, 59 p.

Faulds, J. E., 1994, New insights on the geometry and kinematics of the Black Mountains–Highland Spring Range accommodation zone (BHZ), Arizona and Nevada: Geological Society of America Abstracts with Programs v. 26, no. 2, p. 51.

Faulds, J. E., Geissman, J. W., and Mawer, C. K., 1990, Structural development of a major extensional accommodation zone in the Basin and Range Province, northwestern Arizona and southern Nevada; Implications for kinematic models of continental extensional, *in* Wernicke, B. P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 37–76.

Faulds, J. E., Feuerbach, D. L., Reagan, M. K., Metcalf, R. V., Gans, P., and Walker, J. D., 1995, The Mount Perkins block, northwestern Arizona: An exposed cross section of an evolving preextensional to synextensional magmatic system: Journal of Geophysical Research, v. 100, p. 15249–15266.

Fenby, S. S., and Gastil, R. G., 1991, Geologic-tectonic map of the Gulf of California and surrounding areas, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The Gulf and Peninsular Province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 79–83, plates 9 and 10, map scale ~1:1,500,000.

Fenneman, N. M., 1928, Physiographic divisions of the United States: Association of American Geographers Annals, v. 18, p. 261–353.

Fenneman, N. M., 1931, Physiography of the western United States: New York, McGraw-Hill Book Company, 534 p.

Ferrusquia, I., and McDowell, F. W., 1988, Time constraints on formation of continental Tertiary basins in the State of Oaxaca, Mexico: Geological Society of America Abstracts with Programs, v. 20, p. 59.

Fitch, T. J., 1972, Plate convergence, transcurrent faults, and internal deformation adjacent to Southwest Asia and the Western Pacific: Journal of Geophysical Research, v. 77, p. 4432–4461.

Fletcher, R. C., and Hallet, B., 1983, Unstable extension of the lithosphere: A mechanical model for basin-and-range structure: Journal of Geophysical Research v. 88, no. B9, p. 7457–7466.

Foster, D. A., Gleadow, A. J. W., Reynolds, S. J., and Fitzgerald, P. G., 1993, Denudation of metamorphic core complexes and the reconstruction of the transition zone, west central Arizona: Constraints from apatite fission track thermochronology: Journal of Geophysical Research, v. 98, no. B2, p. 2167–2185.

Froidevaux, C., 1986, Basin and range large-scale tectonics: Constraints from gravity and reflection seismology: Journal of Geophysical Research, v. 91, p. 3625–3632.

Frost, E. G., and Martin, D. L., editors, 1982, Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, 608 p.

Fuller, R. E., and Waters, A. C., 1929, The nature and origin of the horst and graben structure of southern Oregon: Journal of Geology, v. 37, p. 204–238.

Gans, P. B., Mahood, G. A., and Schermer, E., 1989, Synextensional magmatism in the Basin and Range Province; a case study from the eastern Great Basin: Geological Society of America Special Paper 233, 53 p.

Gastil, G., and Krummenacher, D., 1978, Reconnaissance geologic map of the west-central part of the State of Nayarit, Mexico: Geological Society of America Map and Chart Series, MC-24, scale 1:200,000.

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 Minch, J., 1979, The record of Cenozoic volcanism around the Gulf of California: Geological Society of America Bulletin, part I, v. 90, p. 839–857.

Gianella, V. P., and Callaghan, E., 1934, The earthquake of December 20, 1932, at Cedar Mountain, Nevada, and its bearing on the genesis of Basin Range structure: Journal of Geology, v. 42, p. 1–22.

Gilbert, G. K., 1875, The geology of portions of Nevada, Utah, California, and Arizona, *in* Wheeler, G. M., Report upon geographic and geological explorations and surveys west of the one hundredth meridian, Volume 3, Geology, Part 1: Washington, D.C., U.S. Government Printing Office, p. 21–192.

Gilluly, J., 1928, Basin-Range faulting along the Oquirrh Range, Utah: Geological Society of America Bulletin, v. 39, p. 1103–1130.

Glazner, A. F., and Bartley, J. M., 1984, Time and tectonic setting of Tertiary low-angle normal faulting and associated magmatism in the southwestern United States: Tectonics, v. 3, p. 385–396.

Glazner, A. F., Bartley, J. M., and Walker, J. D., 1989, Magnitude and significance of Miocene crustal extension in the central Mojave Desert, California: Geology, v. 17, p. 50–53.

Golombek, M. P., and Brown, L. L., 1988, Clockwise rotation of the western Mojave Desert: Geology, v. 16, p. 126–130.

Golombek, M. P., McGill, G. E., and Brown, L., 1983, Tectonic and geologic evolution of the Española basin, Rio Grande rift—structure, rate of extension, and relation to the state of stress in the western United States: Tectonophysics, v. 94, p. 483–507.

Gries, J. C., 1979, Problems of delineation of the Rio Grande rift into the Chihuahua tectonic belt of northeastern Mexico, *in* Rieker, R. E., ed., The Rio Grande rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 107–113.

Guth, P. L., 1981, Tertiary extension north of the Las Vegas Valley shear zone, Sheep and Desert Ranges, Clark County, Nevada: Geological Society of America Bulletin, v. 92, part I, p. 763–771.

Hait, M. H., Jr., 1984, Detachment tectonics north of the Snake River Plain, east-central Idaho and southwest Montana: Geological Society of America Abstracts with Programs, v. 16, p. 527.

Hardyman, R. F., and Oldow, J. S., 1991, Tertiary tectonic framework and Cenozoic history of the central Walker Lane, Nevada, *in* Raines, G. L., Lisle, R. E., Schafer, R. W., and Wilkinson, W. H., 1991, Geology and ore deposits of the Great Basin: Reno, Nevada, Geological Society of Nevada, p. 279–301.

Henry, C. D., 1989, Late Cenozoic Basin and Range structure in western Mexico adjacent to the Gulf of California: Geological Society of America Bulletin, v. 101, p. 1147–1156.

Henry, C. D., and Aranda-Gómez, J. J., 1992, The real southern Basin and Range—mid- to late Cenozoic extension in Mexico: Geology, v. 20, p. 701–704.

Henry, C. D., and Fredrikson, G., 1987, Geology of part of southern Sinaloa, Mexico, adjacent to the Gulf of California: Geological Society of America Map and Chart Series MCH063, scale 1:250,000.

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, no. B6, p. 6213–6224.

Henry, C. D., Price, J. G., and McDowell, F. W., 1983, Presence of the Rio Grande rift in west Texas and northern Mexico: Geological Society of America Abstracts with Programs, v. 15, p. 406.

Henry, C. D., Price, J. G., and James, E. W., 1991, Mid-Cenozoic stress evolution and magmatism in the southern Cordillera, Texas and Mexico: Transition from continental arc to interplate extension: Journal of Geophysical Research, v. 96, no. B8, p. 13545–13560.

Hill, D. P., Reasenberg, P. A., Michael, A. J., Arabasz, W. J., Beroza, G. C., Brumbaugh, D. S., Brune, J. N., Castro, R., Davis, S. D., dePolo, D. M., Ellsworth, W. L., Gomberg, J. S., Harmsen, S. C., House, L., Jackson, S. M., Johnston, M. J., Jones, L. M., Keller, R., Malone, S. D., Munguia, L., Nava, S., Pechmann, J. C., Sanford, A. R., Simpson, R. W., Smith, R. B., Stark, M. A., Stickney, M. C., Vidal, A., Walter, S. R., Wong, V., and Zollweg, J. E., 1993, Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake: Science, v. 260, p. 1617–1623

Hintze, L. F., 1975, Geologic highway map of Utah: Brigham Young University Geologic Studies, Special Publication 3, scale 1:1,000,000.

Hodges, K. V., and Applegate, J. D., 1993, Age of Tertiary extension in the Bitterroot metamorphic core complex, Montana and Idaho: Geology, v. 21, p. 161–164.

Hodges, K. V., McKenna, L. W., and Harding, M. B., 1990, Structural unroofing of the central Panamint Mountains, Death Valley region, southeastern California, *in* Wernicke, B. P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 377–390.

Howard, K. A., and John, B. E., 1987, Crustal extension alsong a rooted system of imbricate low angle faults—Colorado River extensional corridor, California and Arizona, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 299–311.

uber, N. K., 1981, Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California—Evidence from the Upper San Joaquin River basin: U.S. Geological Survey Professional Paper 1197, 28 p.

Jachens, R. C., and Moring, B. C., 1990, Maps of the thickness of Cenozoic deposits and the isostatic residual gravity over basement for Nevada: U.S. Geological Survey Open-File Report OF-90-404, scale 1:1,000,000.

Janecke, S. U., 1991, Localized rotation during Paleogene extension in east central Idaho: Paleomagnetic and geologic evidence: Tectonics, v. 10, p. 403–432.

Janecke, S. U., 1994, Sedimentation and paleogeography of an Eocene to Oligocene rift zone, Idaho and Montana: Geological Society of America Bulletin, v. 106, p. 1083–1095.

Jarrard, R. D., 1986, Relations among subduction parameters: Reviews of Geophysics, v. 24, p. 217–284.

John, D. A., Thomason, R. E., and McKee, E. H., 1989, Geology and K-Ar geochronology of the Paradise Peak Mine and the relationship of pre-Basin and Range extension to early Miocene previous metal mineralization in west-central Nevada: Economic Geology, v. 84, p. 631–649.

John, D. A., Stewart, J. H., Kilburn, J. E., Silberling, N. J., and Rowan, L. C., 1993, Geology and mineral resources of the Reno 1° by 2° quadrangle, Nevada and California: U.S. Geological Survey Bulletin 2019, 65 p.

John, D. A., Hudson, M. R., McKee, E. H., and Stewart, J. H., 1994, Multiple periods of late Cenozoic extension in the Paradise and southern Stillwater Ranges, west-central Nevada: Geological Society of America Abstracts with Programs, v. 26, no. 2, p. 62.

Johnson, R. A., and Loy, K. L., 1992, Seismic reflection evidence for seismogenic low-angle faulting in southeastern Arizona: Geology, v. 20, p. 597–600.

Karig, D. E., and Jensky, W. A., 1972, The proto-Gulf of California: Earth and Planetary Science Letters, v. 17, p. 169–174.

Kelley, V. C., 1979, Tectonics, middle Rio Grande rift, New Mexico, *in* Riecker, R. E., ed., The Rio Grande rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 57–70.

Kreps, J., Fritz, W. J., Sears, J. W., and Wampler, J. M., 1992, The 6 Ma Timber Hill basalt flow: Implications for late-Cenozoic drainage systems and the onset of Basin-and-Range style faulting, southwestern Montana: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 22.

Lawrence, R. D., 1976, Strike-slip faulting terminates the Basin and Range Province in Oregon: Geological Society of America Bulletin, v. 87, p. 846–850.

Liggett, M. A., and Childs, J. F., 1977, An application of satellite imagery to mineral exploration, *in* Woll, P. W., and Fischer, W. A., eds., Proceedings of the first annual William T. Pecora Memorial Symposium, October 1975, Sioux Falls, South Dakota: U.S. Geological Survey Professional Paper 1015, p. 253–270.

Lipman, P. W., 1980, Cenozoic volcanism in the western United States; Implications for continental tectonics, *in* Continental tectonics: Washington, D.C., U.S. National Research Council, Geophysical Study Committee, p. 161–174.

Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States; I, Early and middle Cenozoic: Royal Society of London Philosophical Transactions, ser. A., v. 271, p. 217–248.

Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California, *in* Winterer, E. L., Hussong, D. M., and Decker, R. W., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, Geology of North America, v. N, p. 499–521.

Lonsdale, P., 1991, Structural patterns of the Pacific floor offshore of Peninsular California, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The Gulf and Peninsular Province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 87–126.

Lucchitta, I., and Suneson, N. H., 1993, Dips and extension: Geological Society of America Bulletin, v. 105, p. 1346–1356.

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.

Lund, K., and Beard, L. S., 1992, Extensional geometry in the northern Grant Range, east-central Nevada—implications for oil deposits in Railroad Valley, *in* Thorman, C. H., ed., Application of structural geology to mineral and energy resources of the central and western United States: U.S. Geological Survey Bulletin 2012, p. I1–I9.

McCaffrey, R., 1992, Oblique plate convergence, slip vectors, and forearc deformation: Journal of Geophysical Research, v. 97, no. B6, p. 8905–8915.

McFall, C. C., 1968, Reconnaissance geology of the Conception Bay area, Baja California, Mexico: Stanford University Publications, Geological Sciences, v. 10, no. 5, 25 p.

Menges, C. M, and Pearthree, P. A., 1989, Late Cenozoic tectonism in Arizona and its impact on regional landscape evolution, *in* Jenny, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 649–680.

Meyer, J., and Foland, K. A., 1991, Magmatic-tectonic interaction during early Rio Grande rift extension at Questa, New Mexico: Geological Society of America Bulletin, v. 103, p. 993–1006.

Miller, D. M., 1993, Two distinct episodes of Cenozoic extension in the northern Basin and Range province, as indicated by magmatic and structural characteristics: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 121.

Miller, D. M., Pringle, M. S., Nakata, J. K., Sarna-Wojcicki, A., and Meyer, C. E., 1993, Basin development north of Great Salt Lake and implications for Neogene structural history of northern Utah: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 121.

Miller, F. K., 1970, Geologic map of the Quartzite quadrangle, Yuma County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-841, scale 1:62,500.

Miranda-Gasca, M. A., and De Jong, K. A., 1992, The Magdalena mid-Tertiary extensional basin, Aiken, J. L., and Kistler, R. B., 1992, General geology of the Magdalena basin, Sonora, Mexico, *in* Clark, K. F., Roldán-Quintana, J., and Schmidt, R. H., eds., Geology and mineral resources of northern Sierra Madre Occidental, Mexico, Guidebook for the 1992 Field Conference: El

Paso, Texas, El Paso Geological Society, p. 377–384.

Moiola, R. J., 1969, Late Cenozoic geology of the northern Silver Peak region, Esmeralda County [Ph.D. thesis]: Berkeley, University of California, 139 p.

Moore, G., Marone, C., Carmichael, I. S. E., and Renne, P., 1994, Basaltic volcanism and extension near the intersection of the Sierra Madre volcanic province and the Mexican volcanic belt: Geological Society of America Bulletin, v. 106, p. 383–394.

Mora-Alvarez, G., 1992, History of Cenozoic magmatism in the Sierra Santa Ursala, Sonora, Mexico [M.S. thesis]: Austin, University of Texas, 153 p.

Morgan, P., and Golombek, M. P., 1984, Factors controlling the phases and styles of extension in the northern Rio Grande rift, *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., eds., Rio Grande rift—northern New Mexico: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 13–19.

Morgan, P., Seager, W. R., and Golombek, M. P., 1986, Cenozoic thermal, mechanical and tectonic evolution of the Rio Grande rift: Journal of Geophysical Research, v. 91, no. B6, p. 6263–6276.

Mullan, H. S., 1978, Evolution of part of the Nevadan orogen in northwestern Mexico: Geological Society of America Bulletin, v. 89, p. 1175–1188.

Neuhaus, J. A., Cassidy, M., Krummenacher, D., and Gastil, R. G., 1988, Timing of protogulf extension and transtensional rifting through volcanic/sedimentary stratigraphy of the S.W. Isla Tiburon, Gulf of California, Sonora, Mexico: Geological Society of America Abstracts with Programs, v. 20, no. 3, p. 218.

New Mexico Geological Society, 1982, New Mexico highway geologic map, scale 1:1,000,000.

Nielsen, J. E., and Beratan, K. K., 1990, Tertiary basin development and tectonic implications, Whipple Mountain detachment system, Colorado River extension corridor, California and Arizona: Journal of Geophysical Research, v. 95, no. B1, p. 599–614.

Nielson, J. E., Lux, D. R., Dalrymple, G. B., and Glazner, A. F., 1990, Age of the Peach Springs Tuff, southeastern California and northwestern Arizona: Journal of Geophysical Research, v. 95, p. 571–580.

Nourse, J. A., 1989, Geologic evolution of two crustal scale shear zones [Ph.D. thesis]: Pasadena, California Institute of Technology, 396 p.

Nourse, J. A., 1990, Tectonostratigraphic development and strain history of the Magdalena metamorphic core complex, northern Sonora, Mexico, *in* Gehrels, G. E., and Spencer, J. E., eds., Geologic excursions through the Sonoran Desert region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 155–164.

Nourse, J. A., Anderson, T. H., and Silver, L. T., 1994, Tertiary metamorphic core complexes in Sonora, northwestern Mexico: Tectonics, v. 13, p. 1161–1182.

Okaya, D. A., and Thompson, G. A., 1985, Geometry of Cenozoic extensional faulting: Dixie Valley, Nevada: Tectonics, v. 4, p. 107–125.

Oldow, J. S., 1992, Late Cenozoic displacement partitioning in the northwestern Great Basin, *in* Craig, S. D., ed., Walker Lane Symposium—structure, tectonics, and mineralization of the Walker Lane, Proceedings Volume: Reno, Nevada Geological Society, p. 17–52.

Pardee, J. T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America, v. 61, p. 359–406.

Parsons, T., and Thompson, G. A., 1991, The role of magma overpressure in suppressing earthquakes and topography: Worldwide examples: Science, v. 253, p. 1399–1402.

Pasquarè, G., Garduño, V. H., Tibaldi, A., and Ferrari, M., 1988, Stress pattern evolution in the central sector of the Mexican Volcanic Belt: Tectonophysics, v. 146, p. 353–364.

Peirce, H. W., 1984, The Mogollon escarpment: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 14, no. 2, p. 8–11.

Peirce, H. W., 1985, Arizona's backbone: The transition zone: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 15, no. 3, p. 1–6.

Peirce, H. W., Damon, P. E., and Shafiqullah, M., 1979, An Oligocene (?) Colorado Plateau edge in Arizona: Tectonophysics, v. 61, p. 1–24.

Powell, C. M., and Williams, G. H., 1989, The Lewis thrust/Rocky Mountain trench fault system in northwest Montana, USA—An example of negative inversion tectonics?, *in* Cooper, M. A., and Williams, G. D., eds., Inversion tectonics: Geological Society [London] Special Publication 44, p. 223–234.

Powell, J. W., 1895, Physiographic regions of the United States: National Geographic Society, National Geographic Monograph 1, no. 3, p. 65–100.

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.

Raisz, E., 1959, Landforms of Mexico: Cambridge, Massachusetts, Prepared for the Geographic Branch of the Office of Naval Research.

Rehrig, W. A., and Heidrick, T. L., 1976, Regional tectonic stress during the Laramide and late Tertiary intrusive periods, Basin and Range Province, Arizona, *in* Wilt, J. C., and Jenney, J. P., eds., Tectonic digest: Arizona Geological Society Digest, v. 10, p. 205–228.

Rehrig, W. A., Shafiqullah, M., and Damon, P. E., 1980, Geochronology, geology, and listric normal faulting of the Vulture Mountains, Maricopa County, Arizona, *in* Jenney, J. P., and Stone, C., eds., Studies in western Arizona: Arizona Geological Society Digest, v. 12, p. 89–110.

Reynolds, M. W., 1979, Character and extent of Basin-Range faulting, western Montana and east-central Idaho, *in* Newman, G. W., and Goode, H. D., Basin and Range Symposium and Great Basin field conference: Denver, Colorado, Rocky Mountain Association of Geologists and Utah Geological Association, p. 185–193.

Reynolds, S. J., 1988, Geologic map of Arizona, *in* Jenney, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, scale 1:1,000,000.

Reynolds, S. J., and Spencer, J. E., 1985, Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona: Geology, v. 13, p. 53–356.

Richins, W. D., Pechmann, J. C., Smith, R. B., Langer, C. J., Goter, S. K., Zollweg, J. E., and King, J. J., 1987, The 1983 Borah Peak, Idaho, earthquake and its aftershocks: Seismological Society of America Bulletin, v. 77, p. 691–723.

Romney, C., 1957, Seismic waves from Dixie Valley–Fairview Peak earthquakes: Seismological Society of America Bulletin, v. 4, p. 301–319.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Review of Earth and Planetary Sciences, v. 15, p. 445–503.

Ross, T. M., Luyendyk, B. P., and Haston, R. B., 1989, Paleomagnetic evidence for Neogene clockwise tectonic rotations in the central Mojave Desert, California: Geology, v. 17, p. 470–473.

Rowley, P. D., Anderson, J. J., Williams, P. L., and Fleck, R. J., 1978, Age of structural differentiation between the Colorado Plateaus and Basin and Range Provinces in southwestern Utah: Geology, v. 6, p. 51–55.

Rowley, P. D., Steven, T. A., Anderson, J. J., and Cunningham, C. G., 1979, Cenozoic stratigraphic and structural framework of southwestern Utah: U.S. Geological Survey Professional Paper 1149, 22 p.

Rowley, P. D., Snee, L. W., Mehnert, H. H., Anderson, R. E., Axen, G. J., Burke, K. J., Simonds, F. W., Shroba, R. R., and Olmore, S. D., 1992, *in* Thorman, C. H., ed., Application of structural geology to mineral and energy resources of the central and western United States: U.S. Geological Survey Bulletin 2012, p. H1–H17.

Russell, R. J., 1928, Basin-Range structure and stratigraphy of the Warner Range, northeastern California: University of California Publications in Geological Sciences, v. 17, p. 387–496.

Saltus, R. W., 1988, Regional, residual, and derivative gravity maps of Nevada: Nevada Bureau of Mines and Geology Map 94B, scale 1:1,000,000.

Sawlan, M. G., 1991, Magmatic evolution of the Gulf of California rift, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The Gulf and Peninsular Province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 301–369.

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., eds., Geology of the Baja California Peninsula: Pacific Section, Society of Economic Paleontologists and Mineralogists, Publication 39, p. 237–251.

Scarborough, R. B., and Peirce, H. W., 1978, Late Cenozoic basins of Arizona, *in* Callender, J. F., Wilt, J. C., and Clemons, R. F., eds., Land of Cochise: New Mexico Geological Society, 29th Field Conference, Guidebook, p. 253–259.

Scarborough, R. B., Christopher, M. M., and Pearthree, P. A., 1983, Map of basin and range (post 15 m.y.a.) exposed faults, grabens, and basalt-dominated volcanism in Arizona: Arizona Bureau of Geology and Mineral Resources Open-File Report 83-21, scale 1:500,000.

Seager, W. R., and Morgan, P., 1979, Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua, *in* Riecker, R. E., ed., The Rio Grande rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 87–106.

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.

Seedorff, E., 1991, Magmatism, extension, and ore deposits of Eocene to Holocene age in the Great Basin—mutual effects and preliminary proposed genetic relationships, *in* Raines, G. L, Lisle, R. E., Schafer, R. W., and Wilkinson, W. H., 1991, Geology and ore deposits of the Great Basin: Reno, Geological Society of Nevada, p. 133–178.

Severinghaus, J., and Atwater, T., 1990, Cenozoic geometry and thermal state of the subducting slabs beneath western North America, *in* Wernicke, B. P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 1–22.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S. J., Rehrig, W. A., and Raymond, R. H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Survey Digest, v. 12, v. 201–260.

Sieh, K., Jones, L., Hauksson, E., Hudnut, K., Eberhart-Phillips, D., Heaton, T., Hough, S., Hutton, K., Kanamori, H., Lilje, A., Lindvall, S., McGill, S. F., Mori, J., Rubin, C., Spotila, J. A., Stock, J., Hong Kie Thio, Treiman, J., Wernicke, B., Zachariasen, J., 1993, Near-field investigations of the Landers earthquake sequence, April to July 1992: Science, v. 260, p. 171–176.

Siem, M., and Gastil, G., 1994, Mid-Tertiary to Holocene extension associated with the development of the Sierra El Mayor metamorphic core complex, northeastern Baja California, Mexico, *in* McGill, S. F., and Ross, T. M., eds., Geologic investigations of an active margin (Geological Society of American Cordilleran Section meeting guidebook): Redlands, California, San Bernardino County Museum Association, p. 107–119.

Slemmons, D. B., 1967, Pliocene and Quaternary crustal movements of the Basin and Range Province, USA, *in* Sea level changes and crustal movements of the Pacific (Pacific Science Congress, 11th, Tokyo, 1966, Symposium 19): Osaka City University, Journal of Geosciences, v. 10, article 1, p. 91–103.

Slemmons, D. B., Van Wormer, D., Bell, E. J., and Silberman, M. L., 1979, Recent crustal movements in the Sierra Nevada–Walker Lane region of California-Nevada—part 1, Rate and style of deformation: Tectonophysics, v. 52, p. 561–570.

Smith, G. I., 1962, Large lateral displacement on the Garlock fault, California, as measured from offset dike swarm: American Association of Petroleum Geologists Bulletin, v. 46, p. 85–104.

Smith, J. T., 1991, Cenozoic marine mollusks and paleogeography of the Gulf of California, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The Gulf and Peninsular Province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 637–666.

Snyder, W. S., Dickinson, W. R., and Silberman, M. L., 1976, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States: Earth and Planetary Science Letters, v. 32, p. 91–106.

Spencer, J. E., and Reynolds, S. J., 1986, Some aspects of the middle Tertiary tectonics of Arizona and southeastern California: Arizona Geological Society Digest, v. 16, p. 102–107.

Spencer, J. E., and Reynolds, S. J., 1989, Middle Tertiary tectonics of Arizona and adjacent areas, *in* Jenney, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 539–574.

Spencer, J. E., and Reynolds, S. J., 1991, Tectonics of mid-Tertiary extension along a transect through west central Arizona: Tectonics, v. 10, p. 1204–1221.

Stevens, J. B., and Stevens, M. S., 1985, Basin and Range deformation and depositional timing, Trans-Pecos Texas, *in* Dickerson, P. W., and Muehlberger, W. R., eds., Structure and tectonics of the Trans-Pecos Texas: West Texas Geological Society Publication 85-81, p. 157–163.

Stewart, J. H., 1980, Regional tilt patterns of late Cenozoic basin-range fault blocks, western United States: Geological Society of America Bulletin, part I, v. 91, p. 460–464.

Stewart, J. H., 1988, Tectonics of the Walker Lane belt, western Great Basin—Mesozoic and Cenozoic deformation in a zone of shear, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States (Rubey Volume 7): Englewood Cliffs, New Jersey, Prentice Hall, p. 683–713.

Stewart, J. H., 1992a, Walker Lane Belt—An overview, *in* Craig, S. D., ed., Structure, tectonics and mineralization of the Walker Lane: Reno, Geological Society of Nevada, p. 1–16.

Stewart, J. H., 1992b, Paleogeography and tectonic setting of Miocene continental strata in the northern part of the Walker Lane Belt, *in* Craig, S. D., ed., Structure, tectonics and mineralization of the Walker Lane: Reno, Geological Society of Nevada, p. 53–61.

Stewart, J. H., and Crowell, J. C., 1992, Strike-slip tectonics in the Cordilleran region, western United States, *in* Burchfiel, B. C., Lipman, P. W., and Zoback, M. L., eds., The Cordilleran Orogen—Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 609–627.

Stewart, J. H., and Diamond, D. S., 1990, Changing patterns of extensional tectonics—Overprinting of the basin of the middle and upper Miocene Esmeralda Formation in western Nevada by younger structural basins, *in* Wernicke, B. P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 447–476.

Stewart, J. H., and Johannesen, D. C., 1979, Map showing regional tilt patterns of late Cenozoic basin-range fault blocks in western United States: U.S. Geological Survey Open-File Report 79-1134, scale 1:2,500,000.

Stewart, J. H., and Roldán-Quintana, J., 1994, Map showing late Cenozoic extensional tilt patterns and associated structures in Sonora and adjacent areas, Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-2238, scale 1:1,000,000.

Stickney, M. C., and Bartholomew, M. J., 1987, Seismicity and late Quaternary faulting of the northern Basin and Range Province, Montana: Seismological Society of America Bulletin, v. 77, p. 1602–1625.

Stimac, J., and Wark, D. A., 1983, Geology of the Cusihuiriachic–Buenos Aires area, Chihuahua, Mexico, *in* Clark, K. F., and Goodell, P. C., eds., Geology and mineral resources of north-central Chihuahua, Guidebook for the 1983 Field Conference: El Paso, Texas, El Paso Geological Society, p. 205–212.

Stock, J. M., 1993, Geologic map of southern Valle Chico and adjacent regions, Baja California, Mexico: Geological Society of America Map and Chart Series MCH076, scale ~1:25,000.

Stock, J. M., and Hodges, K. V., 1989, Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific plate: Tectonics, v. 8, p. 99–115.

Stock, J. M., and Hodges, K. V., 1990, Miocene to recent structural development of an extensional accommodation zone, northeastern Baja California, Mexico: Journal of Structural Geology, v. 12, p. 315–328.

Stock, J. M., Martín-B, A., Suárez-V., A., and Miller, M. M., 1991, Miocene to Holocene extension tectonics and volcanic stratigraphy of NE Baja California, Mexico, *in* Walawender, M. J., and Hanan, B. B., eds., Geologic excursions in southern California and Mexico (Geological Society of America Annual Meeting Guidebook): San Diego, California, San Diego State University, p. 44–67.

Suter, M., Quintero, O., and Johnson, C. A., 1992, Active faults and state of stress in the central part of the Trans-Mexican volcanic belt, Mexico 1.—The Venta de Bravo fault: Journal of Geophysical Research, v. 97, p. 11983–11993.

Suter, M., Carrillo-Martínez, M., López-Martínez, M., and Farrar, E., 1995, The Aljibes half-graben—Active extension at the boundary between the trans-Mexican volcanic belt and the Basin and Range Province, Mexico: Geological Society of America Bulletin, v. 107, p. 627–641.

Taylor, W. J., Bartley, J. M., Lux, D. R., and Axen, G. J., 1989, Timing of Tertiary extension in the Railroad Valley–Pioche transect, Nevada: Constraints from $^{40}Ar/^{39}Ar$ ages of volcanic rocks: Journal of Geophysical Research, v. 94, no. B6, p. 7757–7774.

Thenhaus, P. C., and Barnhard, T. P., 1989, Regional termination and segmentation of Quaternary fault belts in the Great Basin, Nevada and Utah: Seismological Society of America Bulletin, v. 79, p. 1426–1438.

Tweto, O., 1979, The Rio Grande rift in Colorado, *in* Riecker, R. E., ed., The Rio Grande rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 36–56.

Walker, G. W., 1973, Geologic map of Oregon east of the 121st Meridian: U.S. Geological Survey Miscellaneous Field Studies MF-495, scale 1:500,000.

Walker, G. W., and MacLeod, N. S., 1991, Geologic map of Oregon: U.S. Geological Survey, scale 1:500,000.

Wallace, C. A., Lidke, D. J., and Schmidt, R. G., 1990, Faults of the central part of the Lewis and Clark line and fragmentation of the Late Cretaceous foreland basin in west-central Montana: Geological Society of America Bulletin, v. 102, p. 1021–1037.

Wells, M. L., Snee, L., and Blythe, A., 1994, Mesozoic and Cenozoic extensional history of northeastern Great Basin: Insights from the Raft River, and Grouse Creek Mountains: Geological Society of America Abstracts with Programs, v. 26, no. 2, p. 103.

Wells, R. E., and Hillhouse, J. W., 1989, Paleomagnetism and tectonic rotation of the lower Miocene Peach Spring Tuff—Colorado Plateau, Arizona, to Barstow, California: Geological Society of America Bulletin, v. 101, p. 846–863.

Wernicke, B. P., 1990, ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, 511 p.

Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B. C., Lipman, P. W., and Zoback, M. L., eds., The Cordilleran orogen—Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 553–581.

Wernicke, B., Guth, P. L., and Axen, G. J., 1984, Tertiary extensional tectonics in the Sevier thrust belt of southern Nevada, *in* Lintz, J., Jr., Western geological excursions, Volume 4: Reno, Nevada, Mackay School of Mines, p. 473–495.

Wernicke, B. P., Christiansen, R. L., England, P. C., and Sonder, L. J., 1987, Tectonomagmatic evolution of Cenozoic extension in North American Cordillera, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society [London] Special Publication 28, p. 203–221.

Wernicke, B. P., Axen, G. J., and Snow, J. K., 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738–1757.

Witkind, I. J., 1964, Reactivated faults north of Hebgen Lake, *in* The Hebgen Lake, Montana earthquake of August 17, 1959: U.S. Geological Survey Professional Paper 435-G, p. 37–50.

Wust, S. L., 1986, Regional correlation of extension directions in Cordilleran metamorphic core complexes: Geology, v. 14, p. 828–830.

Young, R. A., and Brennan, W. J., 1974, Peach Springs Tuff: Its bearing on structural evolution of the Colorado Plateau and development of Cenozoic drainage in Mohave County, Arizona: Geological Society of America Bulletin, v. 85, p. 83–90.

Zoback, M. L., 1989, State of stress and modern deformation of the northern Basin and Range province: Journal of Geophysical Research, v. 94B, no. 6, p. 7105–7128.

Zoback, M. L., 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, ser. A, v. 300, p. 407–434.

Zuber, M. T., Parmentier, E. M., and Fletcher, R. C., 1986, Extension of continental lithosphere: A model for two scales of Basin and Range deformation: Journal of Geophysical Research, v. 91, p. 4826–4838.

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