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A brief overview of Cenozoic extensional tectonism in western North America

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ABSTRACT

The extensional provinces of western North America form the largest and most structurally diverse extensional orogen in the world. Rift styles include classic metamorphic core complexes, wide rifting, narrow rifting, and actively rupturing continental lithosphere. In general, extended terrains overlap with previously thickened crust. Extension began in Eocene time in the northwestern United States and southwestern Canada with rapid, large-magnitude metamorphic core complex extension in a supra-subduction, intra-arc setting. Farther south, the Laramide subduction slab was flat, magmatism was concentrated farther east, and extension had not yet begun. These early, northwestern core complexes lie mostly outside of the physiographic Basin and Range province, which developed later. Extension became widespread in the western US and Mexico in Oligocene to early Miocene time. Extension became widespread in Oligocene to early Miocene time in the Northern Basin and Range of eastern and central Nevada and western Utah, in the Southern Basin and Range of Arizona and Mexico, and in the Rio Grande Rift of New Mexico and west Texas, with the highest rates and magnitudes of extension in early to mid-Miocene time. This event was broadly associated with widespread calc-alkaline volcanism, including the ignimbrite flare-up. Both extension and volcanism probably were triggered by heating of the base of the North American lithosphere due to inflow of asthenosphere in response to removal of the Laramide flat-subduction slab. Slab removal occurred by irregular slab rollback in the northern Basin and Range and eastern Mexico and by the northward migration of the north edge of a slab window in northwestern Mexico, Arizona, and southeastern California. An unextended and amagmatic corridor occupied the northeastern Mojave Desert and Central Basin and Range of southern Nevada and southeastern California at this time, suggesting that slab removal occurred later at that latitude. Volcanism became more strongly alkaline and bimodal in mid-Miocene time, but core complex extension continued, finally slowing and being replaced by wide-rift-style extension in late middle Miocene time. In mid-Oligocene time (~29 Ma) the transform plate margin began to evolve from the previous subduction margin, elongating generally smoothly to the north, but growing southward by jumps due to microplate capture, causing extension in the inner California continental borderland and clockwise vertical-axis rotation of the western Transverse Ranges – Channel Islands block of California. By middle Miocene time the central San Andreas fault (the part north of the western Mojave Desert) and dextral faults farther west along the coast were well established. Also at this time, extension in the southern Basin and Range was slowing, onset of rapid extension in the central Basin and Range had connected the northern and southern Basin and Range provinces for the first time; by late middle Miocene time the extension direction there rotated clockwise to the present generally northwesterly direction seen in the Walker Lane of western Nevada and eastern California. By latest Miocene time the modern southern San Andreas fault was established in the Salton trough, oblique extension in the Gulf of California was rapid, and rupture of the continental lithosphere was beginning.

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INTRODUCTION

Western North American extended terrain (WNAET; Fig. 1) constitutes the largest, most diverse, geologically young and active extensional orogen (taphrogen) in the world. Western North America was the source of many advances in understanding of extensional tectonics that have been subsequently applied to extended terrains worldwide.

This paper presents a short, very broad overview of North American extensional tectonics, but no effort is made to provide an in-depth or newly updated synthesis. A number of relatively recent review articles have discussed all or parts of the North American extended terrains (Henry and Price, 1986; Davis and Lister, 1988; Wernicke et al., 1988; Gans et al., 1989; Spencer and Reynolds, 1989; Henry et al., 1991; Henry and Aranda-Gomez, 1992; 2000; Wernicke, 1992; Axen et al., 1993; Sedlock et al., 1993; Spencer et al., 1995; Wernicke and Snow, 1998; Chapin and Cather, 1994; Dickinson, 2002, 2006; Ingersoll, 2003; McQuarrie and Wernicke, 2005; Ferrari et al., 2007). The most thorough, province-wide review is by Bill Dickinson (2002), to whom this volume is dedicated.

The well-known Basin and Range (B&R) physiographic province is smaller than the full extent of western North American extended terrain, which includes the northern Rocky Mountains metamorphic core complex belt of southwestern Canada and northwestern United States (US) and the "inner continental borderland" offshore of southern California and northern Baja California (Fig. 1). The extended terrains are broken into various parts, the most common of which are named in Figure 1. Many of the boundaries between these parts are diffuse or imprecisely defined. Some of the subregions have experienced complex extensional histories that may include one or more phases of extension, during which times the style and direction of extension may have changed. As such, the western North American extended terrain embodies spatial and temporal complexity akin to most long-lived major contractional orogens (Dickinson, 2002).

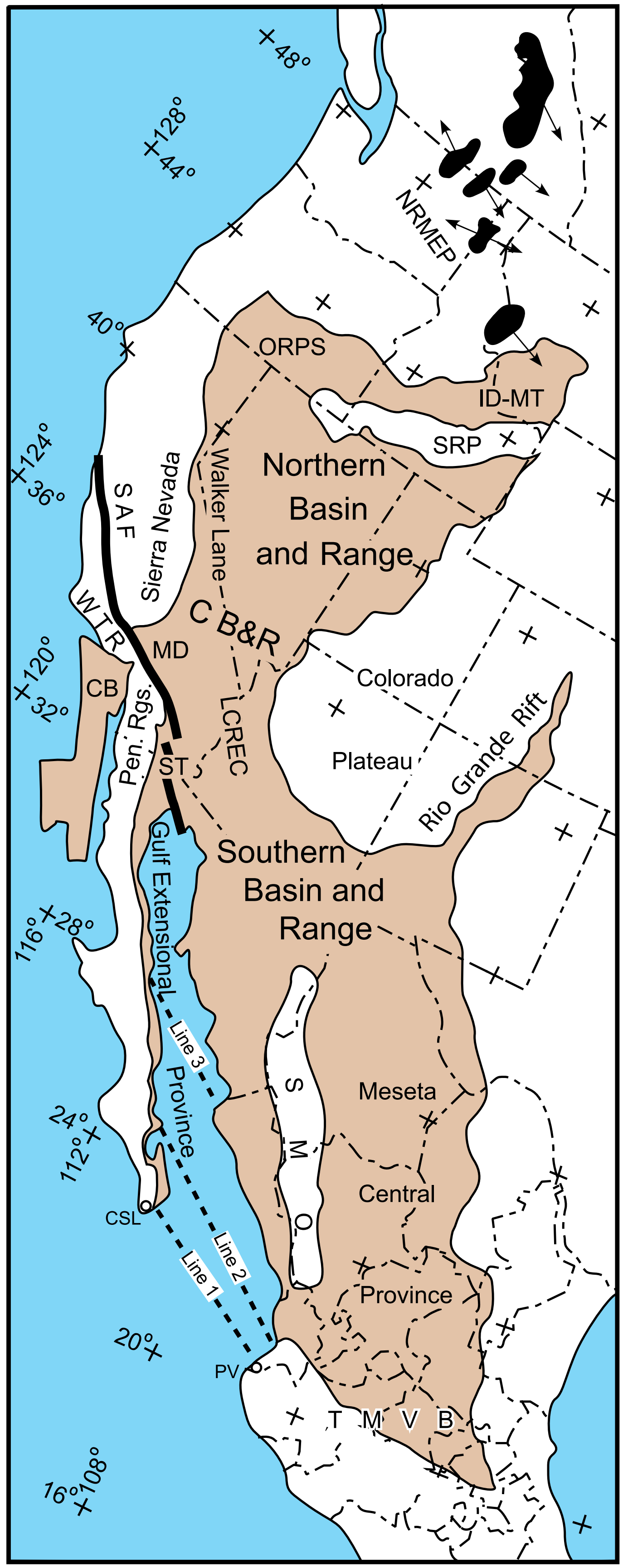

Figure 1. Simplified map of the North American extended terrains. Basin and Range province is colored tan. Black areas are metamorphic core complexes of the Northern Rocky Mountains with arrows showing direction of upper-plate transport (from Dickinson, 2002). Dashed lines in southern Gulf of California are wide-angle seismic reflection lines discussed in text and shown in figure 3. Province abbreviations, from north to south: NRMEP – Northern Rocky Mountains extensional province; ID-MT – Idaho-Montana segment of the Northern Basin and Range; ORPS – Oregon plateau segment of the Northern Basin and Range; SRP – Snake River Plain; SAF – San Andreas fault; CB&R – Central Basin and Range; WTR – Western Transverse Ranges; MD – Mojave Desert; CB – continental borderland; ST – Salton Trough; LCREC – Lower Colorado River extensional corridor; Pen Rgs. – Peninsular Ranges; SMO – Sierra Madre Occidental; TMVB – Trans-Mexican Volcanic Belt. Cities: CSL – Cabo San Lucas; PV – Puerto Vallarta.

Perhaps the scientifically most significant discovery from the WNAET is the recognition of crustal-scale, low-angle normal faults (or detachment faults) and their mid-crustal equivalents as mylonitic shear zones (e.g., Crittenden et al., 1980), which has had important implications for continental and oceanic tectonics (see Axen, 2007). These faults individually accommodated up to several tens of kilometers of horizontal extension, and typically bound footwall metamorphic core complexes (MCCs) comprising intrusive and metamorphic rocks exhumed from mid-crustal depths by detachment slip, with the upper footwall recording the evolution from ductile to brittle shear (e.g., Wernicke, 1981; Davis, 1983). As described below for individual sections of the WNAET (Figs. 1 and 2), the extension direction of the MCCs varies systematically along the strike of the orogen, being generally subperpendicular to trend of the older, contractional orogenic grain (Wust, 1986; Dickinson, 2002). This strongly favors gravitational spreading as an important driving force for extension (Coney and Harms, 1984). Much attention has been focused on these MCCs due to their localized, large-magnitude extension and to controversy over existence of low-angle normal faults (e.g., Jackson, 1987), but they form just one end-member tectonic style in which large-magnitude extension occurs. Elsewhere, large-magnitude extension is accommodated by domino- or bookshelf-style normal fault systems (e.g., Proffett, 1977; Chamberlin, 1983), clustered brittle low-angle normal faults (e.g., Wernicke et al., 1988; Axen et al., 1990; Bartley et al., 1988), and, locally, magmatic replacement of old crust by new juvenile crust (Fuis et al., 1982; Fuis and Kohler, 1984).

NORTHERN ROCKY MOUNTAINS EXTENSIONAL PROVINCE

The earliest major extension of Cenozoic age began in the Rocky Mountains of the northwestern US and southwestern Canada (Fig. 1) in Late Paleocene to Middle Eocene time (Dickinson, 2002, and references therein). Extension in this region was dominated by formation of large MCCs that formed in an intra-arc setting with a general west-northwest – east-northeast extension direction. Extension in these MCCs migrated generally southward, roughly synchronous with early migration of the arc magmatic front, from which rollback of a previously flat subducted slab is inferred. Thus, it appears likely that intrusion of an asthenospheric wedge, with attendant heating of the base of the North American lithosphere, triggered extensional collapse of overthickened lithosphere. However, the west-northwest – east-southeast average extension direction of these MCCs (reviewed by Dickinson, 2002) is oblique to the upper crustal orogenic fabric (generally north to north-northwest trending), so it seems likely that extension here was not driven solely by orthogonal collapse of the pre-existing orogenic welt, and that the extension direction was influenced by superimposed forces, perhaps related to dextral shear applied at the plate boundary or basal forces related to slab rollback.

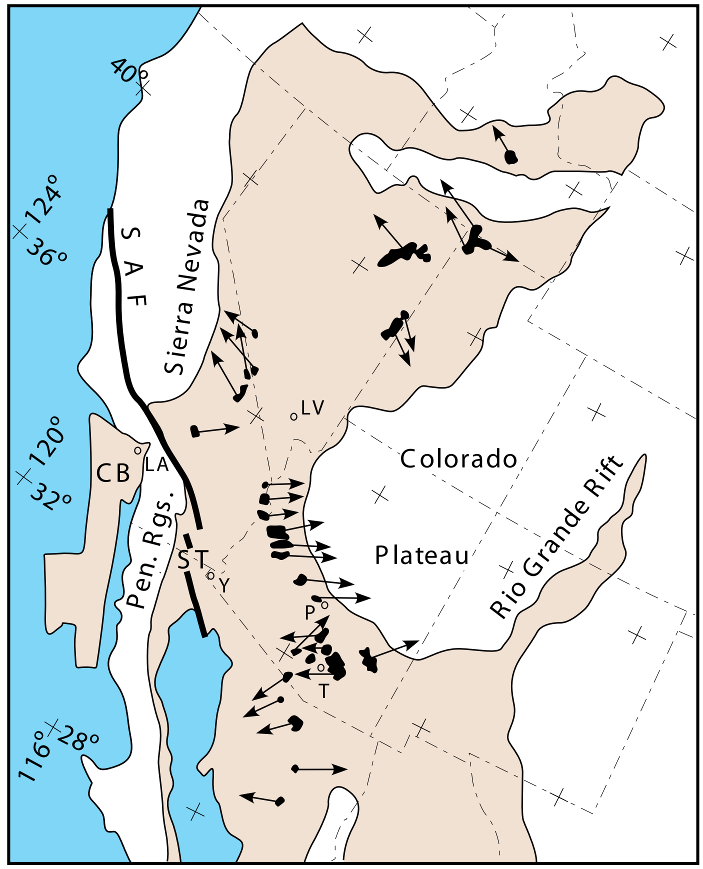

Figure 2. Map showing metamorphic core complexes of the Basin and Range province (black areas with arrows as in figure 1). Cities: LA – Los Angeles; LV – Las Vegas; P – Phoenix; Y – Yuma; T – Tucson. Other abbreviations as in Figure 1.

BASIN AND RANGE EXTENSIONAL PROVINCE

The B&R province (Fig. 1) is characterized physiographically by alternating mountain ranges and intervening basins formed primarily by normal faulting with some areas of significant strike-slip faulting. The B&R runs generally north-northwest – south-southeast for >2500 km from ~21° N latitude in central Mexico, north of the trans-Mexican volcanic belt, to ~45° N latitude in western Montana, north of the Snake River plain, and is several hundred kilometers wide for much of that length. It is divided into the subprovinces described individually below. Many of these B&R subdivisions are somewhat arbitrary, and commonly the boundaries are vaguely defined. In large part, this stems from (1) the lengthy and complex history of extension in the B&R – most subprovinces have experienced more than one extensional event, (2) emphasis by different authors on different aspects of the extensional history, with subdivision accordingly, and (3) early definitions based upon topographic/morphologic characteristics rather than geologic history. The B&R contains two significant unextended blocks, completely enclosing the Sierra Madre Occidental, Mexico and wrapping around three sides of the Colorado Plateau (Fig. 1). These blocks may have resisted extension due to being stronger than their surroundings. This seems particularly likely for the Colorado Plateau, which also remained little-deformed during earlier contractional tectonism. The Sierra Madre, locus of voluminous pre-and synextension magmatism is probably underlain by batholithic crust, but may still have been hot and weak when its surroundings extended, so perhaps was topographically low and lacking gravitational potential energy to drive extension. Unextended batholithic belts of the Sierra Nevada and Peninsular Ranges bound most of the western side of the B&R and were probably cold and strong at the onset of extension.

Northern Basin and Range

The Northern B&R (NB&R; Fig. 1) includes all of Nevada plus western Utah, east-central California, southeastern Oregon, eastern Idaho and western Montana. The internally drained Great Basin forms its central core. It has also been termed the "Numic subtaphrogen" recently (Sengor and Natal'in, 2001; Dickinson, 2002). The younger to partly coeval, volcanic Snake River plain cuts obliquely across the northeast part and separates the Idaho-Montana segment from the rest of the northern B&R. The northwestern part of the NB&R is called the Oregon Plateau segment (Fig. 1). The southern part of the NB&R has been called the Central B&R (Wernicke et al., 1988), and connects the unextended southern Sierra Nevada to the western Colorado Plateau at the latitude of Las Vegas, Nevada and Death Valley, California (Fig. 1). The western parts of the Northern and Central B&R in western Nevada and east-central California form the northwest-trending Walker Lane (Stewart, 1988), which is morphologically and structurally distinct from the simpler, north-elongated basins and ranges farther north and east.

A belt of MCCs runs north-south in the eastern part of the NB&R from the Pioneer Mountains of Idaho to the Snake Range of east-central Nevada (Fig. 2). These MCCs largely began to form earlier than the range-bounding normal faults that define most of the NB&R morphology. This belt also forms the southward continuation of the Northern Rocky Mountains MCC belt of high extension, with onset of MCC extension also migrating south from Middle Eocene to Middle Oligocene time (Axen et al., 1993). Some of the MCCs experienced either two distinct extensional events or a single prolonged extensional event, with large-magnitude detachment slip and footwall exhumation continuing into Middle Miocene time. Extension in this belt was generally oriented west-northwest – east-southeast (Dickinson, 2002, and references therein). Non-MCC extension of Eocene-Oligocene age in this belt occurred south of the Snake Range, to about 38° latitude, on a low-angle normal fault system with too little slip to unroof metamorphic tectonites (Bartley et al., 1988). Farther west, a second north-south belt of Eocene-Oligocene extension ran parallel to the MCC belt nearly as far south as Death Valley, but was separated from it by a narrow unextended terrain (Axen et al., 1993). Presumably, extension in this second belt was of lower magnitude.

These two north-south extensional belts were nearly orthogonal to the broadly coeval, east-trending, south-migrating volcanic front (Stewart and Carlson, 1976; Best et al., 1989; Christiansen et al., 1992), so that extension in their northern parts generally postdated onset of volcanism, extension in their central parts was synchronous with volcanism (e.g., Gans et al., 1989) and extension in their southern parts largely pre-dated volcanism (Axen et al., 1993). Formation of major caldera complexes generally lagged behind initial effusive andesitic volcanism by a few million years (Stewart and Carlson, 1976), and most major caldera complexes formed preferentially within the previously extended belts (Axen et al., 1993).

By Middle Miocene time, extension had spread across most of the NB&R and the modern system of range-bounding faults had initiated, forming this archetypical wide rift (e.g., Stockli, 1999). About this time, the nature of volcanism changed from calcalkaline andesitic effusive volcanism plus dacite-rhyolite ingnimbrite eruptions to more alkaline, bimodal basaltic-rhyolitic volcanism (Christiansen and McKee, 1980). Extension began later in the Central B&R than it did to the north or south (see below), disrupting the last bit of unextended terrain between the Colorado Plateau and the Sierra Nevada and connecting the previously separate northern and southern B&R. Large-magnitude west-southwest – east-northeast extension started in the eastern Central B&R in Middle Miocene time (Wernicke et al., 1988; Axen et al, 1990). The locus of rapid extension migrated west, and the extension direction rotated clockwise to approximately northwest in the western Central B&R, reaching the Death Valley region in late Miocene time. (Wernicke et al., 1988; Snow and Wernicke, 2000; McQuarrie and Wernicke, 2005). The Central B&R is one of the few parts of the B&R that has experienced only one period of extension.

The Central B&R differs structurally from most other parts of the B&R in that large-slip, low-angle normal faults slipped in concert with major conjugate strike-slip fault systems comprising west-northwest- to north-northwest-striking dextral faults and generally northeast-striking sinistral faults. This unique structural evolution, combined with offset markers known from well-understood pre-B&R geology, has allowed net extension of ~240 km toward ~N75W to be calculated across the Central B&R (Wernicke et al., 1988; McQuarrie and Wernicke, 2005).

The western Central B&R includes the southern Walker Lane (Fig. 1), which is a zone of combined extension and dextral shear, the latter being locally focused on individual dextral faults but elsewhere distributed across arrays of northeast-striking, sinistral, map-view domino-style faults that experience clockwise vertical-axis rotation (Stewart, 1988). MCCs formed locally in releasing left stepovers between dextral faults, the largest being footwall range blocks east and north of Death Valley (Fig. 2). These MCCs are younger than other Cordilleran MCCs, having formed in latest middle to late Miocene time (see review in Dickinson, 2002). Southward, the Walker Lane ends at the left-lateral Garlock fault but the northwest-trending dextral shear zone continues south into the Mojave Desert as the Eastern California shear zone (Savage et al., 1990; Dokka and Travis, 1990), a system of mainly dextral strike-slip faults that traverses the Mojave Desert, connecting southward to the southern San Andreas fault system in the Salton Trough via the eastern Transverse Ranges. The combined Walker Lane – Eastern California shear zone accommodated several tens of kilometers of dextral shear, and currently carries about 25 percent of relative Pacific – North American plate motion (see review *in* McQuarrie and Wernicke, 1995).

"Southern" and Mexican Basin and Range

The "Southern" Basin and Range (SB&R), as traditionally defined, includes southern and western Arizona, southeastern California, southwestern New Mexico, southwestern Texas, and adjacent parts of Sonora and Chihuahua, in northern Mexico. The SB&R, plus a "transition zone" of lower magnitude extension, wrap around the southern and western Colorado Plateau. This US-centric view of the SB&R ignores the vast tracts of less well-studied Mexican B&R farther south that comprise roughly half of the total B&R area (Henry and Aranda-Gomez, 1992). Here, the term "southern Basin and Range" is retained in its traditional sense. Together, the Southern and Mexican B&R recently have been termed the "Piman subtaphrogen" (Sengor and Natal'in, 2001; Dickinson, 2002). East of the Colorado Plateau, the SB&R merges with the narrow, north-trending Rio Grande Rift.

A belt of MCCs runs southeast across the SB&R (e.g., Davis and Lister, 1988; Spencer and Reynolds, 1989; Fig. 2). The northwest end is in the "lower Colorado River extensional corridor" (Fig. 1), where kinematically related MCCs lie astride the Colorado River south of Las Vegas, Nevada and northeast of Yuma, Arizona. Many detachment faults of the lower Colorado River corridor are probably directly correlative from one MCC to the next, had very similar top- northeast slip of ≥50 km, and root northeast under the transition zone. Fastest slip on these detachments was in early to middle Miocene time. MCCs continue southeast to Phoenix, Arizona with similar age and kinematics, then between Phoenix and Tucson, Arizona the upper-plate transport direction reverses (Fig. 2). The MCC belt continues south from Tucson into Mexico, with variable extension directions ranging from nearly north-south to west-southwest-east-northeast, and ends in the Sierra Mazatán near Hermosillo, Sonora (Nourse et al., 1994; Wong and Gans, 2003).

The SB&R MCCs evolved in Late Oligocene to Middle Miocene time, generally beginning and ending earlier in the south than in the northwest. Thus, MCC activity in the NB&R and SB&R migrated toward one another, and the two halves of the B&R were finally joined when extension began in the Central B&R in mid-Miocene time.

The Mojave Desert, here included in the SB&R, is not extending at present, but its central part was highly extended in early Miocene time (pre-18 Ma) when the central Mojave MCC was active (Dokka, 1989; Glazner et al., 1989). At present, the Mojave Desert is a regime of distributed dextral shear within the eastern California shear zone (Savage et al., 1990; Dokka and Travis, 1990).

The Rio Grande Rift also began to form in late Oligocene time, with extension concentrated around silicic caldera complexes (Chapin and Cather, 1994; Cather et al., 1994; Ingersoll, 2001). By middle Miocene time, rapid extension was ongoing along the length of the Rio Grande Rift, which comprised separate, morphologically closed lacustrine basins separated by accommodation zones across which the transport direction of master normal fault systems reversed. The extension rate slowed in latest Miocene time, allowing the formerly closed basins to fill and become integrated into the through-going Rio Grande River system.

The Mexican B&R is contiguous with the SB&R, and runs south to the Trans-Mexican Volcanic belt, where young arc volcanoes formed above slabs subducting along the Middle America trench (Henry and Aranda-Gomez, 1992, 2000; Ferrari et al., 2007). The Mexican B&R is divided into the eastern Meseta Central province and the western Gulf Extensional Province, separated by the north-trending Sierra Madre Occidental volcanic plateau and underlying batholithic belt (Fig. 1; Dickinson, 2002; Ferrari et al., 2007). The Gulf Extensional Province was originally defined as the region around the Gulf of California that is affected by young extension related to opening of the gulf (Gastil et al., 1975; Stock and Hodges, 1989), but the northern and eastern boundaries were poorly defined. Dickinson (2002) recently expanded the Gulf Extensional Province to include the southwestern part of the SB&R and all of the western Mexican B&R. In general, the Mexican B&R, particularly the Meseta Central Province, is less well studied and described than the rest of the B&R, so may be the most fertile ground for new discoveries.

Extension began in the Meseta Central province in Oligocene time (Henry and Aranda-Gomez, 2000; Ferrari et al., 2007) and continued into Miocene but probably was of generally low to moderate magnitude. The onset of extension migrated generally westward through time, beginning in latest Oligocene to early Miocene time in the eastern part of the Gulf extensional province, and in middle Miocene time in the western part (e.g., Henry, 1989; Gans, 1997).

Early extension in the Southern and Mexican B&R was broadly coeval with voluminous eruptions of generally subalkaline ignimbrite and basaltic andesite of the Southern Cordilleran Basaltic Andesite association (SCORBA; Cameron et al., 1989; see review in Ferrari et al., 2007). Ignimbrites of the Sierra Madre Occidental volcanic province (much larger in area than the unextended Sierra Madre Occidental of Figure 1) form one of the largest silicic igneous provinces on Earth. By late middle Miocene time, volcanism had migrated west and narrowed into a more typical fringing continental arc centered approximately in the present Gulf of California (e.g., Hausback, 1984; Sawlan, 1991; Ferrari et al., 2007).

GULF EXTENSIONAL PROVINCE

The Gulf Extensional Province (GEP) is unique within the B&R because it now contains the Pacific-North American plate boundary. The continental lithosphere has been ruptured there, and juvenile oceanic and quasi-continental crust is forming in narrow spreading centers connected by northwest-striking, dextral transform faults in the Gulf of California and contiguous Salton Trough (which forms the northern end of the gulf depression) (e.g., Lonsdale, 1989).

The eastern parts of the GEP were extending in early to middle Miocene time, in an intra- to back-arc, subduction setting (Henry, 1989; Gans, 1997; Ferrari et al., 2007). Extension was ongoing along the length of the GEP by ~14-12 Ma (e.g., Stock and Hodges, 1989). By about 15 Ma, the buoyancy of the young Farallón plate subducting under North America had caused subduction to slow, presumably as coupling to the edge of the continent increased (e.g., Bohannon and Parsons, 1995). Subduction apparently ended by ~14 Ma, as indicated by sediments of that age at the base of the offshore Magdalena fan, which was deposited on a microplate (Yeats and Haq, 1981). These events presumably record detachment of the preserved microplates from the already subducted and inexorably sinking slab. The Farallón plate then fragmented into microplates and the spreading direction between the microplates and the Pacific plate systematically rotated to become increasingly parallel to Pacific-North America motion (Lonsdale, 1991; Atwater and Stock, 1998; Michaud et al., 2006), also presumably reflecting the coupling between the microplates and the west edge of the continent. Spreading slowed rapidly after ~12 Ma (Atwater, 1970; Lonsdale, 1991; Atwater and Stock, 1998) and had ended completely by ~8 Ma (Michaud et al., 2006) during which time the continental-margin sliver west of the Tosco-Abreojos-San Benito fault system (in the continental borderland west of Baja California; Spencer and Normark, 1979; Michaud et al., 2004) was almost completely transferred to the Pacific Plate.

The modern phase of GEP opening began at ~12 Ma. Significant dextral slip probably continued on the Tosco-Abreojos-San Benito fault system west of Baja California, with extension partitioned mainly to the east (Spencer and Normark, 1979, 1989; Stock and Hodges, 1989). This traditional, strain-partitioned view has been challenged recently (e.g., Gans, 1997), which is supported by recognition of more transform-parallel extension in the southern gulf (~450 km; Lizarralde et al., 2007) than can be accommodated in the northern gulf (~320 km; e.g., Oskin and Stock, 2003) and because the submarine Magdalena fan probably formed farther north than originally postulated (Fletcher et al., 2007). These relationships imply that ~150 km of dextral shear may be unaccounted for in western mainland Mexico, which may have a transtensional history like the Walker Lane. By ~5.5 Ma, dextral transform faulting "jumped" into the GEP (Crowell, 1981), initiating the modern southern San Andreas fault and the plate boundary system in the Gulf of California, and leading to final rupture of the continental lithosphere in the GEP and marine flooding shortly thereafter (Oskin and Stock, 2003).

The relative contributions of possible extensional driving forces in the Gulf of California remains unclear. Before opening, the region presently occupied by the gulf may have been elevated and had thick, hot, weak crust left from older shortening and Miocene arc volcanism, so gravitational potential energy may have been important. As described above, events relating to fragmentation of the Farallón plate into microplates and their subsequent rotation and capture also suggest that basal drag between the microplates and the continental margin may have been significant. This may have been significant as early as ~12 Ma, when mid-ocean ridge spreading had ended (Lonsdale, 1991) or was waning (Michaud et al., 2006), and almost certainly by ~8 Ma, by which time mid-ocean ridge volcanism had ended (Michaud et al., 2006).

A recent onshore-offshore wide-angle reflection seismic experiment in the southern gulf (Lizarralde et al., 2007) imaged crustal structure along three northwest-southeast, transform-parallel transects that connect conjugate margins (Figs. 1 and 3). In the mouth of the gulf, between Cabo San Lucas, Baja California Sur and Puerto Vallarta, Jalisco, approximately 55 km (measured parallel to the transect) of slightly thick (~7 km) oceanic crust formed under the Maria Magdalena Rise beginning at ~4.5 Ma (Line 1, Figs. 1 and 3). Subsequently, ~175 km of normal-thickness (~6 km) oceanic crust formed at the East Pacific Rise, which propagated into the mouth of the gulf at ~3.5 Ma. The continental margin of Baja California is narrow (~90 km along the profile) and continental crust thickens rapidly to the northwest. The continental margin to the southeast is wider: it is strongly thinned (to only ~9-13 km) for ~80 km, then thickens southeastward to >25 km over ~100 km of horizontal distance. Thus, the Cabo San Lucas-Puerto Vallarta transect was a narrow rift before sea floor spreading began, and it displayed normal to slightly robust magmatism once spreading began.

In the Alarcón basin, across one transform system and only ~100 km to the northeast (Line 2, Figs. 1 and 3), normal oceanic crust is only ~135 km wide and did not begin to form until ~3.6 Ma (DeMets, 1995). Extension in the continental margins is also asymmetric, with a somewhat narrower margin (~280 km along the transect) on the Baja California side and a wider (>380 km), strongly and very irregularly thinned (to ~7-27 km) continental margin on the southeast end of the transect. Significant local Moho relief is preserved along this line (up to ~5 km relief in ~40 km of horizontal distance).

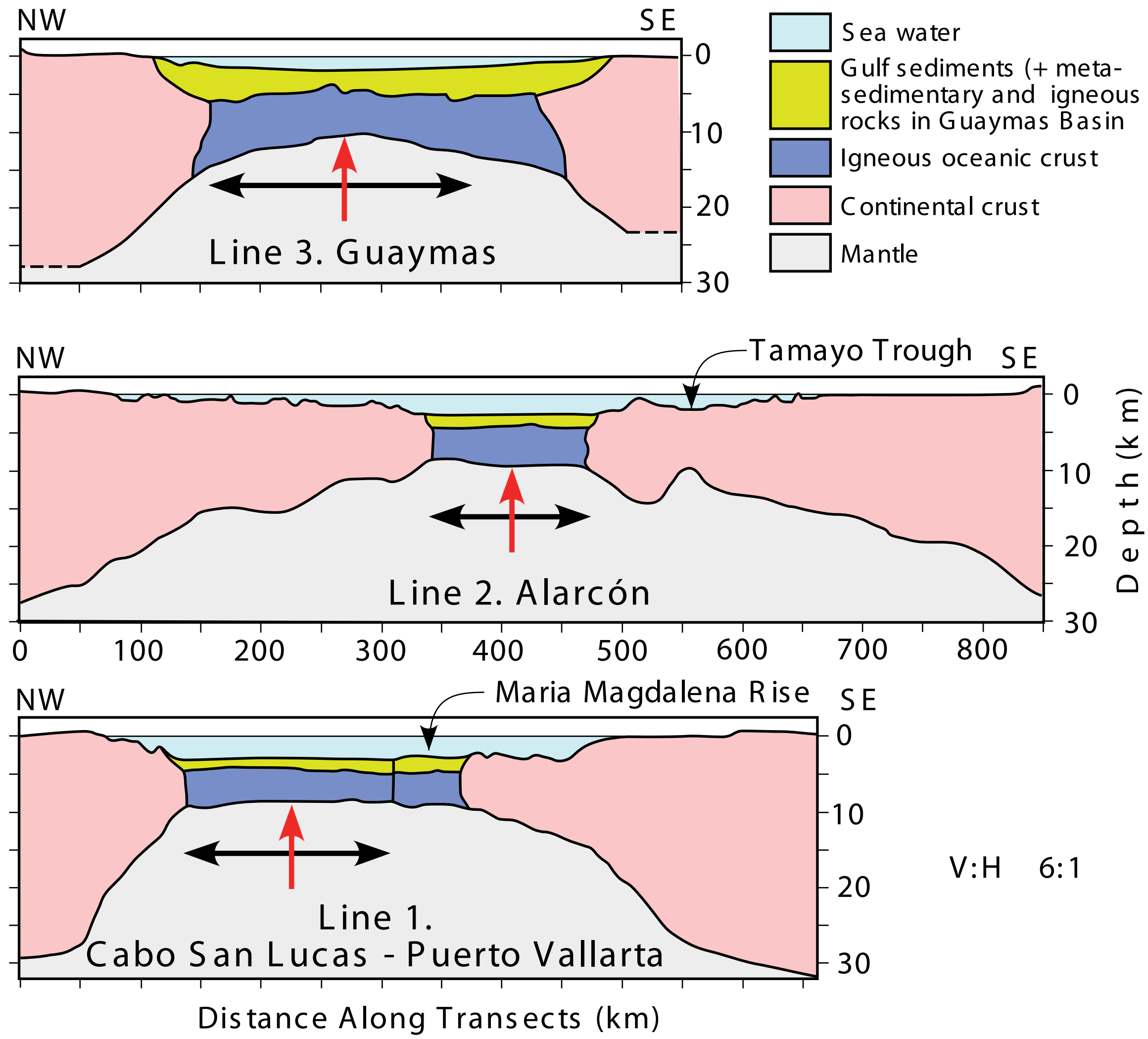

Figure 3. Gross crustal structure along three transects parallel to transform faults in the southern Gulf of California (simplified from Lizarralde et al., 2007; locations of transects shown on figure 1). Red arrows show loci of modern spreading and double-headed black arrows show regions of symmetric spreading at those axes.

The Alarcón transect appears to have been a cold, wide rift that was magmatically starved.

Thus, (1) gulf opening in the Alarcón transect was accommodated entirely by continental extension from ~4.5-3.5 Ma, while oceanic spreading was ongoing immediately to the southwest in the mouth of the Gulf, (2) the net widths (measured parallel to the transforms) of the pre-oceanic rift segments changed rapidly along strike from ~270 km between Cabo San Lucas and Puerto Vallarta to ~660 km in the Alarcón transect, and (3) substantially less new oceanic crust formed in the Alarcón transect (~135 km) than in the Cabo San Lucas-Puerto Vallarta transect (~175 km) since ~3.5 Ma, requiring that oceanic spreading and continental extension were synchronous in the Alarcón transect for a significant portion of that time.

Farther north, in Guaymas basin (Line 3, Figs. 1 and 3), ~280 km (northwest-southeast) of oceanic crust is abnormally thick (up to ~8 km) and lies under ~2 km of sediment. The continental margins are narrow (together only ~ 150 km wide). So, the Guaymas segment appears to have been a narrow rift that was magmatically robust after sea floor spreading began.

The crustal structure of the northern gulf is less well known (Persaud et al., 2003; González-Fernández et al., 2005; Aragón-Arreola and Martín-Barajas, 2007), but is probably similar to the structure of the Salton trough (Figs. 1 and 4), which is relatively well understood. Sedimentary deposits, mainly of the Colorado River delta, fill the Salton Trough (Winker and Kidwell, 1996). The west side is bounded by the west Salton detachment fault (Axen and Fletcher, 1998), which dips gently east and has the stable Peninsular Ranges as its footwall (Fig. 4). The northeastern side is defined mainly by the southern San Andreas fault. P-wave velocity structure of the edges of the Salton trough is typical of continental crust: a sedimentary layer no more than a few kilometers thick overlies a layer of typical felsic to intermediate velocity (e.g.,

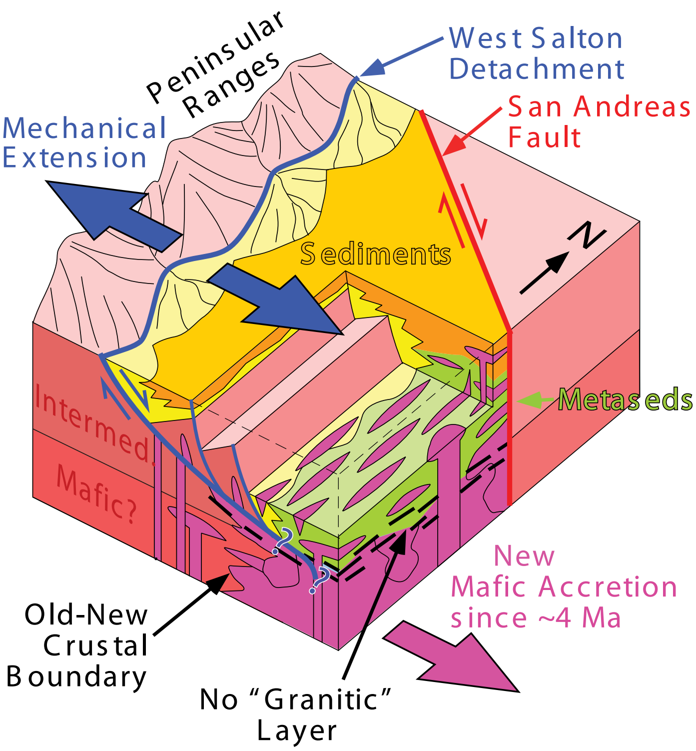

Figure 4. Schematic block diagram, viewed to the northwest, of the Salton Trough from ~4? Ma to ~1.1 Ma, while the west Salton detachment was slipping synchronously with the southern San Andreas fault and with generation of new mafic lower crust. Juvenile "quasi-continental" crust that lacks a granitic layer (Fuis and Kohler, 1984) underlies the central Salton Trough (front corner of the diagram). Note that the west Salton detachment has only about 20 km of net slip whereas the San Andreas fault slipped ~150-200 km during that time frame. See text for discussion.

~6.3 km/s) that, in turn, overlies mafic lower crust (Fuis et al., 1982; Fuis and Kohler, 1984).

In contrast, the central Salton Trough is underlain by juvenile crust ~25 km thick (Elders et al., 1972; Fuis et al., 1982; Fuis and Kohler, 1984; Fig. 4). Based upon seismic P-wave velocities and well data, the upper ~12 km consists of sediments that grade rapidly downward into metasediments, with both probably intruded by downward-increasing volumes of juvenile igneous bodies: P-wave velocity increases smoothly with depth from ~2 km/s to ~5.8 km/s (Fuis et al., 1982; Fuis and Kohler, 1984). A well drilled to ~3 km depth in this succession bottomed in greenschist facies metasediments of Pleistocene age at ~300°C (Elders and Sass, 1988). The metasediments are underlain by ~12 km of juvenile mafic crust, with a transition ~1 km thick in which P-wave velocity increases from ~5.8 to ~7.2 km/s. The maximum age of this mafic basement is not known, but the Salton Trough appears, on the basis of the total thickness of mafic lower crust, to have been magmatically robust. Formation of a mid-ocean ridge was precluded by Colorado River deposition that continually buried the spreading center and kept mafic lavas from interacting with cold seawater. Thus, the sediment-over-mafic layering resembles oceanic crust but the thickness is like thin continental crust, and I refer to this new crust as "quasi-continental". The crustal structure of the northern gulf is probably similar.

CALIFORNIA CONTINENTAL BORDERLAND

The remaining highly extended part of western North America is in the California continental borderland (Legg et al., 1991; Crouch and Suppe, 1993; Bohannon and Parsons, 1995), which lies off shore of southern California and northernmost Baja California, Mexico (Fig. 1). The northeastern part of this region, termed the inner borderland, was rapidly denuded in middle Miocene time in a fairly unique "transrotational" mode in response to Pacific-plate capture of former Farallon plate fragments (e.g., Nicholson et al., 1994). Plate-capture kinematics were similar to, but ~5 Myr older than, those described above for onset of the GEP extension. The captured microplates beneath the borderland dragged the south end of a sliver of marginal North America to the northwest, away from the San Diego, California area. The north end of that sliver, however, remained coupled to North America north of Los Angeles, and the sliver rotated ~100° clockwise around this fulcrum (see review by Dickinson, 1996), denuding the inner borderland, opening the early Los Angeles basin, and exposing high-grade subduction-complex rocks of the Catalina Schist. The rotated sliver now comprises the southernmost Western Transverse Ranges and Channel Islands block northwest of Los Angeles.

After transrotational denudation of the inner borderland but before initiation of the southern San Andreas fault in the Salton trough at ~5.5 Ma, dextral transform slip probably passed south through the Los Angeles basin (Ingersoll and Rumelhart, 1999) and connected to the Tosco-Abreojos-San Benito fault system off shore of Baja California (Spencer and Normark, 1979; 1989; Legg et al., 1991). Releasing steps in this dextral fault system caused additional local extension of the continental borderland (Legg et al., 1991; Lonsdale, 1991; Michaud et al., 2004).

SUMMARY

The western North American extended terrains represent a complexly evolving extensional orogen that rivals many collisional orogenic belts in scale, life span, and complexity of tectonic activity. Extension generally began in an evolving supra-subduction setting as the formerly flat Laramide slab collapsed or rolled back in an irregular fashion, exposing the base of the North American lithosphere to hot asthenospheric influence. Thus much of B&R extension was either intra- or back-arc in nature. B&R extension was widespread by middle Miocene time, with most of the province active and much MCC extension ongoing and rapid. It is likely that MCC extension was largely driven by gravitational potential energy relict from earlier contractional tectonics (e.g., Coney and Harms, 1984; Wust, 1986) but triggered by sublithospheric kinematics of the subducted slab (particularly for pre-Miocene MCCs) and/or by evolution of the transform margin (e.g., Atwater, 1970; Glazner and Bartley, 1984; Atwater and Stock, 1998; Axen et al., 1993; Humphreys, 1995). This ~60 Myr history of diachronous continental extensional activity culminated in a narrow sliver of the continental margin (Baja California and southwestern California) rifting away from the mainland as early as ~12 Ma and finally being torn from North America and mostly transferred to the Pacific plate within the last ~5 Myr, in a strongly oblique event related to oceanic microplate capture along the west coast (Atwater, 1970; Nicholson et al., 1994; Atwater and Stock 1998). This was probably driven by traction between the captured microplates and the base of the continent and/or by gravitational potential energy of previously thickened crust.

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REFERENCES CITED

Aragón-Arreola, M., and Martín-Barajas, A., 2007, Westward migration of extension in the northern Gulf of California, Mexico: Geology, v. 35, p. 571-574.

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.

Atwater, T., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States - An update: International Geology Review, v. 40, p. 375-402.

Axen, G. J., 2007, Research focus: Significance of large-displacement, low-angle normal faults: Geology, v. 35, n. 3, p. 287-288.

Axen, G. J., and Fletcher, J. M., 1998, Late Miocene-Pleistocene extensional faulting, northern Gulf of California, Mexico and Salton Trough, California: International Geology Review, v. 40, p. 217-244.

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, n. 1, p. 56-76.

Axen, G. J., Wernicke, B., Skelly, M. F., and Taylor, W. J., 1990, Mesozoic and Cenozoic tectonics of the Sevier thrust belt in the Virgin River Valley area, southern Nevada, *in* Wernicke, B., ed., Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 123-153.

Bartley, J. M., Axen, G. J., Taylor, W. J., and Fryxell, J. E., 1988, Cenozoic tectonics of a transect through eastern Nevada near 38° N. latitude, *in* Weide, D. L., and Faber, M. L., eds., This extended land; Geological Excursions in the southern Basin and Range: Las Vegas, Nevada, University of Nevada, p. 1-20.

Best, M. G., Christiansen, E. H., Deino, A. L., Grommé, C. S., McKee, E. H., and Noble, D. C., 1989, Eocene through Miocene volcanism in the Great Basin of the western United States, *in* Chapin, C. E., and Zidek, J., eds., Field excursions to volcanic terrains in the western United States, Volume II: Cascades and Intermountain west: Socorro, New Mexico, New Mexico Bureau of Mines and Mineral Resources, p. 91-133.

Bohannon, R. G., and Parsons, T., 1995, Tectonic implications of post-30 Ma Pacific and North America plate motions: Geological Society of America Bulletin, v. 107, n. 8, p. 937-959.

Cameron, K. L., Nimz, G. J., Kuentz, D., Niemeyer, S., and Gunn, S., 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, p. 7817-7840.

Cather, S. M., Chamberlin, R. M., Chapin, C. E., and McIntosh, W. C., 1994, Stratigraphic consequences of episodic extension in the Lemitar Mountains, 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. 157-170.

Chamberlin, R. M., 1983, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico: A summary, *in* Chapin, C. E., and Callender, J. F., eds., Guidebook, 34th Field Conference, Socorro Region II: Socorro, New Mexico, New Mexico Geological Society, p. 111-118.

Chapin, 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. 5-26.

Christiansen, R. L., and McKee, E. H., 1980, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia intermontaine regions, *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. 283-311.

Christiansen, R. L., Yeats, R. S., Graham, S. A., Niem, W. A., Niem, A. R., and Snavely, P. D., 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, The Geology of North America: v. G-3, p. 261-406.

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

Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., 1980, Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, 490 p.

Crouch, J. K., and Suppe, J., 1993, Late Cenozoic tectonic evolution of the Los Angeles basin and inner California borderland: A model for core complex-like crustal extension: Geological Society of America Bulletin, v. 105, p. 1415-1434.

Crowell, J. C., 1981, An outline of the tectonic history of southeastern California, *in* Ernst, W. G., ed., The Geotectonic Development of California: Rubey Volume I: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., p. 583-600.

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., Burchfiel, B. C., and Suppe, J., eds., Processes in Continental Lithospheric Deformation: Geological Society of America Special Paper 218, p. 133-159.

Davis, G. H., 1983, Shear-zone model for the origin of metamorphic core complexes: Geology, v. 11, p. 342-347.

DeMets, C., 1995, A reappraisal of seafloor spreading lineations in the Gulf of California: Implications for the transfer of Baja California to the Pacific plate and estimates of Pacific-North America motion: Geophysical Research Letters, v. 22, p. 3545-3548.

Dickinson, W. R., 1996, Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system: Geological Society of America Special Paper 305, 46 p.

Dickinson, W. R., 2002, The Basin and Range province as a composite extensional domain: International Geology Review, v. 44, p. 1-38.

Dickinson, W. R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, p. 353-368; doi: 10.1130/GES00054.1.

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

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

Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T., and Biehler, S., 1972, Crustal spreading in southern California: Science, v. 178, p. 15-24.

Elders, W. A., and Sass, J. H., 1988, The Salton Sea scientific drilling project: Journal of Geophysical Research, v. 93, p. 12,953-12,968.

Ferrari, L., Valencia-Moreno, M., and Bryan, S., 2007, Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America, *in* Alaniz-Álvarez, S. A., and Nieto-Samaniego, Á. F., eds., Geology of México: Celebrating the Centenary of the Geological Society of México: Geological Society of America Special Paper 422, p. 1–39, doi: 10.1130/2007.2422(01).

Fletcher, J. M., Grove, M., Kimbrough, D. L., Lovera, O., and Gehrels, G. E., 2007, Ridge-trench interactions and the Neogene tectonic evolution of the Magdalena shelf and southern Gulf of California: Insights from detrital zircon U-Pb ages from the Magdalena fan and adjacent areas: Geological Society of America Bulletin, v. 119, p. 1313-1336; doi: 10.1130/B26067.1.

Fuis, G. S., and Kohler, W. M., 1984, Crustal structure and tectonics of the Imperial Valley region, California, *in* Rigsby, C. A., ed., The Imperial Basin - tectonics, sedimentation, and thermal aspects: Los Angeles, California, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 40, p. 1-13.

Fuis, G. S., Mooney, W. D., Healey, J. H., McMechan, G. A., and Lutter, W. J., 1982, Crustal structure of the Imperial Valley region: U. S. Geological Survey Professional Paper 1254, p. 25-49.

Gans, P. B., 1997, Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwest Mexico: Tectonics, v. 16, p. 388-408.

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, 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.

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

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

González-Fernández, A., Dañobeitia, J. J., Delgado-Argote, L. A., Michaud, F., Córdoba, D., and Bartolomé, R., 2005, Mode of extension and rifting history of upper Tiburón and upper Delfín basins, northern Gulf of California: Journal of Geophysical Research, v. 110 (B01313), p. 1-17; doi:10.1029/2003JB002941.

Hausback, B. P., 1984, Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico, *in* Frizzell, V. A., Jr., ed., Geology of the Baja California Peninsula: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 39, p. 219-236.

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, n. 9, p. 1147-1156.

Henry, C. D., and Aranda-Gomez, J. J., 1992, The real southern Basin and Range: Mid- to late Cenozoic extension in Mexico: Geology, v. 20, n. 8, p. 701-704.

Henry, C. D., and Aranda-Gomez, J. J., 2000, Plate interactions control middle-late Miocene, proto-Gulf and Basin and Range extension in the southern Basin and Range: Tectonophysics, v. 318, p. 1-26.

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, n. B6, p. 6,213-6,224.

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 intraplate extension: Journal of Geophysical Research, v. 96, n. B8, p. 13,545-13,560.

Humphreys, E. D., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, n. 11, p. 987-990.

Ingersoll, R. V., 2001, Structural and stratigraphic evolution of the Rio Grande Rift, northern New Mexico and southern Colorado: International Geology Review, v. 43, p. 867-891.

Ingersoll, R. V., 2003, Structural and stratigraphic evolution of the Rio Grande Rift, northern New Mexico and southern Colorado, *in* Klemperer, S. L., and Ernst, W. G., eds., The lithosphere of western North America and its geophysical characterization: The George A. Thompson volume: Columbia, Maryland, Bellwether Publishing, Ltd., International Book Series, p. 251-275.

Ingersoll, R. V., and Rumelhart, P. E., 1999, Three-stage evolution of the Los Angeles basin, southern California: Geology, v. 27, p. 593-596.

Jackson, J. A., 1987, Active normal faulting and crustal extension, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society [London] Special Publication 28, p. 3-17.

Legg, M. R., Wong-O., V., and Suarez-V., F., 1991, Geologic structure and tectonics of the inner continental borderland of northern Baja California, *in* Dauphin, J. P., and Simoneit, B. T., eds., Gulf and peninsular province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 145-178.

Lizarralde, D., Axen, G. J., Brown, H. E., Fletcher, J. M., González-Fernández, A., Harding, A. J., Holbrook, S. W., Kent, G. M., Paramo, P., Sutherland, F., and Umhoefer, P. J., 2007, Variation in styles of rifting in the Gulf of California: Nature, v. 448, p. 466-469.

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, The Geology of North American, v. N, p. 499-522.

Lonsdale, P., 1991, Structural patterns of the Pacific floor offshore of Peninsular California, *in* Dauphin, J. P., and Simoneit, B. T., eds., Gulf and peninsular province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 87-125.

McQuarrie, N., and Wernicke, B. P., 2005, An animated tectonic reconstruction of southwestern North America since 36 Ma: Geosphere, v. 1, p. 147-172; doi: 10.1130/GES00016.1.

Michaud, F., Royer, J.-Y., Bourgois, J., Dyment, J., Calmus, T., Bandy, W., Sosson, M., Mortera-Gutiérrez, C., Sichler, B., Rebolledo-Viera, M., and Pontoise, B., 2006, Ocean-ridge subduction vs. slab break off: Plate tectonic evolution along the Baja California Sur continental margin since 15 Ma: Geology, v. 34, p. 13-16, doi: 10.1130/G22050.1.

Michaud, F., Sosson, M., Royer, J.-Y., Chabert, A., Bourgois, J., Calmus, T., Mortera, C., Bigot-Cormier, F., Bandy, W., Dyment, J., Pontoise, B., and Sichler, B., 2004, Motion partitioning between the Pacific plate, Baja California and the North American plate: The Tosco-Abreojos fault revisited: Geophysical Research Letters, v. 31, L08604, doi:10.1029/2004GL019665.

Nicholson, C., Sorlien, C. C., Atwater, T., Crowell, J. C., and Luyendyk, B. P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas as a low-angle fault system: Geology, v. 22, n. 6, p. 491-495.

Nourse, J. A., Anderson, T. H., and Silver, L. T., 1994, Tertiary metamorphic core complexes in Sonora, northwestern Mexico: Tectonics, v. 13, n. 5, p. 1161-1182.

Oskin, M. E., and Stock, J., 2003, Marine incursion synchronous with plate boundary localization in the Gulf of California: Geology, v. 31, p. 23-26.

Persaud, P., Stock, J. M., Steckler, M. S., Martín-Barajas, A., Diebold, J. B., González-Fernández, A., and Mountain, G. S., 2003, Active deformation and shallow structure of the Wagner, Consag, and Delfín Basins, northern Gulf of California, Mexico: Journal of Geophysical Research, v. 108 (2355), n. B7, p. 1-17; doi:10.1029/2002JB001937.

Proffett, J. M., Jr., 1977, Cenozoic geology of the Yerington District, Nevada, and implications for nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247-266.

Savage, J. C., Lisowski, M., and Prescott, W. H., 1990, An apparent shear zone trending north-northeast across the Mojave Desert into Owens Valley, eastern California: Geophysical Research Letters, v. 17, p. 2113-2116.

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 Provinces of the Californias: American Association of Petroleum Geologists Memoir 47, p. 301-370.

Sedlock, R. L., Ortega-Gutiérrez, F., and Speed, R. C., 1993, Tectonostratigraphic terranes and tectonic evolution of Mexico: Geological Society of America Special Paper 278, 153 p.

Sengor, A. M. C., and Natal'in, B. A., 2001, Rifts of the world, *in* Ernst, R. E., and Buchan, K. I., eds., Mantle plumes: Their identification through time: Geological Society of America Special Paper 352, p. 389-482.

Snow, J. K., and Wernicke, B. P., 2000, Cenozoic tectonism in the central Basin and Range: Magnitude, rate and distribution of upper crustal strain: American Journal of Science, v. 300, p. 659-719.

Spencer, J. E., and Normark, W. R., 1979, Tosco-Abreojos fault zone: A Neogene transform plate boundary within the Pacific margin of southern Baja California, Mexico: Geology, v. 7, p. 554-557.

Spencer, J. E., and Normark, W. R., 1989, Neogene plate-tectonic evolution of the Baja California Sur continental margin and the southern Gulf of California, Mexico, *in* Winterer, E. L., Hussong, D. M., and Decker, R. W., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, The Geology of North American, v. N, p. 489-497.

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: Tucson, Arizona Geological Society Digest 17, p. 539-574.

Spencer, J. E., Richard, S. M., Reynolds, S. J., Miller, R. J., Shafiqullah, M., Gilbert, W. G., and Grubensky, M. J., 1995, Spatial and temporal relationships between mid-Tertiary magmatism and extension in southwestern Arizona: Journal of Geophysical Research, v. 100, p. 10,321-10,351.

Stewart, J. H., 1988, Tectonics of the Walker Lane belt, western Great Basin: Mesozoic and Cenozoic deformation in a shear zone, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States: Englewood Cliffs, NJ, Prentice Hall, p. 683-713.

Stewart, J. H., and Carlson, J. E., 1976, Cenozoic rocks of Nevada: Nevada Bureau of Mines and Geology, scale 1:1,000,000.

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.

Stockli, D. F., 1999, Regional timing and spatial distribution of Miocene extension in the northern Basin and Range province: Stanford University, 239 p.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645-648.

Wernicke, B.P., 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.: The geology of North America: Boulder, Colorado, Geological Society of America, The Geology of North American, v. G-3, p. 553-582.

Wernicke, B., 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.

Wernicke, B. P., and Snow, J. K., 1998, Cenozoic tectonism in the central Basin and Range: Motion of the Sierran-Great Valley block, *in* Ernst, W. G., and Nelson, C. A., eds., Integrated Earth and environmental evolution of the southwestern United States: Columbia, Maryland, Bellwether Publishing, p. 111-118.

Winker, C. D., and Kidwell, S. M., 1996, Stratigraphy of a marine rift basin: Neogene of the western Salton Trough, California, *in* Abbott, P. L., and Cooper, J. D., eds., Field conference guidebook and volume for the annual convention, San Diego, California, May, 1996: Bakersfield, California, Pacific Section, American Association of Petroleum Geologist, p. 295-336.

Wong, M. S., and Gans, P. B., 2003, Tectonic implications of early Miocene extensional unroofing of the Sierra Mazatán metamorphic core complex, Sonora, Mexico: Geology, v. 31, n. 11, p. 953-956.

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

Yeats, R. S., and Haq, B. U., 1981, Deep-sea drilling off the Californias: Implications of Leg 63, *in* Yeats, R. S., et al., eds., Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, p. 949-961.