

Middle Miocene to early Pliocene oblique extension in the southern Gulf of California

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ABSTRACT

A multichannel seismic (MCS) experiment spanning 600 km across the Alarcón Rise and its conjugate rifted margins in the southern Gulf of California (western North America) provides insight into the spatial and temporal evolution of extension between Baja California and the mainland (Mexico). Stratigraphic analysis of multiple rift basins within the Alarcón spreading corridor indicates an initial stage of oblique extension starting ca. 14–12 Ma. This initial phase of extension was characterized by the formation of several large basins in the center of the gulf and on the southeast margin with negligible synrift sedimentation. A second phase of oblique extension, likely synchronous with large-scale basin opening in the central and northern Gulf of California, began ca. 8–5 Ma and was characterized by the formation of smaller half-grabens distributed across the conjugate margins that contain both synrift and postrift deposits. A key feature imaged within the MCS data is a highly reflective, rosey layer at the top of basement, interpreted to be either volcanic rocks from the 25–12 Ma Comondú Group, and/or early rifting volcanic rocks that are between 11 and 9 Ma, or younger. This volcanic layer is extensively faulted, suggesting that it predates the episode of early extension. Upper crustal extension appears to be equally distributed across conjugate margins, forming

a symmetrical continental rift. Two styles of rifted basin are observed; older basins (estimated as 14–11 Ma using sedimentation rates) show distributed extension with extensive basement faulting. In contrast, the younger basins (likely post–6 Ma) are asymmetrical with synrift deposits thickening into the basin-bounding faults. The northeast-southwest geomorphic expression of the Tamayo bank and trough and other features provides additional evidence that northwest-southeast oblique extension began ca. 12 Ma. These new spatial and temporal constraints, when combined with a crustal thickness profile obtained across the entire Alarcón corridor, suggest that significant northwest-southeast oblique extension within the Gulf of California started well before 6 Ma, in contrast to earlier models.

INTRODUCTION

The Gulf of California formed and evolved over the past ~12 Ma due to a tectonic reorganization when the Magdalena rise stalled off the west coast of North America and a new Pacific–North America plate boundary was established behind the Baja California batholith. The known bounding points on this system are the Magdalena spreading ridge stalling off the west coast of Baja ca. 12 Ma (Stock and Hodges, 1989) and the onset of seafloor spreading in the southern Gulf of California ca. 3.5 Ma. The distribution, both geographical and temporal, of the dextral and extensional components of the plate motion between these two events is still debated (Stock and Lee, 1994; DeMets, 1995; Lonsdale,

1995; Dixon et al., 2000; Michaud et al., 2006; Plattner et al., 2007). Microplate capture of this Cretaceous arc terrain resulted in a highly oblique, rifted continental margin with marked differences in extensional style from north to south. The northern Gulf of California and Salton Trough are buried under kilometers of sediment originating from the Colorado River; sediment burial of these segments likely affects rifting, which is typified by widely distributed zones of deformation with no oceanic seafloor spreading (Nagy and Stock, 2000; Persaud et al., 2003; González-Fernández et al., 2005). In contrast, the southern gulf is poorly sedimented and the southernmost gulf segment, the Alarcón segment, hosts an unsedimented mid-oceanic ridge system similar in many respects to open-ocean mid-oceanic ridge systems throughout the Pacific (Larson, 1972). Most of the present-day deformation is localized on the main plate boundary in the central and southern gulf, but the width and style of rifting prior to this localization vary greatly from the mouth to the central gulf (Lizarralde et al., 2007).

The PESCADOR Experiment (Premiere Experiment, Sea of Cortez, Addressing the Development of Oblique Rifting) was designed to compare and contrast rifting architecture across three different segments in the gulf, including the Guaymas Basin, Alarcón Basin, and the Cabo San Jose to Puerto Vallarta segment, with coincident two-dimensional (2D) multichannel seismic (MCS) and ocean-bottom seismometer transects oriented parallel to transform faults (Fig. 1A) (Lizarralde et al., 2007). Results from these three PESCADOR profiles complement an existing, coincident wide-angle

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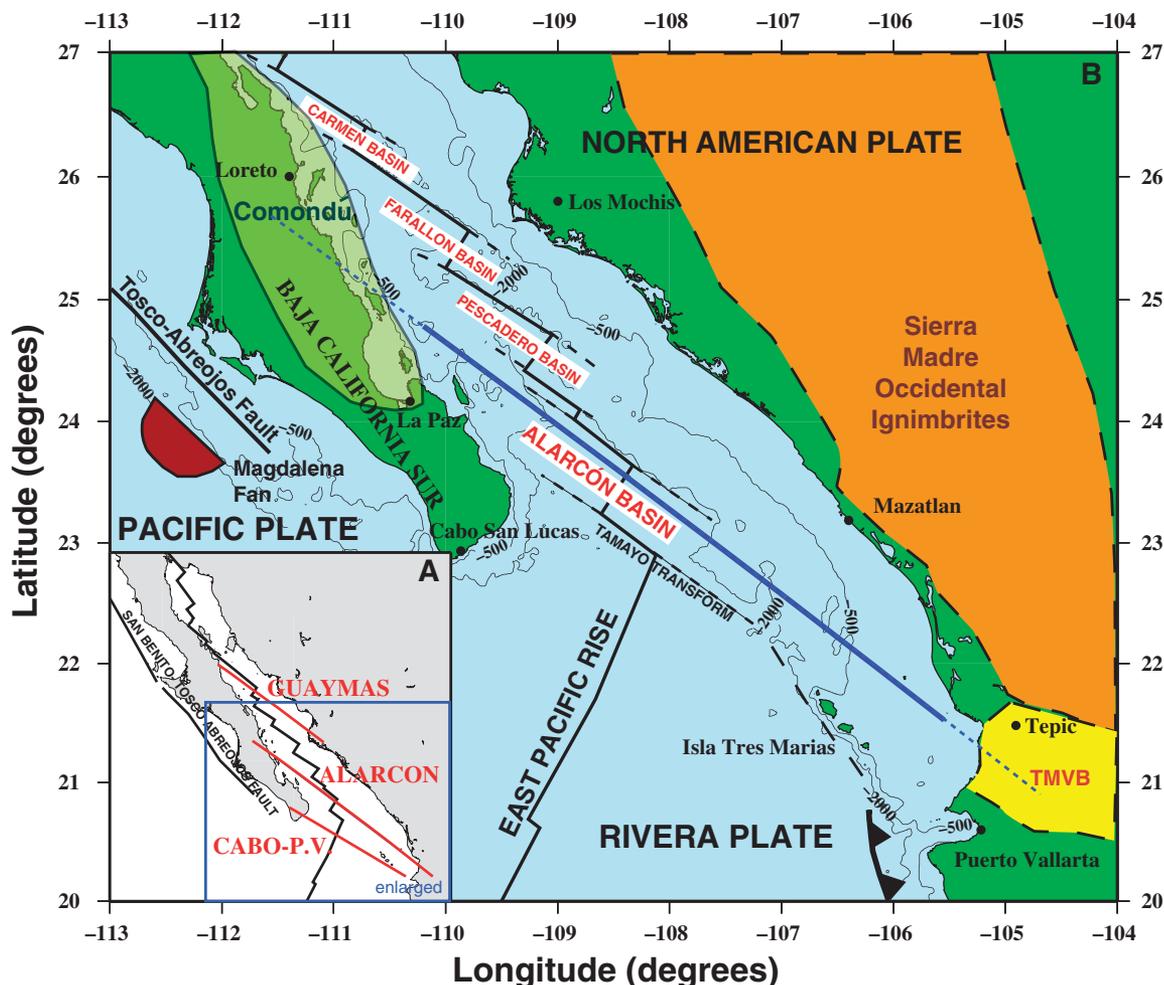


Figure 1. Southern Gulf of California map; major geologic and tectonic features are shown. (A) Three cross-gulf seismic transects (Guaymas, Alarcón, and Cabo San Jose to Puerto Vallarta, [Cabo-P.V.]) acquired during this experiment are shown in red. (B) Southern Gulf of California. The Alarcón profile is shown in blue. Dashed line indicates entire line including refraction data, and the blue solid line shows the extent of multichannel seismic data. Major geologic provinces are the Comondú formation, Sierra Madre Occidental, and Trans-Mexican Volcanic Belt (TMVB). The location of the Magdalena Fan is also highlighted.

and reflection profile across the northern Gulf of California from the CORTES Experiment (Crustal Offshore Research Transect by Extensive Seismic Profiling) (González-Fernández et al., 2005). The two-ship PESCADOR seismic reflection and refraction experiment using R/V *Maurice Ewing* and R/V *New Horizon* was conducted in fall 2002. MCS reflection profiles collected across the Alarcón Basin, the southernmost basin in the Gulf of California (Fig. 1), are presented herein, defining the spatial and temporal history of extensional deformation across this conjugate rifted margin. The seismic refraction profiles, including the Alarcón transect, were presented in Lizarralde et al. (2007). The tectonic evolution of the southern Gulf of California is constructed from interpretation of a 2D reflection seismic profile across the Alar-

cón transect, combined with available geologic information from the Baja California peninsula, mainland Mexico, several offshore islands, and rock dredge hauls.

We infer that the late Comondú Group volcanic units (prerift), along with possible early synrift volcanic rocks, were deposited over much of the basement along the Alarcón transect before and during early stages of continental rifting. Based on sediment thickness and estimated sediment depositional rates in the large basins, we infer that rifting in the southern gulf may have begun as early as 14–11 Ma, as the Cocos-Magdalena subduction waned west of Baja California. This age estimate is consistent with evidence for an early (and controversial) marine incursion (McDougall, 2006). Thus, we infer that northwest-southeast-oriented oblique

extension (the direction of extension is not perpendicular to the continental margin) has been ongoing since the inception of rifting within the Gulf of California, with strain partitioning varying spatially and temporally along the gulf. For example, in the northern Gulf of California much of the extension appears to have occurred east of the present-day gulf (e.g., Gans, 1997; Fletcher et al., 2007). These observations differ from the two-stage rifting models, where rifting switches from an east-west orientation to the oblique northwest-southeast-oriented rifting ca. 6 Ma (Stock and Hodges, 1989). Our conceptual model sees no change in rifting orientation and predicts that oblique northwest-southeast extension has been the rifting style since 14–11 Ma. This conclusion, when coupled with the recent interpretation of an estimate of 425–485 km

total offset across the southern Gulf of California since 12 Ma (Sutherland, 2006; Lizarralde et al., 2007), implies that the rate of northwest-southeast extension across the gulf may have increased ca. 6 Ma, but that significant extension must have been accommodated across the Alarcón transect prior to this.

Tectonic History

The western edge of the North American continent was a convergent margin from the Cretaceous through the Middle Miocene as the Farallon plate subducted beneath the North American plate. Starting ca. 29 Ma, the Pacific–Farallon Ridge began to approach the trench. Between 14 and 12 Ma, seafloor spreading and subduction of the Magdalena plate slowed and ceased west of northwestern Mexico, and a new dextral plate boundary between the North American and Pacific plates began to form (Lonsdale, 1991). Michaud et al. (2006) purported that the demise of seafloor spreading was more long lived, ending near 8 Ma, although the inferred spreading rates west of the trench were negligible during this time frame. The total amount of dextral slip between the Pacific and North American plates since 12 Ma is estimated to be ~600 km (corresponding to an average rate of 50 cm/yr) (Stock and Hodges, 1989). The question of how this relative motion was accommodated through time is debated (e.g., Oskin et al., 2001; Fletcher et al., 2007). Early models of microplate capture partitioned northwest-southeast-directed Pacific–North American plate motion between approximately north-northwest–south-southeast-oriented strike-slip faults (i.e., Tosco-Abreojos and San Benito faults) within the borderlands west of Baja California and east-west-directed extension within the nascent Gulf extensional province (Stock and Hodges, 1989). The strike of faults mapped onshore near Loreto, Baja California, and nearby islands (Umhoefer et al., 2002) is consistent with this early proto-gulf rifting phase, with normal fault orientation trending roughly north-south, thus requiring an ~35°–40° change in rotation direction from latest Miocene to Pliocene time.

The two-stage model of Stock and Hodges (1989) has deformation beginning at 12 Ma with ~300 km slip on the Tosco-Abreojos fault system between 12 and 6 Ma, synchronous with only small amounts of west-east-oriented extension in the region of the Gulf of California. At 6 Ma, strike-slip motion is thought to have jumped east into the gulf, initiating northwest-southeast extension that, because of along-strike segmentation, resulted in a continental margin that was oblique to the extension direction. The

main evidence supporting this model is: (1) the inferred translation, by the Tosco-Abreojos fault system, of the Magdalena Fan from a proposed original location near the mouth of the gulf to its current position (Yeats and Haq, 1981) (Fig. 1B); (2) correlations of the San Felipe tuff across the northern gulf by Oskin and Stock (2003a) that indicate ~300 km of northwest-southeast-directed extension since 6 Ma; and (3) the lack

of mappable units recording substantial extension prior to 6 Ma.

An alternative model for Gulf of California tectonic evolution (Fig. 2) suggests that northwest-southeast-directed extension began much earlier, possibly ca. 12 Ma (Gans, 1997). This model does not infer a clean jump of the Pacific–North America plate boundary, but a somewhat gradual change, with early extension

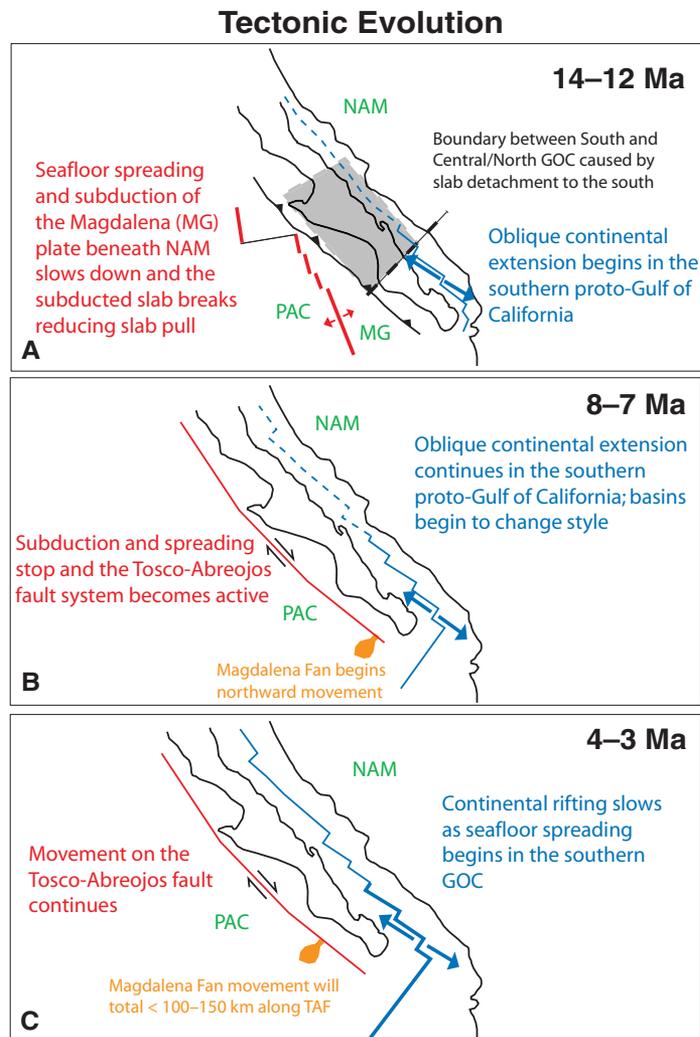


Figure 2. The model for the tectonic evolution of the Gulf of California (GOC). (A) The starting point of the evolution of the GOC began 14–12 Ma, where the Magdalena rise stalled off the west coast of Baja California; there was also a marked change in the style of volcanism. Plate motion was split between the dying spreading ridge, subduction zone, and the new highly oblique extension in the proto-GOC. During this time, the dipping part of the subducted plate appears to have broken off, opening a slab window beneath the southern Baja peninsula. NAM—North American plate; PAC—Pacific plate. (B) Another major change in the system occurs near 8–7 Ma, where the volcanic style changes once again with many lavas of unusual composition deposited. Any minor component of spreading finally ceases and the Tosco-Abreojos fault forms within the borderlands west of Baja. Oblique extension continues in the GOC. (C) Seafloor spreading begins at the Alarcón Rise between 4 and 3 Ma. Small amounts of movement continue along the Tosco-Abreojos fault (TAF); even today the Baja peninsula is not fully transferred to the Pacific plate.

in the Gulf extensional province beginning at 12 Ma in compensation to Pacific–Magdalena spreading and Magdalena plate subduction that both slowed significantly (Michaud et al., 2006). Studies over the Tosco-Abrejos fault indicate that it may not have activated until 8 Ma (Michaud et al., 2004; Brothers et al., 2012), and therefore the Tosco-Abrejos fault may not have been an important component of Pacific–North America plate motion early on, but rather a later fault system that began to accommodate motion ~4 Ma after extension in the gulf began. This distribution of Pacific–North America plate motion is likely still ongoing, as the Baja microplate is still not fully transferred to the Pacific plate, with 3–7 mm/yr dextral slip recorded today (Michaud et al., 2006).

This model is supported by sediment provenance studies and dating of zircons from the Magdalena Fan. These studies place the fan's source region at most only ~100–150 km south of its current location (Fletcher et al., 2007), indicating a smaller magnitude of slip on the faults west of Baja California Sur. This model thus requires that ~450–500 km of dextral slip must have occurred in the gulf since its formation in order to accommodate the total ~600 km of Pacific–North America plate separation since 12 Ma. Correlation of the San Felipe tuff across the northern gulf suggests that there has been ~300 km of northwestward motion of the Baja California microplate since 6 Ma (Oskin and Stock, 2003a, 2003b). This interpretation is supported by seismic observations from Guaymas Basin, where ~300 km of new igneous crust is imaged along a plate kinematic flow line across the northern Guaymas segment (Lizarralde et al., 2007). Consequently, a tectonic model that invokes primarily northwest-southeast extension within the Gulf extensional province since ca. 12 Ma requires at least an additional 150–200 km of northwest-southeast extension and dextral slip during the 12–6 Ma time frame in order to accommodate the full 600 km of Pacific–North America relative motion. This extra 150–200 km of extension is not observed within the marine basins of the central and northern gulf (Oskin and Stock, 2003a, 2003b), but may be located farther east in Sonora, Mexico (Gans, 1997).

A key observation in support of a two-stage tectonic model for the Gulf extensional province is the obvious existence of dominantly north-south-oriented older normal faults along the east coast of Baja California. However, the strike of these faults may not be a reliable indicator of the overall direction of early gulf extension. A present-day analog may be the northern Walker Lane deformation belt, located between the Sierra Nevada mountain range and

the Basin and Range proper. Approximately 10% of plate motion within this province is accommodated along north-south–striking normal faults, while the majority of Sierra Nevada microplate motion is accommodated through either northwest-southeast obliquely oriented fault structures to the east (Unruh et al., 2003; Dingler et al., 2009), or through rotations of domains (Wesnousky et al., 2012). This kinematic strain partitioning observed along the eastern Sierra Nevada today may help explain similar fault structures observed from Loreto to La Paz, Baja California Sur, where normal faults dominate the western margin of the Gulf of California extensional province (Umhoefer et al., 2002, 2008).

There are many similarities between the Walker Lane and the Gulf of California, suggesting that Walker Lane is a plausible modern analogue to the early opening of the gulf. In each instance, localization of Basin and Range–style extension is or was driven by increased coupling between North America and a subducting microplate. The resulting extensional provinces are bounded to the west by an accreted Mesozoic batholithic arc fragment. This batholith serves to both localize extension and, because the batholithic crust is apparently stronger than the pre-thinned crust to the east, create an extensional province with an axis of rifting that is oblique to the extension direction. Such a comparison also predicts the high-standing, north-south–trending normal faults along the eastern Baja margin. These faults would have been active during the 12–6 Ma time period, but they would have accommodated relatively little extension, and so would have undergone only minor tectonic subsidence as a consequence. The analogy further predicts that the older faults characterized by dextral slip and accommodating the bulk of the 12–6 Ma extension are mostly to the east, under the Gulf of California.

The Alarcón rift and spreading segment provides an ideal locale to test this alternative tectonic model, because the submarine portion of this segment is bounded by northwest-southeast–trending fracture zones, including the Tamayo Fracture Zone, along most of its length, and the subaerial zones of extension between the gulf escarpment on Baja California and the Sierra Madre Occidental on mainland Mexico are relatively narrow.

Volcanism and Early Marine Sedimentation

Volcanism associated with the subduction of the Farallon plate beneath North America played a dominant role in the geologic evolution of Baja California and western Mexico throughout the Cenozoic. Westward migra-

tion of the volcanism started during the Oligocene, coincident with the initiation of Basin and Range extension (Dickinson and Snyder, 1978), which occurred from southern Mexico north to southern Oregon and Idaho (Henry and Aranda-Gomez, 2000). Beneath Mexico a possible asthenospheric window opened, initiating the eruption of the extensive Sierra Madre Occidental ignimbrites that erupted in mainland Mexico and northward (past the current United States–Mexico border) mainly from 34 to 27 Ma. In the southern Sierra Madre Occidental, a younger episode of eruptions occurred from 25 to 17 Ma (Ferrari et al., 2007). These ignimbrites swept both westward and southward; the youngest outcrops are located at 21°S near the mainland Mexico coastline (Ferrari et al., 2002).

Across Baja California Sur, an unconformity separates older Tertiary marine strata and Cretaceous granites from younger Oligocene–Miocene terrestrial volcanic and clastic sequences of the Comondú Group (Hausback, 1984; Umhoefer et al., 2001). The base of this sequence contains clastic rocks with numerous common tuffs dated as 25–17 Ma (Umhoefer et al., 2001; Schwennicke and Plata-Hernández, 2003; Drake, 2009; Hosack, 2006), and corresponds to the distal facies of the younger Sierra Madre Occidental ignimbrite province (Ferrari et al., 2002, 2007). The volcanic arc completed its westward migration ca. 19 Ma, and the Early–Middle Miocene calc-alkaline volcanic rocks of the Comondú Group were emplaced within the gulf and along the eastern edge of what is now the Baja California peninsula (Hausback, 1984; Umhoefer et al., 2001). The Comondú arc remained active until ca. 12 Ma; a change in both the amount and geochemistry of volcanism occurred ca. 12 Ma (Umhoefer et al., 2001; Calmus et al., 2011). The subduction-related calc-alkaline volcanism waned, and unusual and heterogeneous lavas erupted, interpreted to be the result of a slab tear beneath the Gulf extensional province.

Additional insight into post-12 Ma volcanism and the geology of extended continental crust in the southern Gulf of California comes from dredge samples and Baja California's numerous offshore islands. For example, Orozco-Esquivel et al. (2010) found a host of submerged, silica-rich intrusive and extrusive igneous rocks ranging in age from early-rift to 21–17 Ma. The islands Carmen, Monserrat, and San Jose, located 26°–25°N, have basement rocks of the Comondú Group and Cretaceous granite overlain by Late Miocene and Pliocene marine sedimentary strata (Backus et al., 2005; Johnson et al., 2005; Umhoefer et al., 2007). Miocene to Pliocene marine basins on Isla Carmen were studied

by Dorsey et al. (2001), who found 850–900 m of marine strata below a mudstone and marlstone unit dated as 3.5–3.1 Ma that was deposited at ~500 m water depth; the basin changed dramatically to a shallow-marine environment shortly after 3 Ma, and sedimentation ceased. Located at 25°N, Isla San Jose (Fig. 3) underwent normal faulting and basin subsidence; older synrift deposits are ca. 6–5 Ma to 2.5 Ma (Umhoefer et al., 2007). Similar to Isla Carmen, the Isla San Jose basin shows a major shift from deep marine to shallow marine ca. 2.5 Ma; sedimentation ended soon after because of a reorganization of faulting. Offshore of La Paz, Isla Espiritu de Santo (Fig. 3) has a granitic basement overlain by andesite flows and tuff of the Comondú

Group, suggesting close proximity to the volcanic arc (Hausback, 1984).

The presence of marine fossils in the northern and central gulf suggests that an early marine incursion may have occurred in the Middle Miocene (14–11 Ma) (McDougall, 2006). A later marine incursion in the southern gulf is well documented by a Neogene sedimentary sequence on Isla Maria Madre (one of the Islas Tres Marias), which is located at the mouth of the gulf between 21°N and 22°N (Fig. 4). Subsidence and sediment deposition began 8.2 Ma; the total sedimentary sequence is ~1150 m thick (McCloy et al., 1988), yielding rough constraints on sedimentation rates in the southern gulf. Data from the San Jose del Cabo basin also

suggest onset of basin formation well before 8 Ma and more likely at 12–10 Ma, the age of the first marine strata being 10–8 Ma (Carreño, 1992; Fletcher et al., 2000; McTeague, 2006). Nevertheless, in the northern gulf, the oldest marine sediments recovered to date are latest Miocene–early Pliocene, indicating a marine incursion ca. 6 Ma (McDougall et al., 1999; Oskin and Stock, 2003b).

This evidence provides us with a basic temporal framework for the southern Gulf of California. The initiation of extension suggested by paleontological evidence places the marine incursion at no later than 8 Ma, but may have begun ca. 14–11 Ma when the Comondú arc was still active, but waning. The subaerial evi-

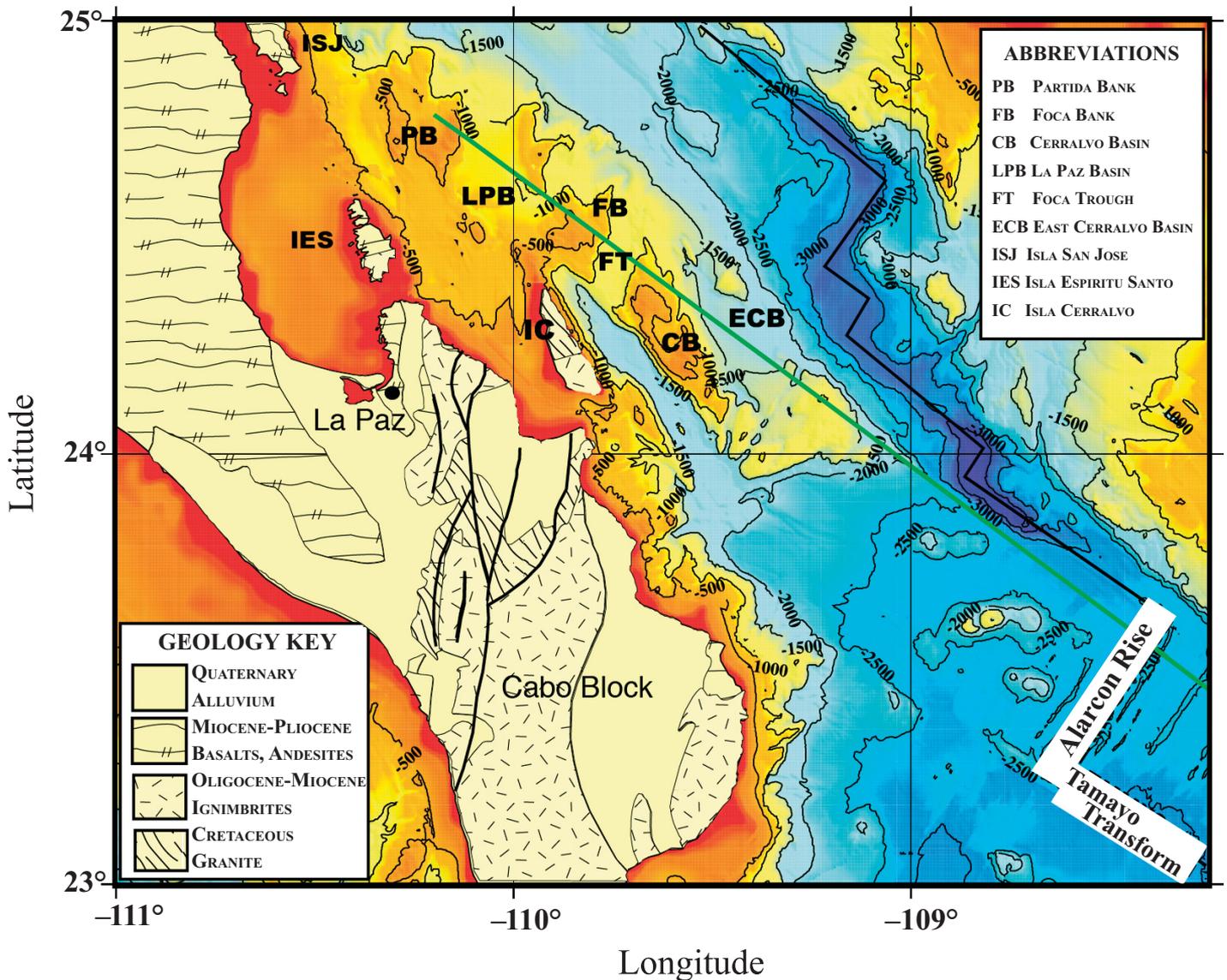


Figure 3. Northwestern (Baja) margin with location of multichannel seismic profile 16 shown in green, with the northwesternmost point of this profile corresponding to position 167 km along the joint reflection-refraction transect (refraction data not shown here continue onto the Baja peninsula). The Cretaceous granites compose the Cabo block.

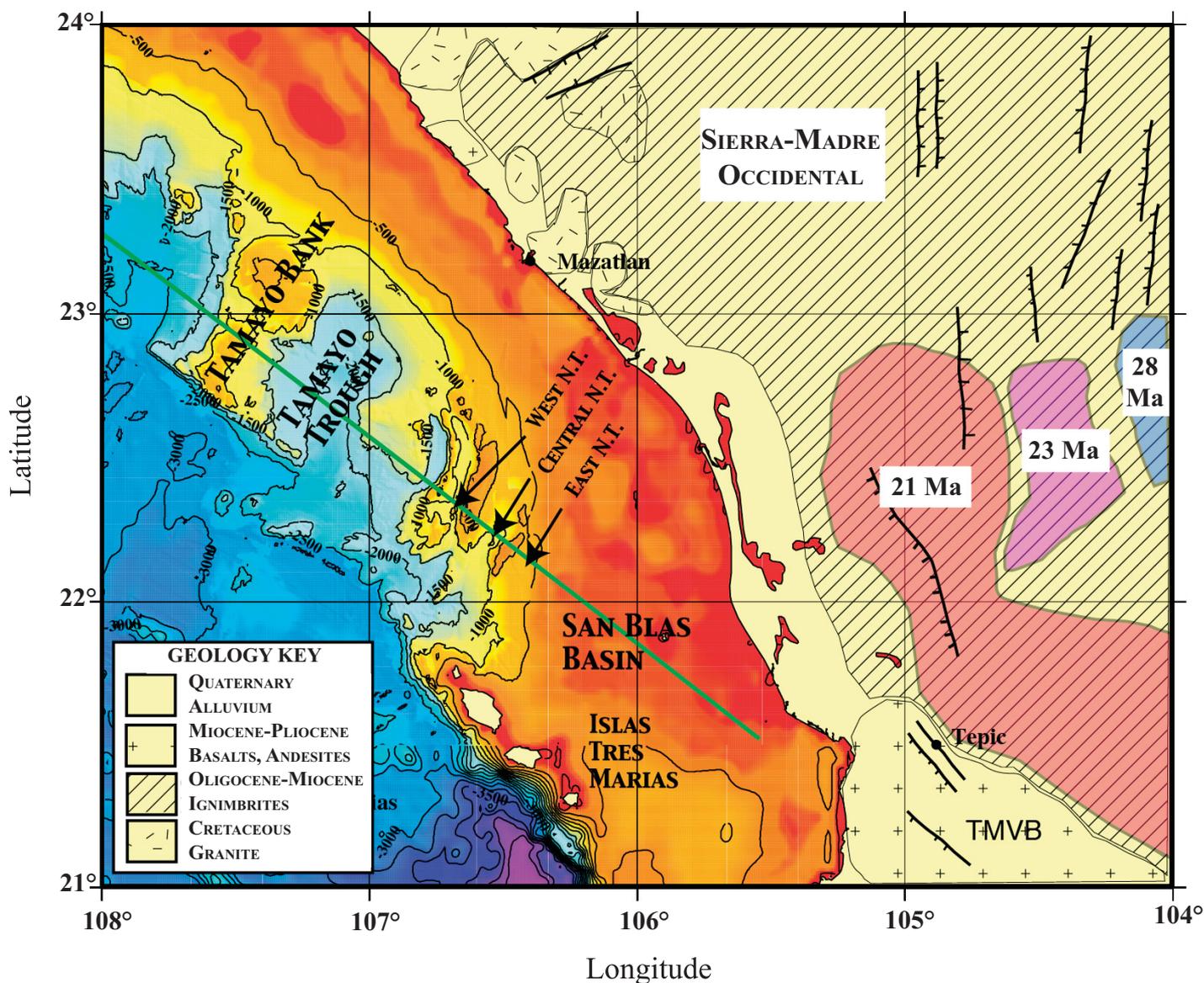


Figure 4. Southeastern (mainland) margin with location of composite of multichannel seismic profiles 16b and 20 highlighted in green; the southeasternmost point of this profile corresponds to a position 767 km along the joint reflection-refraction transect. Simplified geology from INEGI (Instituto Nacional de Estadística y Geografía) and Ferrari et al. (2002) is overlain, including the Sierra Madre Occidental boundary, with dated ignimbrites flares outlined. Location of TMVB (Trans-Mexican Volcanic Belt) is also shown. N.T.—Nayarit trough.

dence for extension and subsidence starting ca. 8 Ma is also recorded by sedimentary sequences on offshore islands of both margins as well as in the Cabo basin.

MCS DATA

The 2D MCS reflection data for the Alarcón profile span the middle 600 km of the 881 km total profile length (Figs. 5 and 6), which incorporates coincident wide-angle refraction data from the land-based IRIS-PASSCAL (Incorporated Research Institutions for Seismology—Program for Array Seismic Studies of the Con-

tinental Lithosphere) and ocean-bottom seismographs (Sutherland, 2006; Lizarralde et al., 2007). To the northwest, the composite MCS profile begins at location 167 km and continues to the southeast, ending at location 767 km (Fig. 5). All locations are given in terms of distance along the 881 km refraction profile starting from 0 km on the Baja California peninsula. MCS data were collected aboard the R/V *Maurice Ewing* using a 480-channel, 6-km-long streamer with 12.5-m receiver groups, recording energy from a 128.8 L (7860 in) tuned 20 airgun array. These data were collected in three separate profiles, each shot northwest to south-

east. Data northwest of the Alarcón Rise (line 16) were collected at 50 m shot spacing (Fig. 5), yielding 60-fold data with 6.25 m common midpoint (CMP) spacing. Due to acquisition issues at sea, the two profiles (lines 16b and 20) south of the Alarcón Rise were shot at a lower repetition rate, 150 m shot spacing, so as to be simultaneously suitable for recording by both the ocean-bottom and PASSCAL seismometers for the refraction profile. This increased shot-rate interval should have reduced the data to 20-fold, but CMP bin spacing was doubled to 12.5 m, yielding 40-fold data. This reduction in spatial sampling prevented the straight-

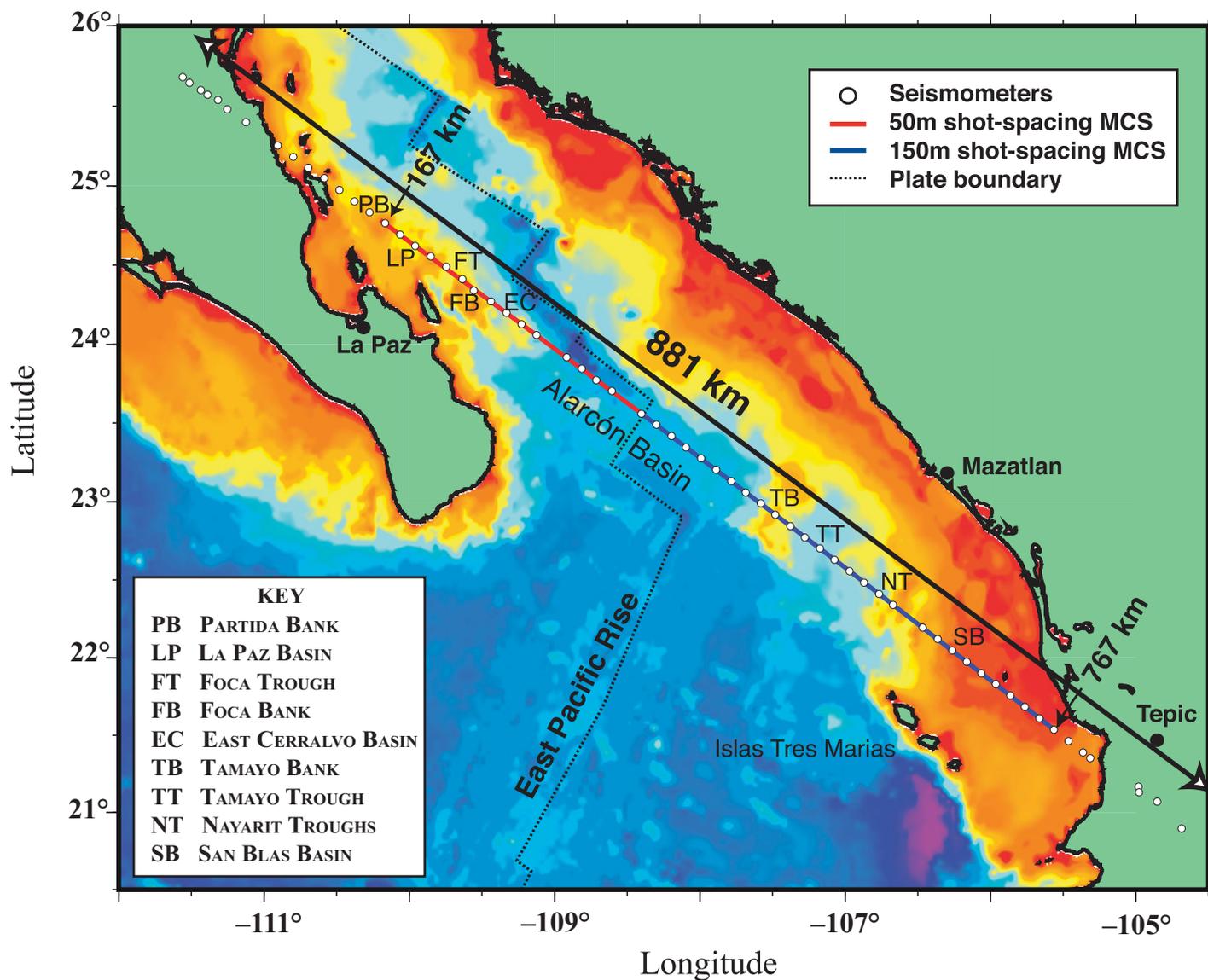


Figure 5. Map showing location of Alarcón transect and the major basins along the profile.

forward use of several processing techniques to improve image quality, such as $f-k$ demultiple techniques, which would have greatly enhanced imaging beneath the shallow-marine shelf across the San Blas basin. Velocity analysis using semblance techniques was carried out every 150–250 CMP for the 50 m shot-spacing data, and every 100 CMP on the 150 m shot-spacing data. The data were bandpass filtered at 15–40 Hz, normal moveout was applied, and the data were stacked. Post-stack time migration was followed by gain correction. Clear images of the basement and sedimentary structures were produced, but no lower crustal or Moho reflections were observed, even in areas with thin oceanic crust.

We outline the basement character, sedimentary sequences, and faults imaged within each

extensional basin from northwest to southeast along the MCS transect. Most basins show multiple sedimentary sequences; several are separated by rift-related geometries (e.g., rotation and divergence of the sedimentary packages). Synrift sedimentary sequences are defined by a thickening of a sedimentary unit toward an apparent fault, indicating deposition of sediments during active fault movement or tectonically induced accommodation. Postrift sequences typically do not show thickening of units toward the fault plane or disruptions of stratigraphic layering, and are more regionally deposited and often mantle underlying structures. Thus, the cessation of active, large-scale extension and accommodation (i.e., space creation) within a basin is commonly marked by the change from synrift to postrift sedimentary

sequences (Falvey, 1974). It is important to note that there are some difficulties inherent to this approach in regions where rates of tectonic deformation have diminished markedly but are still ongoing or in regions with low, episodic sedimentation. It is well known that the southwestern margin of the gulf, including the northwest end of the Alarcón transect, has many basins that show such a change, from relatively rapid faulting rates to much slower, but still active faulting, ca. 3–2 Ma (Dorsey et al., 2001; Umhoefer et al., 2002, 2007).

Northwestern Margin

The northwestern MCS transect spans 230 km between Partida bank (170 km along transect) and the Alarcón ridge crest (400 km

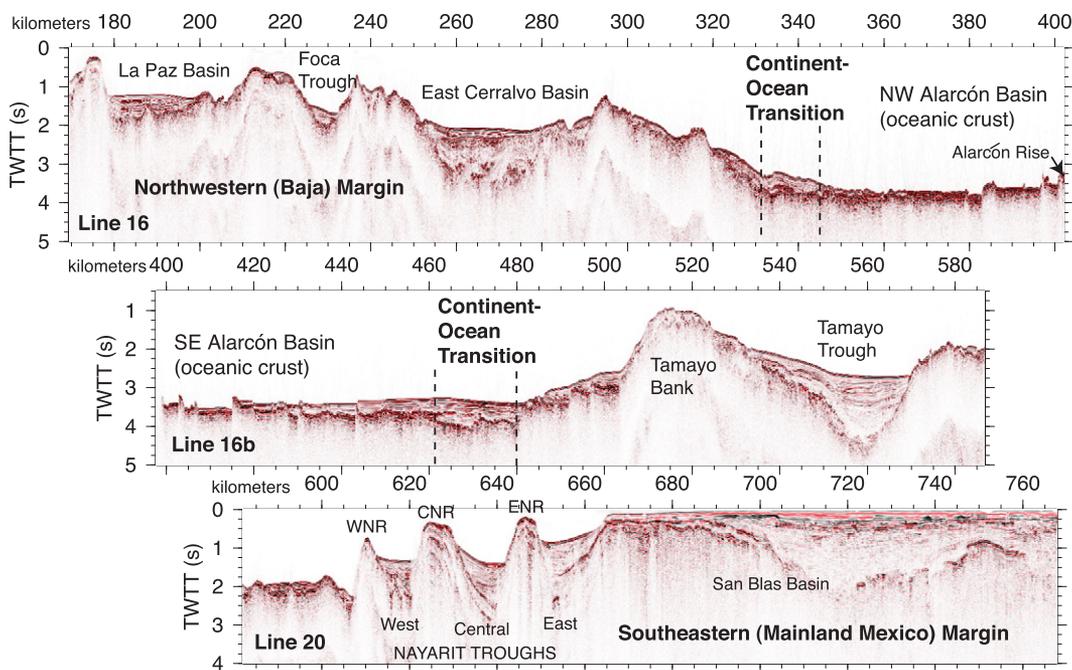


Figure 6. An overview of multi-channel seismic transect data presented in this paper. Seismic data are post-stack time migrated. TWTT—two-way traveltime.

along transect) (Figs. 5 and 6). We image two major basins on the extended continental crust of this margin west of the continent-ocean transition, the La Paz and East Cerralvo basins. The topography of the extended continental crust of the eastern Baja California margin has multiple topographic highs and basins. The margin is poorly sedimented, due mostly to the arid climate of Baja California Sur, and most sediment is supplied as storm-related runoff and is trapped in basins close to the peninsula (Nava-Sanchez et al., 2001), although in some locations, such as near the Cabo block, efficient pathways for sediment delivery to deeper gulf basins exist. The northwesternmost basin imaged by the MCS data is a deeper section of the La Paz basin, located 185 km along the Alarcón transect (Fig. 7). This basin has a simple structure, with a down-to-the-southeast normal bounding fault located to the northwest. Maximum sediment thickness is 0.6 s two-way traveltime (TWTT; all thicknesses are given in TWTT in this discussion, and are later converted to depth using estimated sediment velocities). The sediments thin toward the south, but the parallel concordant layering without major rotation suggests that most sedimentation is postdeformation, implying either very low or negligible slip rates on bounding faults. Minor displacement along the border fault and differential subsidence could account for the subtle dip of the basal sequence to the northwest. The upper portion of this package appears to be current controlled with differential erosion and nondeposition between 195 and 200 km, often referred to as

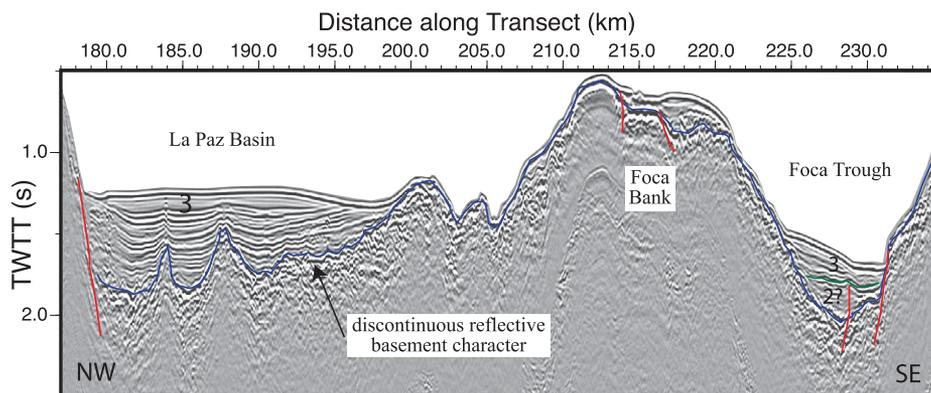


Figure 7. La Paz basin and Foca trough. Basement is indicated by blue line, faults are highlighted in red. Unit 2 is synrift sedimentation and unit 3 is postrift. Note the ropey character of reflections underlying basement, which is typical of most sections along this entire profile. The Foca bank shows some small-scale faulting and the Foca trough may have a small, lower synrift sedimentary sequence (indicated in green), but most sediments appear to be postrift based on stratal geometry and acoustic character. TWTT—two-way traveltime.

moating, around basement highs. The basement has a distinctive ropey character that is interpreted to be of volcanic origin. The next basin along the MCS profile is the narrow Foca trough (Fig. 7), which has a maximum 0.4 s of sediment, possibly a lower synrift sequence, and a pair of northwest-facing normal faults along its southeastern scarp.

At 265 km along the profile, to the east of the Cerralvo bank, a deep basin exhibits the most complicated sedimentary sequences along this transect. This basin was previously unnamed; we refer to it as the East Cerralvo basin (Fig. 8).

The basement character is similar to that of the La Paz basin and Foca trough, and it is likely of volcanic origin. There is no visible basin-bounding fault where the sedimentary sequences dip toward the master fault, suggesting that the majority of the accommodation was created rapidly relative to sedimentation rate. The main episode of faulting and subsidence is not recorded by the imaged sedimentary sequences, or it is possible that the transect did not cross the main basin-bounding fault. The majority of the observed faulting exhibits offsets of <~1 km; only the basement and the

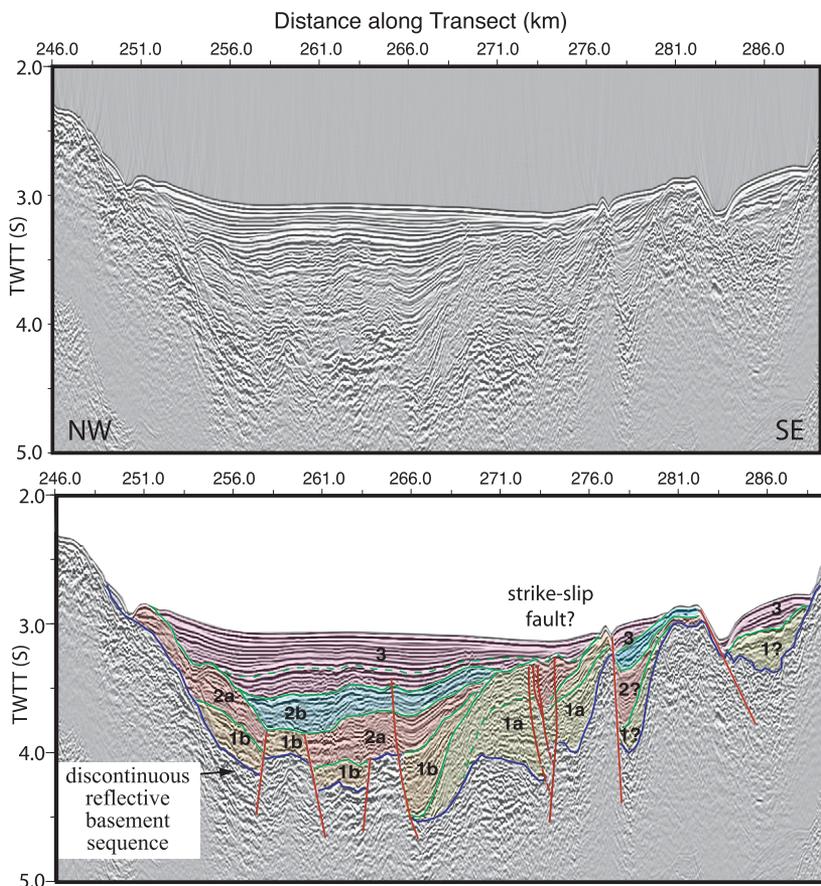


Figure 8. East Cerralvo basin. The uninterpreted (top) and interpreted (bottom) seismic profiles are shown. TWTT—two-way travelttime. Basement reflections are highlighted in blue, and sedimentary sequence boundaries are separated by green lines, with faults shown in red. Basement has a reflective discontinuous appearance. Unit 1 (divided into 1a and 1b) is a synrift deposit, with a chaotic character; unit 2 (divided into 2a and 2b) exhibits rotation and divergence and appears to be synrift; unit 3 consists of postrift, layered deeper water marine sediments. Two surface-cutting normal faults at the southeast end appear younger than the main basin, although the exact relationship of faulting is unclear and they appear to be overprinted by current-controlled erosion.

lowest sedimentary sequences are offset. The total sedimentary thickness is 1.3 s; the units are numbered 1, 2, and 3 to correlate with the Tamayo trough, but additional unconformities within the East Cerralvo basin warrant further separation of these sequences into 1a, 1b, 2a, and 2b. From either side, the lowest unit 1a thickens toward a possible fault at 274 km. An interpretation of this sequence provides evidence for two opposite-sense normal faults early in the basin's history to create the stratal geometry of these deposits, which have more recently been cut by a strike-slip fault near 274 km. Unit 1b was deposited synchronously with slip on the fault at 265 km. Unit 2a shows a possible slump feature at 254 km, and may also be synrift, along with unit 2b. The youngest unit 3 appears to transition from basin filling

(unit 2b) to more of a regional deposit that is well layered above the green dashed line shown in Figure 8. The change in character through the sequences is most likely indicative of changing the process of sediment emplacement, from possibly subaerial and/or nearshore-derived gravity debris flows that are seismically less reflective with chaotic layering, to more layered, deeper water, hemipelagic sedimentation. Near the southeastern side of the basin, there are two likely younger faults at 277 km and 283 km that form smaller basins and appear to offset the surface. It is difficult to relate the sedimentary sequences in these smaller basins to those observed in the main basin, but the oldest layer in both subbasins has a more chaotic, discontinuous appearance similar to the older units in the main basin, and may have been

deposited during the early stages of rifting. The stratal character of sediments abutting the fault at 277 km suggests the initiation of fault movement and subbasin formation during the deposition of unit 2, and may continue to move at slower rates through the present. The fault at 283 km appears to be more recent, creating a small bathymetric low. The bathymetric low near the fault at 283 km appears to be current controlled with moating around the bathymetric high, as is likely near 277 km and 250 km.

Alarcón Basin

Extensional deformation in the Alarcón Basin culminated in active seafloor spreading. The flanks of this basin prior to the onset of seafloor spreading (Fig. 9) have been reconstructed with the assistance of wide-angle refraction data (Sutherland, 2006; Lizarralde et al., 2007). The southeast side of the basin is marked by a large sequence of inactive down-to-the-northwest normal faults, which step up to the Tamayo bank. These faults show basement offsets to 0.5 s, and basement is draped with postrift sediment, which also reaches a thickness of 0.5 s. The basement shows the same volcanic character observed elsewhere along the profile, and the small-scale faulting likely occurred after the deposition of this volcanic layer. Due to the proximity of our 2D profile to the nearby Pescadero fracture zone, measured sediment thickness is approximately half of the maximum observed in other high-resolution reflection profiles within the Alarcón Basin (Lonsdale and Kluesner, 2010).

Oceanic Crust

The continent-ocean transitions on both sides of the Alarcón Basin are sharp: basement depths across the northwest boundary suggest that the transition is between 330 and 345 km; modeling from the coincident refraction profile also shows the crust thinning abruptly to oceanic crustal thickness with a corresponding increase in velocity at 345 km (Sutherland, 2006). Based on basement structure, the southeastern transition seems to occur between 457 and 480 km along this transect (Fig. 6), and crustal thicknesses from modeling of refraction data show the transition to be at or near 480 km (Sutherland, 2006). The oceanic crust southeast of the spreading center has thicker sediment relative to the crust northwest of the ridge, most likely related to increased sediment supply from mainland Mexico. The magnetic anomalies across the floor of the Alarcón Basin suggest that spreading began between ca. 3.7 and 3.5 Ma (south to north) (Lonsdale, 1989, 1995).

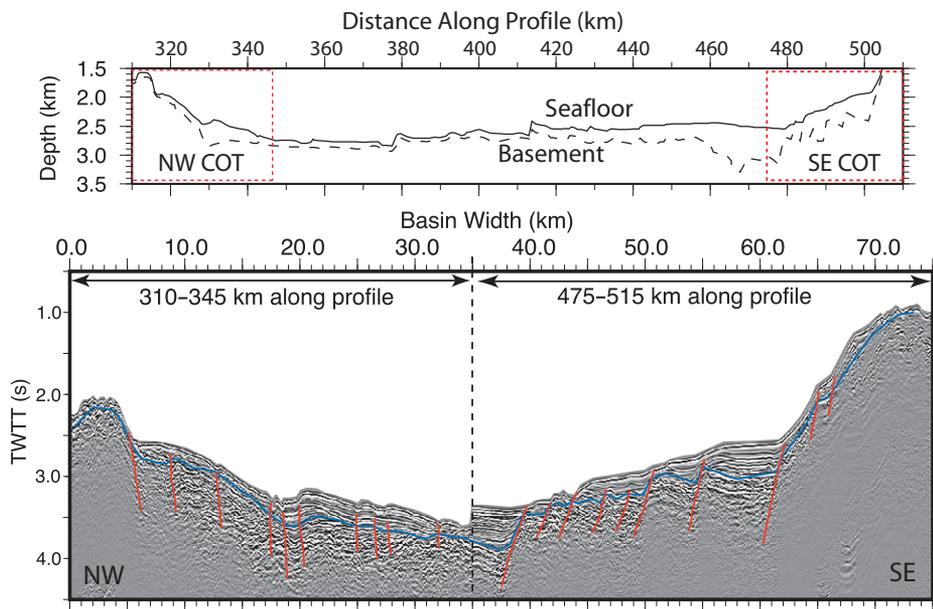


Figure 9. Reconstructed Alarcón Basin joined at the conjugate continent-ocean transition (COT). Top illustration indicates where selected seismic data are located; plot is converted to depth to show sediment thickness. On the time-migrated seismic line below, basement is shown with a blue line and faults are highlighted in red. Sediments appear to be postrift and drape the faulted, volcanic basement. TWT—two-way travelttime.

Southeastern Margin

The Tamayo trough (Fig. 10), located 555 km along the profile, is enigmatic in that it is a relatively deep (~1.6 s of sediments and underfilled) subbasin, the stratigraphic and structural expressions of which provide ambiguous clues as to how extension and associated crustal thinning were accommodated, and yet thinning was extreme in this location (Lizarralde et al., 2007). It is also strikingly different in its seismic stratigraphic character than the other large basins along the Alarcón transect. We have identified three sedimentary sequences within the basin that probably document the subsidence of the basin from terrestrial to shallow marine to a deep-marine environment, and are similar to those of the East Cerralvo basin in internal seismic character but not in the geometry of the sequences (Fig. 8). The lowest, unit 1, is mostly unreflective; the middle, unit 2, shows some layering with increased acoustic reflectivity upward; and the youngest, unit 3, consists of layered deep-marine sediments similar to the postrift packages in other basins along the transect at depths below the continental shelves. None of the sedimentary sequences exhibits substantial rotation and/or divergence that would be indicative of synrift deposition (though unit 1 exhibits minor thickening toward faults), suggesting that the majority of faulting and basin subsidence may have occurred prior to deposi-

tion of at least units 1–3. Given that most of the extensional deformation and subsidence predated deposition, it is difficult to reconstruct the style of the deformation in the Tamayo trough. However, two factors make the trough complex: (1) deposition into the trough is from the north-northeast, approximately perpendicular to the transect and along the axis of the trough (see Fig. 4), and so it adds some complexity to the depositional process; (2) the Tamayo trough is substantially underfilled, currently 1–1.5 km below the top of the banks and shelf surrounding it on three sides (Fig. 4).

Fault offset within the sediments also suggests that only minor amounts of extension occurred subsequent to the deposition of units 2 and 3, and possibly even unit 1. The most obvious faults within the sediments include normal faults near 566 km that cut units 2 and 3, and normal faults near 545 km and 550 km that cut mostly unit 2 sediments. Together, these faults represent very little extension. Stratigraphic features within unit 3 near 549 km appear to be related to contourite-style deposition and minor surficial slumping, and features within this unit northwest of 550 km appear to be related to channel deposition. Despite what appears to be minor faulting, unit 1 is only in the basin center, and units 2 and 3 are substantially thicker in the basin center than along the northwestern margin of the basin. Therefore, there was clearly a mechanism to create substantial accommodat-

ing space in the basin center that is not explained by the faults imaged in the seismic line.

Basin formation for the Tamayo trough is recorded in the seismic profile only indirectly by what can be inferred from the basement reflectivity and the relationship between basin morphology and crustal thickness. The key observations are the character of the basement and subbasement reflections, the apparent lack of abrupt offsets of the basement reflector, and the coincidence (or colocation) of the deepest basement depression within the trough and underlying acute crustal thinning (Sutherland, 2006; Lizarralde et al., 2007). We also note the marked asymmetry of the basin, i.e., a more gently dipping northwest margin and a steeper southeast margin; this may suggest that the basin-bounding fault is along the southeast margin. The seismic character of basement reflections is similar to the interpreted volcanic style observed on the northwestern conjugate margin. However, in the Tamayo trough, basement faulting barely produces visible offsets in the volcanic layer, in contrast to the East Cerralvo basin (Fig. 8), where offsets of as much as 0.5 s are observed. In addition, the thickness of the rosey character, subbasement layer is fairly uniform across the Tamayo Trough, though it appears thinner on the southeast margin of the basin between 560 and 568 km.

There are several possible explanations for the lack of obvious abrupt offsets of the basement surface and the subbasement layer, interpreted to be volcanics. Deposition of the volcanic layer may have occurred after large-scale faulting in the Tamayo trough was complete. However, as we describe in the following, we interpret the volcanic layer, which is seen along a great extent of the line, to be coeval with the Comandú arc, with an age of ca. 19–12 Ma. Deposition of the volcanic layer subsequent to basin formation would mean that extensive localized crustal extension was far earlier than can be inferred from any other observation within the Gulf extensional province, unless the Tamayo trough has pre-gulf, Basin and Range–age extension, such as the faulting documented in mainland Mexico (e.g., Gans, 1997; Henry and Aranda-Gomez, 2000) but rare in the main gulf. Basin formation subsequent to emplacement of the volcanic layer could be accomplished in several ways that leave behind only minor high-angle offsets of the basement surface. Basin formation could have been via one or more low-angle normal faults, including one that tracks along or near the southeastern basement flank and possibly a second, noncoincident one near the basement surface from 548 to 558 km. Such faults could in principle leave the overlying sediments largely uncut and would have a

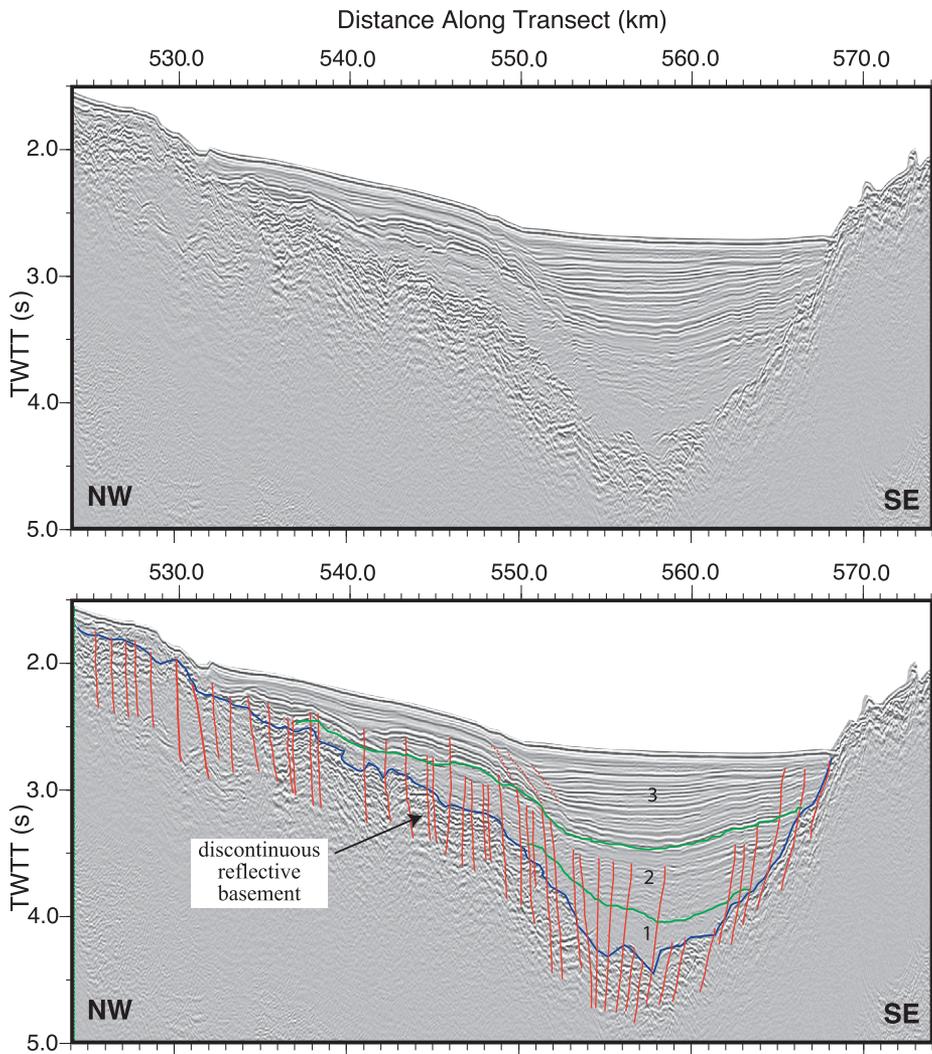


Figure 10. Tamayo trough. Although the basement is finely faulted (red lines), there is no major synrift sedimentation or large, single basin-bounding fault. The top of basement, indicated in blue, has a highly reflective ropey character; sedimentary sequence boundaries are shown in green. TWTT—two-way traveltime. Sedimentary sequences appear similar to those in the East Cerralvo basin (Fig. 8). Dashed red lines highlight contourite depositional patterns and are unlikely to be related to low-angle faulting.

seismic expression consistent with the observed basement, including the apparent thinning of the ropey layer along the southeastern edge of the basin. One large low-angle normal fault on the southeast side of the basin would explain the basin asymmetry and the thinner volcanic layer on the southeast side. However, there are two difficulties with this mode of faulting. First, both of the potential fault surfaces are very low angle, between 11° and 15° (this range of angles is at the lower end of the range of examples of low-angle normal faults in the Basin and Range province (e.g., Wernicke, 1992; Axen, 2004)). Second, in contrast to the low-angle normal faults in the Basin and Range, the Moho has great relief under the Tamayo trough (Lizarralde

et al., 2007). In order to achieve the observed crustal thinning, with a very shallow Moho located directly beneath the deepest portion of the trough, both potential low-angle normal faults would have had to work in sequence, with the final active fault soling out near the crust-mantle interface. The combination of both of these requirements seems unlikely.

Basin formation via high-angle normal faults requires faults distributed along the southeast side of the basin to create the observed asymmetry, with localized deepening of the basin centered at 557 km. Another alternative is that the uppermost surface, being a terrestrial clastic and volcanic layer, might easily erode, forming talus slopes, landslides, and local alluvial fans

that mask fault offsets. This notion is consistent with the thickness of the ropey layer beneath the center of the trough and the transparency of unit 1; the ropey layer and unit 1 may together represent a chaotic synrift sedimentary unit. Further research is required to resolve between these scenarios; however, on the basis of the existing data, we prefer a basin-formation model that involves high-angle normal faulting along the southeast margin early in the basin's history and basement offset that is largely masked by erosional overprinting.

Farther along the transect, between 585 and 600 km, there are several small-offset faults before the West Nayarit ridge. The West Nayarit ridge is bounded on its northwestern side by a large down-to-the-northwest normal fault scarp, and has accumulated only 0.25 s of sediments (Fig. 6). A sequence of three troughs, the West Nayarit (615 km), Central Nayarit (635 km), and East Nayarit (655 km), show similar sedimentary structures, i.e., a lower synrift sedimentary sequence overlain by postrift sedimentation (Fig. 11). There seems to be a change in basement character across the Central Nayarit ridge. The West Nayarit trough has a discontinuous reflective basement character similar to that observed in the Tamayo trough and farther to the northwest. In contrast, the Central and East Nayarit troughs have thinner, less chaotic reflective upper basements. The West Nayarit trough (615 km) has three down-to-the-northwest normal faults with as much as 0.8 s of sediment thickness. The Central and East Nayarit troughs (635 km and 655 km) are opposite-sense half-grabens forming a horst, the East Nayarit ridge positioned between them. Sediment thickness in the Central Nayarit trough is as much as 1.1 s and, in the East Nayarit trough, as much as 1.6 s. The thickness of postrift sedimentary sequences increases systematically toward the east.

The San Blas basin (Fig. 12) is the largest (~70 km wide) basin along this transect and it is likely that the transect did not reach its southeast boundary. Low-fold seismic data and the shallow (~50 m) water depths made processing difficult and precluded the effective use of multiple suppression techniques. Nevertheless, it is clear that the basement is highly faulted, although there is no obvious main bounding fault. Note, however, that on other seismic lines from the PESCADOR experiment, there are large-offset (0.5–0.8 s) normal faults south of the southeast end of the Alarcón transect on the shelf (Brown, 2007). There are also variations in basement character, from a highly reflective lower basement sequence in the shallow northern edge of the basin, to areas with no clear basement reflector, such as the center of the basin. The sediments reach a thickness of 2.0 s and reveal

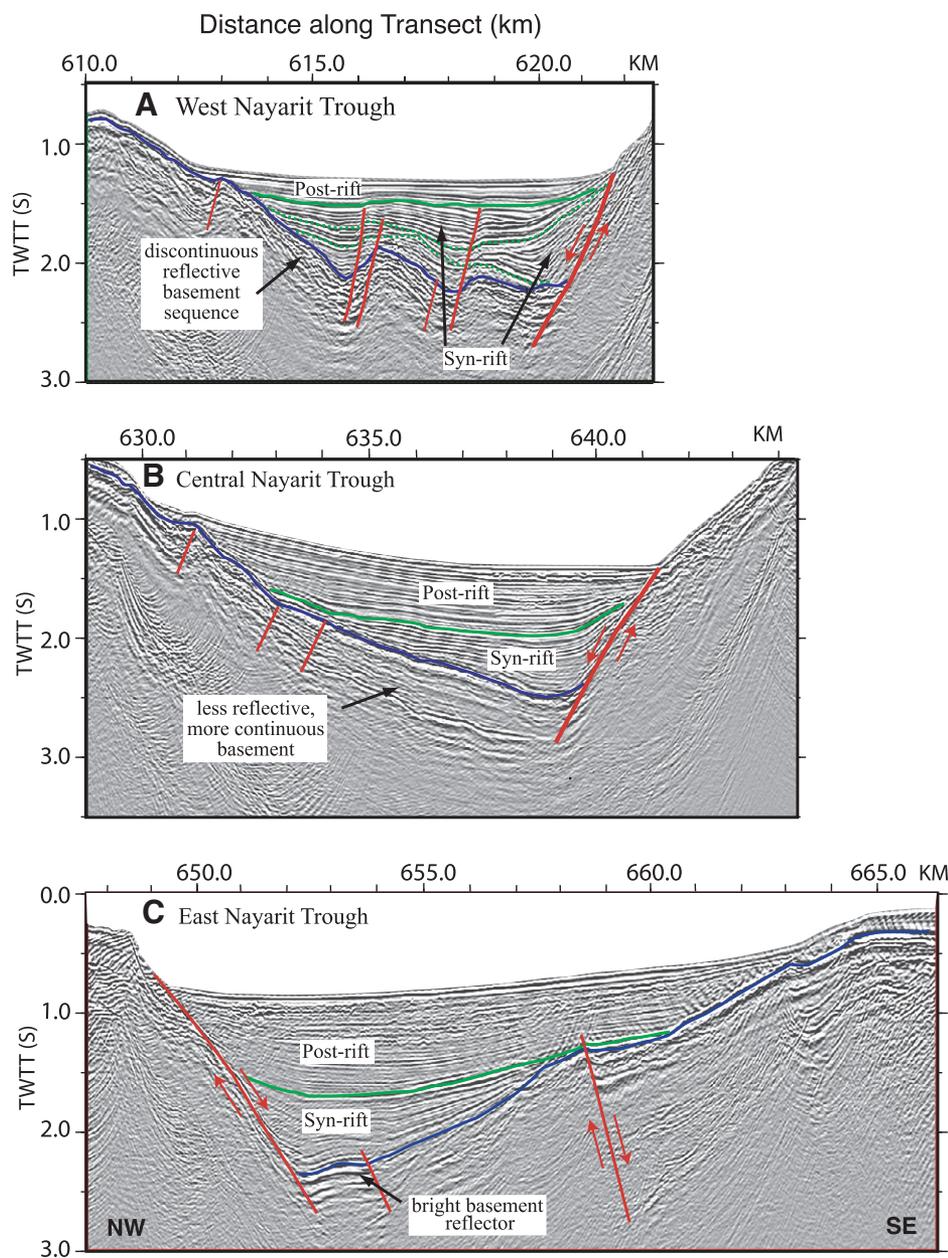
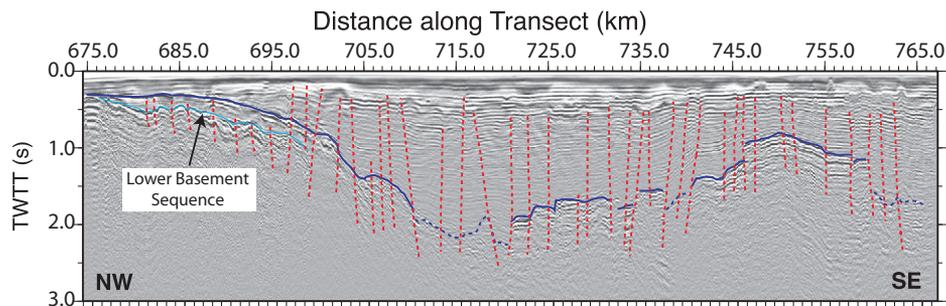


Figure 11. Seismic images of the Nayarit troughs. TWTT—two-way traveltime. (A) West. (B) Central. (C) East. Basement is indicated in blue, faults are in red, and stratigraphic boundaries are in green. The West Nayarit trough shows the reflective, ropey character, faulted basement layer observed farther to the northwest on the transect, whereas the Central and Eastern troughs are simple half-grabens with a single more continuous basement acoustic character.

Figure 12. San Blas basin. This basin has several visible basement offsets, but lack of quality imaging of deeper sediments prevents confidence in our interpretation. Possible minor faults are shown with dashed red lines. TWTT—two-way traveltime.



small-scale deformation from the faults that crosscut conformable stratigraphy across the basin, but have no strong indication of synrift deposition.

Basement Velocity Structure Analysis

The top of basement along much of the reflection profile has a distinctive ropey seismic character, which may be indicative of a volcanic layer, and must have been emplaced either prior to or during the early stages of extension. To investigate this layer further, supergathers of MCS data were used to model shallow vertical velocity structure. A supergather combines several CMP gathers along the transect to produce the equivalent of a 6 km refraction profile, the response of which, owing to the CMP geometry, approximates that of 1D media (for details, see Husseiner et al., 2002). The supergather records the seafloor reflection, subsurface reflections, and a set of refractions that, when combined, aids in the determination of a detailed velocity profile with depth. Fitting traveltime curves to these reflection and refraction arrivals produces a P-wave velocity-depth profile (Fig. 13) that can provide insight into the internal structure and origin of the acoustic basement.

Our modeling of 40 supergathers shows a distinctive layer present beneath much of the transect; this layer has a relatively low velocity of 2.5–2.8 km/s, and a thickness of 250–500 m (Fig. 14). In contrast, geophysical borehole logs in highly fractured granites show P-wave velocities of ~5 km/s (Boness and Zoback, 2004), indicating that this layer may be sedimentary or volcanoclastic in origin, rather than highly fractured intrusive basement. To confirm that this analysis produces reasonable results, a supergather on the oldest oceanic crust at 475 km along the transect was modeled. This result shows sediments overlying basement with a P-wave velocity of ~4 km/s. Similar analysis of ca. 3.5 Ma oceanic crust across the Juan de Fuca Ridge gives a basement velocity of ~3.5 km/s (Nedimovic et al., 2008), which is similar but may indicate that 475 km along transect is at the very edge of the continent-ocean transition.

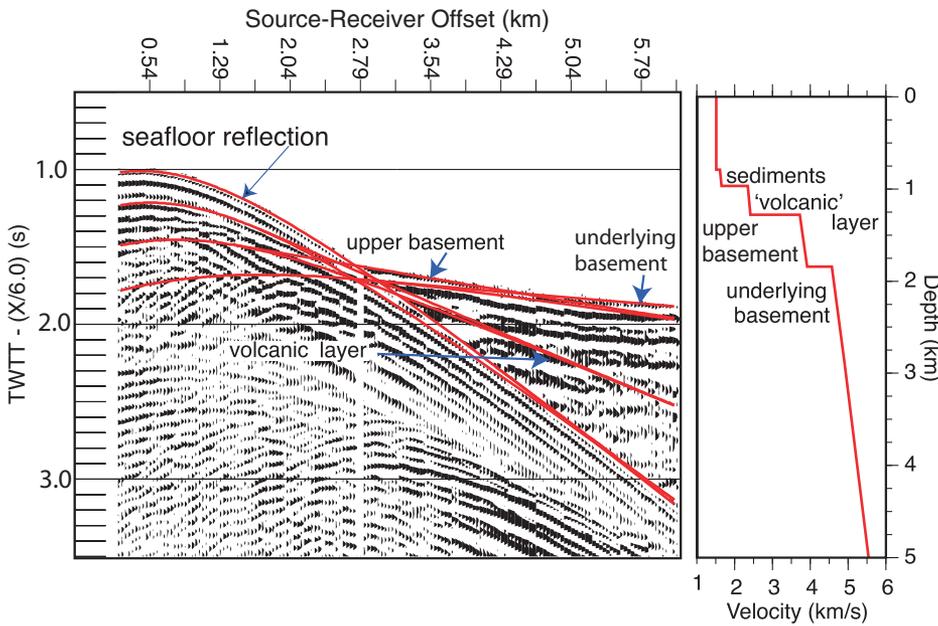


Figure 13. Example of supergather plot with traveltime curve (left) and corresponding velocity-depth function (right) located at 517 km along transect (Tamayo bank). TWTT—two-way traveltime. The dominant features of the supergather are the seafloor reflection, followed by reflected and/or refracted arrivals from three layer boundaries, which form a triplication in traveltime. Vertical axis is reduced traveltime with velocity reduction of 6 km/s.

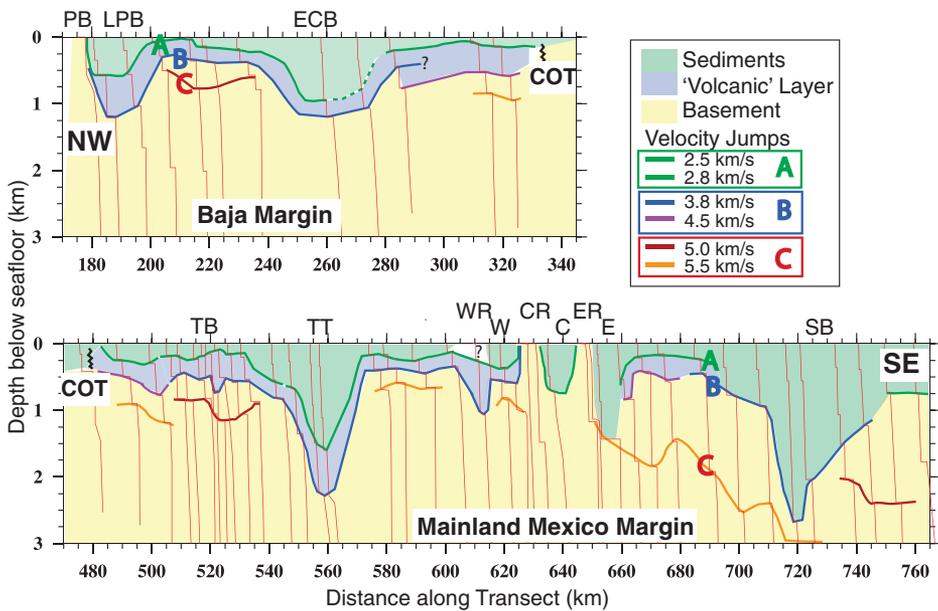


Figure 14. Interpretation of supergather velocity results. Velocity models are plotted in depth and reduced to a seafloor datum. The velocity-depth profiles are shown in red. There are two main layers: sediments (A) and the volcanic layer (B) overlying faster basement (C). At each level the velocities could be split into a faster and slower trend. In some areas, there is an additional layer resolved within the basement, which may correspond to the upper to mid-crustal boundary. Abbreviations: COT—continent-ocean transition; PB—Partida bank; LPB—La Paz basin; ECB—East Cerralvo basin; TB—Tamayo bank; TT—Tamayo trough; WR—West Nayarit ridge; W—West Nayarit trough; CR—Central Nayarit ridge; C—Central Nayarit trough; ER—East Nayarit ridge; E—East Nayarit trough; SB—San Blas basin.

When the velocity-depth profiles are converted back into TWTT, this low-velocity layer clearly corresponds to the discontinuous, highly reflective layer observed in the MCS images. Across the Baja California margin, this ropey layer is observed extending from the La Paz basin to the continent-ocean transition, and on the mainland Mexico side, it is seen from the continent-ocean transition to the West Nayarit trough. Closer to the continent-ocean transitions, this layer and the underlying basement are seismically faster. The layer does not appear to be present beneath the Central and East Nayarit troughs, although fewer refractions suitable for modeling were observed in these basins, making interpretation more difficult. The ropey acoustic layer reappears to the southeast for 40 km on the lip of the San Blas basin, although it is not observed beneath the San Blas basin proper (Fig. 14). There are three areas where normal basement is present at the seafloor with no sediments or volcanic layer observed: the Partida bank, Central Nayarit ridge, and East Nayarit ridge.

The West Nayarit ridge has an interesting structure, 200 m of material with a velocity of 2.2 km/s (possibly fast sediments) overlying the volcanic layer. Along much of this transect, we also observe an interface within the basement that marks a transition in velocity from ~4 km/s above to 5.0+ km/s beneath (typical crystalline basement). This layer is ~300 m thick where observed beneath the Baja California margin and in the vicinity of the Tamayo bank, and appears to thicken significantly beneath the San Blas basin to ~1 km, although results from the deepest basins are less certain.

The Tamayo region (500–575 km along transect) is of particular interest because of the lack of obvious faulting responsible for the accommodated structure of the basin. A more detailed interpretation of this area is shown in Figure 15; the schematic diagram shows an interpretation of velocity-depth profiles reduced to a seafloor datum (top), and the MCS profile shows these layers converted back into TWTT (bottom). We see that the volcanic layer follows the ropey basement structure and appears to be continuous from the bank down into the trough, where it is thicker, with modest thinning on the basin's eastern side. Three main sedimentary units are observed in the Tamayo trough: the uppermost layer has velocities similar to the recent pelagic drape observed across the entire transect; beneath this layer boundary velocities increase to ~2.1 km/s; and the lowest layer, corresponding to the nonreflective character seen in the seismic section, has velocities of ~2.3 km/s. The volcanic layer is faster underneath the Tamayo trough, as would be expected with compaction.

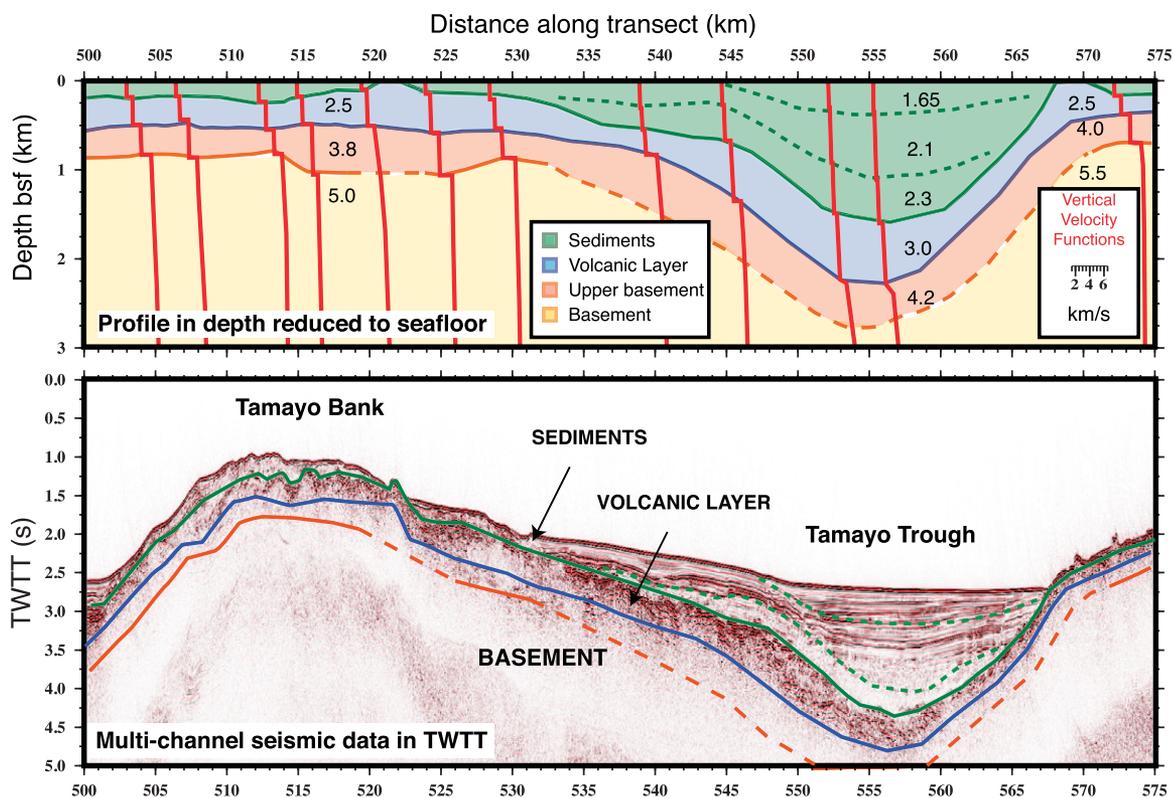


Figure 15. Detailed velocity results and interpretation across the Tamayo bank and trough. Top plot shows velocity-depth (bsf—below seafloor) profiles reduced to a seafloor datum in red. Sediment basement interface is shown in green, the base of the volcanic layer in blue, and the upper–mid-basement boundary is in orange. Lower plot shows these layers converted into two-way traveltime (TWTT) and plotted on top of migrated multichannel seismic data.

DISCUSSION

Sedimentary Sequences and Fault Timing

We observe two styles of basin development along the Alarcón profile. (1) Larger basins (East Cerralvo basin, Tamayo trough, and San Blas basin) are characterized by large subsidence without a clear basin-bounding fault that offsets the ropey layer or mantling sedimentary sequences; these basins contain small amounts of synrift sedimentation (particularly East Cerralvo), but this synrift sedimentation appears to be associated with small-scale basement faulting, not large-scale basin formation. (2) Smaller basins (La Paz basin, Foca trough, and West, Central, and East Nayarit troughs) are generally half-grabens, with one basin-bounding normal fault and synrift and postrift sedimentary sequences. Unlike the smaller, younger basins, the larger basins are complex and vary greatly in their geometry and fault patterns. East Cerralvo basin has many features that suggest a transtensional basin: early normal faults without a major basin-bounding fault, one later strike-slip fault, and nonorthogonal basin boundaries. The seismic line clearly only crossed a portion

of the San Blas basin, and other seismic lines on the large shelf near the Tres Marias islands and mainland Mexico show many moderate to large normal faults indicative of an array of early rift basins (Brown, 2007). The Tamayo trough remains an enigma, and is distinctly different from any of the other basins across the Alarcón transect.

It is important to note that in oblique extensional environments, numerous normal and strike-slip faults can splay off the main basin-bounding fault systems and may not be well imaged by the orientation of our seismic survey. An oblique orientation of the basin-bounding faults relative to the seismic line could also potentially explain why the observed sediment wedges do not exhibit marked rotation and divergence. In addition, some of the basins along the transect were likely to have had depositional systems that delivered sediments to the basins at high angles to the seismic line (Figs. 3 and 4). A final caveat is that our seismic line only imaged the uppermost crust, and therefore we cannot evaluate adequately lower to middle crustal processes.

Nevertheless, the important observation is that the basin-forming events that created much

of the observed relief across the Alarcón corridor in the southern Gulf of California postdate the ropey volcanic or volcanoclastic deposits, because there is clear evidence of faulting within these units. Moreover, it would appear that the larger basins were formed through distributed extension, reducing the overall thickness of the volcanic layer in the absence of focused extension; notable exceptions are the Central and East Nayarit basins, where the volcanic layer is absent on the footwall of the basin-bounding fault (and to a lesser extent the Tamayo trough). The youngest sediments within the basins are postrift sequences, so it appears that there has been minimal extension away from the spreading center during the past few million years. This is in agreement with other studies that show no active faulting (e.g., Aragon-Arreola et al., 2005; Brown, 2007) and no large earthquakes (e.g., Goff et al., 1987) on the east side of the central and southern Gulf of California.

The two styles of basin architecture identified along the transect suggest two distinct phases of extension, one forming the larger, more complex basins through distributed extension and transtension, and a subsequent second phase forming the smaller, mostly more distal basins

characterized by focused extension along basin-bounding fault systems. The Alarcón Basin seems to belong to the first phase of extension: it has a reconstructed width of ~60 km (Fig. 9), but only shows small-scale basement faulting with few to no synrift sedimentary sequences. It would appear that extension then refocused into the Alarcón Basin during the second basin-forming phase, resulting in full rupture of the lithosphere. Without drilling we cannot be certain of sediment ages and sources, but we can estimate the age of the basins from the thickness of sediments, assuming reasonable sedimentation rates. Hemipelagic sedimentation rates can be estimated by comparing the sediment thickness to the age of the oceanic crust, which is known from magnetic anomalies. An additional estimate is obtained from a stratigraphic section on Isla Maria Madre, located on the southwestern edge of the San Blas basin (McCloy et al., 1988). Dividing the thickness of sediments by the sedimentation rate provides a first-order estimate of time for a given deposit to accumulate and therefore an estimate of basin age. Note that this estimate of sediment ages largely pertains to the upper marine sequences in the basins, and therefore our estimates of the age of the lower portions of the basins are more speculative.

To estimate the sedimentation rate for each basin, we considered the likely sedimentary sources and processes of emplacement. We acknowledge the high level of uncertainty in the estimation of sedimentation rates, but without a method of dating sediments within the basins, we can only make simple estimates based on data available and take this as a starting point for interpretation. The sediment thickness for each basin was determined from the supergather velocity analysis where appropriate (e.g., Fig. 14). Sedimentation rates can be estimated from the oceanic crust (Fig. 9), because both the age of the crust and the thickness of the sediments are known. The northwestern side of the oceanic crust (on our profile) shows the lowest sedimentation rates, with a doubling of sedimentation rate from 50 to 100 m/Ma between 2.5 and 0.7 Ma. Sediment dispersal along the Baja California coastline is complex with sequestration near the shoreline common (Nava-Sanchez et al., 2001), although sediment shed off the Cabo block is able to supply portions to the Alarcón Basin; in any event sedimentation rates along the northwest seismic profile are likely to be low, but the northwestern oceanic crust is also farther from the sediment source than the La Paz and East Cerralvo basins, so the higher rate of 100 m/Ma is considered a better estimate for the basins along the northwestern margin. The southeastern oceanic crust has significantly more sediment cover than the northwest side

and, because pelagic sedimentation rates will be relatively uniform, this suggests that terrestrial sediments from mainland Mexico reach the oceanic crust, accounting for the differential thickness. The southeastern oceanic crust also shows an increase in average sedimentation rate over time, from 115 to 150 m/Ma over the same 2.5–0.7 Ma time period, and sediment ages from Isla Maria Madre (McCloy et al., 1988) show an average rate of 110 m/Ma prior to 6.7 Ma, increasing to 180 m/Ma thereafter. An average of the oceanic crust sedimentation rates (115 m/Ma) is used for the Alarcón Basin. An average rate of 133 m/Ma from the oceanic crust is used for the Tamayo and West and Central Nayarit troughs. The East Nayarit trough and San Blas basin are closer to the sediment source, and an average rate of 145 m/Ma from Isla Maria Madre is used to estimate their ages. Nevertheless, this may be a low estimate (thus reducing the basin age) as the San Blas basin is fed directly from land runoff and the East Nayarit trough is fed from the overflow of the San Blas basin (Fig. 12).

The estimated ages are shown in Table 1, with the distinct possibility of a few million years of uncertainty in basin formation from the variation in sedimentation rates observed across the transect. Despite this uncertainty, as expected, the 3 larger basins (East Cerralvo, Tamayo, and San Blas) are likely to be much older, and their age estimates suggest that they formed ca. 14–11 Ma (perhaps slightly later), probably at the onset of extension in the gulf. Faulting near Tepic, mainland Mexico (Fig. 4), is dated as having occurred in two episodes, the first between 12 and 8 Ma (Ferrari and Rosas-Elguera, 1999), which overlaps with the estimated dates for the formation and faulting of these basins. The second episode of faulting near Tepic is 5.5–3.5 Ma (Ferrari and Rosas-Elguera, 1999), which corresponds roughly to the ages of the West, Central, and East Nayarit troughs and La Paz basin. With the current data, it is impossible to say whether the apparent age progression in the three Nayarit troughs is purely coincidental, the result of

decreasing sediment supply as we move away from land, or highlights an actual east-west progression in their formation. In addition, the early date for formation of the East Nayarit trough may be incorrect, because it has a significant sediment supply directly from the highly sedimented San Blas basin. Faulting may have been active in the West and Central Nayarit troughs until the onset of seafloor spreading in the Alarcón Basin, possibly as late as ca. 2.5 Ma. Dorsey and Umhoefer (2000) and Dorsey et al. (2001) (see Umhoefer et al., 2007, for an update on the age of strata) documented rapid subsidence in basins along the Baja California margin near Loreto at ca. 2.5–2.3 Ma. Umhoefer et al. (2007) noted the formation of the Isla San Jose basin between 8 and 7 Ma, which coincides with the estimated age of the La Paz basin and its rapid formation. The Isla San Jose basin also had a relatively rapid interval of subsidence at ca. 3.5–2.5 Ma. The facies in all of these basins at the end of the rapid subsidence event are fine grained deep marine, suggesting that like the La Paz basin, they were underfilled and received most of their sediment over a short period of time during rapid faulting. The basins at the margin of the Gulf were uplifted to fault reorganizations after the rapid subsidence, while the La Paz basin farther out in the Gulf continued to receive post-rift sediments.

Our combined observations of the ages and styles of basins suggest the sequential development of basins across the gulf along the Alarcón transect. The larger, older basins are in the axial part of the gulf and at the southeast margin of the transect. There is a distinct intermediate area on both sides of the transect with no early basin formation. These areas on the seismic line are the area northwest of East Cerralvo basin and the area of the Nayarit basins between the early Tamayo and San Blas basins. These intermediate areas are the location of the younger half-graben La Paz and the Nayarit basins. Thus, extension along the Alarcón transect began with active basins in the axial gulf and at the southeast margin from ca. 14–11 Ma to

TABLE 1. ESTIMATED BASIN AGES BASED ON SEDIMENTATION RATES

Basin	Sediment thickness (m)	Basin age estimate (Ma)	Post-rift sediment thickness (m)	Approximate time of most recent faulting (Ma)
La Paz	500	5	500	5
East Cerralvo	1000	10	750	7.5
Alarcón	400	Pre-3.5	400	3.5*
Tamayo	1500	Pre-11	1500	11
West Nayarit	500	4.0	250	2
Central Nayarit	1000	7.5	500	4
East Nayarit	1500	10	700	5
San Blas	2000	Pre-14	2000	14

*Estimate for Alarcón is likely too young because it is located farthest from sediment sources; other profiles show twice the maximum sediment thickness.

8–5 Ma; these were transtensional and extensional basins. Previous studies have suggested that basins at the northwest margin of the southern gulf along the Baja California peninsula were also active in this early gulf stage (Fletcher et al., 2000; Umhoefer et al., 2002), but this conclusion was not well constrained. A narrow belt between the gulf margins and the axial belt on both sides of the gulf was apparently unfaulted in this early stage and perhaps remained a ridge above sea level. As faulting in the early basins either slowed or ended ca. 8–5 Ma, faulting continued in the central Alarcón Basin. At the same time, new normal faults formed and extended the intermediate ridges that are now the La Paz and Nayarit basins. A basin on the east side of San Jose Island ~50 km northwest of La Paz basin is also estimated to have formed ca. 6–4.5 Ma, and shows transtensional basin and fault characteristics (Umhoefer et al., 2007). Faulting in these intermediate basins ended or slowed substantially ca. 5–2 Ma as seafloor spreading was initiated on the Alarcón Rise (Lizarralde et al., 2007). Basins at the northwest margin of the southern gulf also had slowing of faulting ca. 3–2 Ma (Dorsey and Umhoefer, 2000; Umhoefer et al., 2007). Although the timing of basin formation calculated this way clearly carries some uncertainty, the difference in faulting style of the basins strongly suggests two different phases of extension: an early phase while some seafloor spreading and subduction was shutting off west of Baja (before 8 Ma), and a second phase after 8 Ma when the Tosco-Abrejos fault became active (Brothers et al., 2012) and all activity around the Magdalena plate ceased.

Upper Crustal Extension

The amount of upper crustal extension can be estimated in two ways. The first is to sum the extension created by throw on faults that we observe in the MCS data, measured by horizontal basement offset. The section of the northwestern Baja margin within the limits of the MCS data is 175 km wide (the profile was foreshortened by an estimated extra 125 km of extended crust; Sutherland, 2006), and extension created by observed faults has been estimated at 28 km, yielding a stretching factor (β) of 1.2. The southeastern margin is currently 290 km wide along the extent of these MCS data (an estimated 110 km of extended crust at the southern end of the transect was not imaged), and extension on faults totals 52 km, also producing $\beta = 1.2$. Even if we make an allowance for the fact that extension calculated from fault offsets in MCS data typically underestimates extension by ~35% (Walsh et al.,

1991), this would only increase stretching to $\beta \sim 1.6$. The second method of estimating upper crustal extension ignores the observed faults and instead uses the large-scale basement structure and bathymetry, with the assumption that the bathymetry was originally flat and close to sea level. This may be a more accurate large-scale estimate because we image large basins with no observable basin-bounding faults (e.g., distributed deformation within the East Cerralvo and Tamayo troughs). Higher stretching factors of $\beta \sim 1.6$ for the northwest margin and $\beta \sim 1.5$ for the southeast margin are calculated from this approach. Both estimates show similar degrees of extension on conjugate margins, and although the second estimate is higher, it is still less than the whole crustal structure calculated from the coincident refraction data (Sutherland, 2006; Lizarralde et al., 2007).

Based on the reflection profile alone (~235 km shorter than the estimated width of the conjugate rifted margins), we obtain a range of Pacific–North America separation of 215–298 km (including 135 km of oceanic crust). Whole crustal structure from tomography shows significantly more extension, with stretching factors of $\beta \sim 2.0$ for both margins (Sutherland, 2006). The difference between the extension needed to create the basin and the amount of extension created by visible faulting is most pronounced in the San Blas, Tamayo, and East Cerralvo basins, where there are no observable large basin-bounding faults. In these basins, only a third of the total amount of extension appears to have been accommodated on large faults (Table 2), but the estimated total extension in each of these basins corresponds to stretching factors of 1.75–2.0, so locally there is no discrepancy between upper crustal and whole crustal stretching factors.

Magmatism

In a conventional sense, the southern Gulf of California is a nonvolcanic margin, because there are no seaward-dipping reflector sequences observed or evidence of large-scale underplating or magmatic intrusion, both of which are characteristics of many volcanic rifted margins around the world (e.g., Mutter et al., 1982; White et al., 1987; Menzies et al., 2002). However, a continuous, uniform velocity layer with a reflective,

discontinuous ropey character is mantling basement along much of our MCS transect (Figs. 13 and 14). We interpret this layer as a combination of late-stage Comondú volcanic and volcanoclastics and either an early rift (11–9 Ma) volcanic sequence or volcanism related to the slab tear between 13 and 8 Ma beneath Baja (Calmus et al., 2011).

From the Baja California margin to the West Nayarit trough, the volcanic layer varies in thickness and character to some extent, but generally is ~250–500 m thick, and has an average velocity of ~2.5 km/s, in some areas as high as 3 km/s. A possible explanation for the lack of observed, large-scale faulting forming the largest basins (i.e., Tamayo trough, East Cerralvo and San Blas basins) is that the start of extension and faulting preceded or overlapped this large volcanic episode, which covered these protobasins, concealing both the true amount of extension and the major border faults that created them. A weakness to this argument is the pervasive fine-scale faulting that is observed offsetting the ropey layer throughout this transect, highlighting a pattern of distributed postdepositional faulting.

There are three main geologic units, all volcanic, that are mapped on land that could correspond to the interpreted volcanic layer. The oldest is the upper part of the Comondú Group (Hausback, 1984; Umhoefer et al., 2001), which consists of a series of andesite breccias, lava flows, and ash falls associated with the volcanic arc during the final stages of subduction (mostly 19–12 Ma). The Comondú arc swept westward, covering a large geographic area, and observed thicknesses of this formation vary from 300 m to 1.5 km (Hausback, 1984; Umhoefer et al., 2001), but the latest estimates of the middle to upper volcanic-rich parts of the Comondú Group are 300–600 m in a transect from Loreto to La Paz (Drake, 2009). On the Baja California peninsula and offshore, post-Comondú basalts and diabase dikes are dated as 11–9 Ma (Orozco-Esquivel et al., 2010); younger still are the Pliocene to present andesite to rhyolite volcanics locally found on the eastern edge of the Baja California peninsula (Bigiogerro et al., 1995), that are likely postsubmergence (younger than 6 Ma). However, no post-Comondú volcanism is observed south of ~25°N on the Baja California peninsula. Therefore, considering the scale of each of

TABLE 2. COMPARISON OF EXTENSION IMAGED ON FAULTS AND OVERALL ACCOMMODATION SPACE IN LARGE BASINS

Basin	Current width (km)	Estimated extension (km)	Estimated sum of fault offsets (km)	Fault offsets + 35% error (km)	Total missing extension (km)
San Blas	125	65	20	27	38–45
Tamayo	30	15	5	6.75	8.25–10
East Cerralvo	35	15	6	8	7–9

these deposits compared to the large-scale and continuous nature of the observed layer, and the slow velocity, the Comondú Group volcanics and volcanoclastics appear to be the most likely candidate, with a mantling and/or intermingling of early rift volcanics (Orozco-Esquivel et al., 2010). A low P-wave velocity of 2.5 km/s suggests the major constituent to be a volcanoclastic and/or metasedimentary rock, such as volcanic ash and tuff or debris flow, and is less likely to be a more massive basalt (or andesite) flow (as demonstrated by comparison to the velocity of oceanic crust; ~4 km/s). This favors the interpretation that the upper Comondú Group is the likely source for the majority of this ropey and reflective layer seen throughout the MCS data, although a significant fraction of post-Comondú basalts and diabase dikes cannot be ruled out.

Several lines of evidence hint at an early history of oblique (i.e., northwest-southeast directed) rifting in the gulf, including the vast amount of sediment found in the oldest basins in combination with the northeast-southwest strike of geomorphic features within the Alarcón corridor (e.g., Tamayo bank and trough). Most notably, sedimentation rates provide ages of ca. 12–10 Ma for the largest and oldest basins, significantly older than 6 Ma. This assertion is supported by a refraction-based crustal thickness profile (Sutherland, 2006; Lizarralde et al., 2007) that, within error, has a range of opening that varies between 425 and 485 km out of a possible ~600 km of total plate motion since 12 Ma. In addition, the morphologic expression of the Tamayo bank and trough (and other features) is clearly oriented northeast-southwest on multibeam bathymetry, providing additional evidence for a mode of distributed extension with an onset age for northwest-southeast extension that likely began significantly before 6 Ma. Together, the reflection and refraction data suggest an earlier phase of northwest-southeast-directed rifting in the gulf, which would require much less dextral motion on the Tosco-Abrejos fault system and/or extension farther to the southeast, toward the Sierra Madre Occidental (beyond the end of our profile). The amount of dextral offset on forearc strike-slip faults is certainly less than the 300 km proposed by Yeats and Haq (1981) based on reconstruction of the Magdalena Fan, and seems to bracket the upper limit of 150 km suggested in Fletcher et al. (2007), depending on the amount of extension that exists beyond the southeastern terminus (mainland Mexico) of the refraction profile. If correct, this single-stage gulf-opening model (Fig. 2) contradicts the assertion of Oskin and Stock (2003a) that only 300 km of oblique extension has been accommodated within the gulf proper; sup-

port of a single-stage model would require significant pre-6 Ma extension to the east of the central and northern gulf, within the bounding Mexican states of Sonora and Sinaloa (as suggested by Gans, 1997).

Plate reconstructions by Wilson et al. (2005) that correlate volcanic centers offshore coastal California with predicted slab window volcanics on land place the Baja California peninsula farther south than previous models, indicating ~500 km of oblique slip within the southern Gulf of California. Although several assumptions are made in this analysis, it would appear to be another independent line of evidence that suggests significantly more than the 300 km of oblique opening in the gulf suggested by Oskin and Stock (2003a).

Rifting Style

In the larger context of the Basin and Range province of western North America, the Gulf of California represents concentrated extension within a relatively narrow rift. However, the southern Gulf of California also appears to exhibit a combination of narrow and wide modes of rifting in the sense of Buck (1991). In the Alarcón corridor, we see different basins distributed over a wide region forming at different times; this is often attributed to buoyancy forces created when extending a hot lithosphere that cause the locus of rifting to migrate before a necking instability can develop (Buck, 1991). However, the nearby Guaymas and Cabo San Jose to Puerto Vallarta corridors are characterized as narrow rifts, where rifting quickly led to necking and rupture of the continent. In Lizarralde et al. (2007), the significant differences in crustal structure between rift segments (bounded by transform faults and fracture zones) that exist in the gulf were highlighted, and it was suggested that changes in mantle strength due to dewatering associated with Comondú and/or late Sierra Madre Occidental volcanism might explain these dramatic along-strike differences in rift structure. The difference in rifting style along the axis of the gulf may also be linked to the slab tear beneath the central gulf. All the samples of volcanic rock analyzed by Calmus et al. (2011) that have unusual geochemistry related to the slab tear occur north of 26°N. The heat and upwelling associated with this event may cause a more ductile style of extension, as opposed to a more brittle style in the colder southern Gulf of California. In contrast, recent active source images (Brothers et al., 2012) and mantle tomography (Wang et al., 2009) suggest otherwise, with the missing slab beneath the Baja peninsula confined to the southernmost region south of 26°N.

In either case, there is evidence of significant changes in lithospheric structure just north of the Alarcón segment. Asymmetric margins (Wernicke, 1985) are created by low-angle detachment faults, which result in one margin being composed of upper crustal material and its conjugate being exhumed middle-lower crustal rocks. The presence of the volcanic layer overlying upper crustal material with P-wave velocities of <4 km/s along both the Baja margin and the majority of the mainland Mexico margin implies that the upper layers of both margins are composed of upper crustal material. The Nayarit ridges show a different upper crustal velocity structure, and on a local scale there may have been some exhumation of deeper crustal material in this area. Nevertheless, the similar margin widths, no observed deeper crustal reflections, and similar basin styles across both conjugate margins provide compelling evidence to conclude that the southern Gulf of California is, overall, a symmetric rift, most likely resulting from large-scale pure shear extension (McKenzie, 1978) or from northwest-directed extension in a transtensional system. This interpretation is supported by crustal structure (Sutherland, 2006; Lizarralde et al., 2007), which shows similar degrees of crustal thinning on conjugate margins, in contrast to the northern gulf, where detachment-styled rifting is inferred (González-Fernández et al., 2005; Axen and Fletcher, 1998).

CONCLUSIONS

An MCS profile shows multiple rifted basins spanning 600 km across conjugate rifted margins in the southern Gulf of California. Estimates of the ages of these basins based on sedimentation rates indicate three phases of basin formation. (1) An initial phase, likely starting ca. 12 Ma, formed several larger basins (i.e., Tamayo trough, San Blas, Alarcón, and East Cerralvo basins) mostly concentrated in the middle of the gulf with rapid, distributed extension. In each basin, this initial phase of large-scale faulting was likely followed by the observed small-scale basement faulting, which continued to accommodate extension until a second phase of extension began ca. 8–5 Ma. (2) The second phase is inferred to have formed the smaller half-graben basins across the transect (i.e., La Paz and Nayarit troughs), and its initiation was possibly synchronous with the formation of the ocean basins in the central and northern gulf. The Nayarit troughs show lower synrift sedimentary sequences overlain by postrift sediments, and this change from synrift to postrift sedimentation likely coincides with the third phase. (3) The third phase is the onset

of lithospheric rupture and seafloor spreading, when plate motion became concentrated in the Alarcón Basin, forming the Alarcón Rise at 3.7–3.5 Ma. A pattern of distributed extension followed by more focused crustal thinning and rupture is common to many rift systems, including the Carnarvon Basin of Australia (Driscoll and Karner, 1998).

There is a distinctive basement layer, hundreds of meters thick, along much of the transect that is inferred to be volcanoclastic based on its highly reflective, ropey character and a measured P-wave velocity of ~2.5 km/s. The thickness and widespread occurrence of this layer suggest that it may be part of the 25–12 Ma Comodú formation with a mantling of possible early rift volcanics between 11 and 9 Ma. The pervasive, fine-scale faulting of this layer throughout this profile suggests that the volcanic layer predates the initiation of large-scale faulting and opening of the gulf. If true, the thickness profile of volcanics favors distributed extension in the older basins, which is in contrast to younger basins where this layer is missing or nearly so on the footwall, suggesting more focused extension on a basin-bounding fault system. Sediment thicknesses within the older basins, along with a crustal thickness profile from active-source tomography (Sutherland, 2006), record an earlier start to Gulf of California oblique extension. In addition to the onset of extension, the north-east-southwest orientation of the Tamayo bank (Fig. 3) strongly suggests that it was formed by northwest-southeast-directed extension, not east-west-directed extension.

The traditional model of Gulf of California extension begins at 12 Ma, with moderate amounts of west-east-directed extension in the gulf and 300 km dextral slip along the Tosco-Abrejos fault system within the Baja California borderlands; ca. 6 Ma dextral faulting started in the gulf proper, forming the modern Gulf of California. This model does not fit many of our observations or observations of others (Gans, 1997; Fletcher et al., 2007). To accommodate ~425–475 km (minimum estimate) of space determined from our refraction profile (Sutherland, 2006; Lizarralde et al., 2007), northwest-southeast-directed extension needs to have begun in the gulf closer to 12 Ma. Our data support the latter tectonic model, which differs from an earlier two-stage model both in the timing of the onset of extension and the direction and magnitude of this early extension. We interpret significant dextral slip and northwest-southeast-directed extension in the Gulf of California beginning at 12 Ma, with modest (<100–150 km) dextral accommodation in the Baja California borderlands (i.e., Tosco-Abrejos fault) beginning near or at 8 Ma.

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REFERENCES CITED

- Aragon-Arreola, M., Morandi, M., Martin-Barajas, A., Degado-Argote, L., and Gonzalez-Fernandez, A., 2005, Structure of the rift basins in the central Gulf of California: Kinematic implications for oblique rifting: *Tectonophysics*, v. 409, p. 19–38.
- Axen, G.J., 2004, Mechanics of low-angle normal faults, in Karner, G.D., et al., eds., *Rheology and deformation of the lithosphere at continental margins*: New York, Columbia University Press, p. 46–91.
- 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, doi:10.1080/00206819809465207.
- Backus, D., Ledesma-Vázquez, J., Johnson, M., and Lopez-Perez, R., 2005, Geologic history of the Isla Coronados, Baja California Sur, Mexico [abs.], in Gonzalez Yajimovich, O., ed., VII International Meeting on the Geology of the Baja California Peninsula, Ensenada, Baja California.
- Bigioggero, B., Chiesa, S., Zanchi, A., Montrasio, A., and Vezzoli, L., 1995, The Cerro Meneñares volcanic rift, Baja California Sur: Source and tectonic control on post-subduction magmatism within the gulf rift: *Geological Society of America Bulletin*, v. 107, p. 1108–1122, doi:10.1130/0016-7606(1995)107<1108:TCMVCB>2.3.CO;2.
- Boness, N., and Zoback, M., 2004, Stress-induced seismic velocity anisotropy and physical properties in the SAFOD pilot hole in Parkfield, CA: *Geophysical Research Letters*, v. 31, L15AS17, doi:10.1029/2003GL019020.
- Brothers, D., Harding, A., Gonzalez-Fernandez, A., Holbrook, W.S., Kent, G., Driscoll, N., Fletcher, J., Lizarralde, D., Umhoefer, P., and Axen, G., 2012, Farallon slab detachment and deformation of the Magdalena shelf, southern Baja California: *Geophysical Research Letters*, v. 39, L09307, doi:10.1029/2011GL050828.
- Brown, H., 2007, Crustal rupture, creation, and subduction in the Gulf of California and the role of gas hydrate in the submarine Storegga slide, offshore Norway [Ph.D. thesis]: Laramie, University of Wyoming, 165 p.
- Buck, W., 1991, Modes of continental lithospheric extension: *Journal of Geophysical Research*, v. 96, no. B12, p. 20,161–20,178, doi:10.1029/91JB01485.
- Calmus, T., Pallares, C., Maury, R.C., Aguilon-Robles, A., Bellon, H., Benoit, M., and Michaud, F., 2011, Volcanic markers of the post-subduction evolution of Baja California and Sonora, Mexico: Slab tearing versus lithospheric rupture of the Gulf of California: *Pure and Applied Geophysics*, v. 168, p. 1303–1330, doi:10.1007/s00024-010-0204-z.
- Carreño, A.L., 1992, Neogene microfossils from the Santiago Diatomite, Baja California Sur, Mexico: *Paleontología Mexicana*, v. 59, p. 1–37.
- 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 American motion: *Geophysical Research Letters*, v. 22, p. 3545–3548, doi:10.1029/95GL03323.
- Dickinson, W., and Snyder, W., 1978, Plate tectonics of the Laramide orogeny, in Matthews, V., III, ed., *Laramide folding associated with basement block faulting in the western United States*: Geological Society of America Memoir 151, p. 355–366.
- Dingler, J., Kent, G., Driscoll, N., Seitz, G., Babcock, J., Harding, A., Karlin, B., and Goldman, C., 2009, A high-resolution seismic CHIRP investigation of active normal faulting across the Lake Tahoe basin, California-Nevada: *Geological Society of America Bulletin*, v. 121, p. 1089–1107, doi:10.1130/B26244.1.
- Dixon, T., Farina, F., DeMets, C., Suarez Vidal, F., Fletcher, J., Marquez-Azua, B., Miller, M., and Umhoefer, P., 2000, new kinematic models for Pacific–North America motion from 3 Ma to present: Evidence for a “Baja California shear zone”: *Geophysical Research Letters*, v. 27, p. 3961–3964, doi:10.1029/2000GL008529.
- Driscoll, N., and Karner, G., 1998, Lower crustal extension across the Northern Carnarvon basin, Australia: Evidence for an eastward dipping detachment: *Journal of Geophysical Research*, v. 103, p. 4975–4991, doi:10.1029/97JB03295.
- Dorsey, R., and Umhoefer, P.J., 2000, Tectonic and eustatic controls on sequence stratigraphy of the Pliocene Loreto basin, Baja California Sur, Mexico: *Geological Society of America Bulletin*, v. 112, p. 177–199.
- Dorsey, R., Umhoefer, P., Ingle, J., and Mayer, L., 2001, Late Miocene to Pliocene stratigraphic evolution of north-east Carmen Island, Gulf of California: Implications for oblique-rifting tectonic: *Sedimentary Geology*, v. 144, p. 97–123, doi:10.1016/S0037-0738(01)00137-3.
- Drake, W., 2009, Structural analysis, stratigraphy, and geochronology of the Le Paz Rift segment and San José Island accommodation zone, Baja California Sur, Mexico [M.S. thesis]: Flagstaff, Northern Arizona University, 235 p.
- Falvey, D.A., 1974, The development of continental margins in plate tectonics theory: *Australian Petroleum Production and Exploration Association Journal*, v. 14, no. 1, p. 95–106.
- Ferrari, L., and Rosas-Elguera, J., 1999, Late Miocene to Quaternary extension at the northern boundary of the Jalisco block, western Mexico: The Tepic-Zacoalco rift revisited, in Delgado-Granados, H., et al., eds., *Cenozoic tectonics and volcanism of Mexico*: Geological Society of America Special Paper 334, p. 1–23.
- Ferrari, L., Lopez-Martinez, M., and Rosas-Elguera, J., 2002, Ignimbrite flare-up and deformation in the southern Sierra Madre Occidental, western Mexico: Implications for the late subduction history of the Farallon plate: *Tectonics*, v. 21, 1035, doi:10.1029/2001TC001302.
- 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, A.F., eds., *Geology of Mexico: Celebrating the centenary of the Geological Society of Mexico*: Geological Society of America Special Paper 422, p. 1–39, doi:10.1130/2007.2422(01).
- Fletcher, J.M., Kohn, B.P., Foster, D.A., and Gleadow, A.J.W., 2000, Heterogeneous Neogene cooling and exhumation of the Los Cabos block, southern Baja California: Evidence from fission-track thermochronology: *Geology*, v. 28, p. 107–110, doi:10.1130/0091-7613(2000)28<107:HNCAEO>2.0.CO;2.
- Fletcher, J., Grove, M., Kimbrough, D., 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.
- Gans, P., 1997, Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwestern Mexico: *Tectonics*, v. 16, p. 388–408, doi:10.1029/97TC00496.
- Goff, J.A., Bergman, E.A., and Solomon, S.C., 1987, Earthquake source mechanisms and transform fault tectonics in the Gulf of California: *Journal of Geophysical Research*, v. 92, p. 10,485–10,510, doi:10.1029/JB092iB10p10485.

- Gonzalez-Fernandez, A., Danobeitia, J., Delgado-Argote, L., Michaud, F., Cordoba, D., and Bartolome, R., 2005, Mode of extension and rifting history of the upper Tiburon and upper Delfin basins, northern Gulf of California: *Journal of Geophysical Research*, v. 110, no. B01313, doi:10.1029/2003JB002941.
- Hausback, B., 1984, Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico, in Frizzell, A., ed., *Geology of the Baja Peninsula: Society of Economic Paleontologists and Geologists Special Paper 39*, p. 219–236.
- 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, doi:10.1016/S0040-1951(99)00304-2.
- Hosack, A., 2006, Structure and stratigraphy of the Agua Verde accommodation zone, Baja California Sur, Mexico [M.S. thesis]: Flagstaff, Northern Arizona University, 162 p.
- Husenoeder, S., Detrick, R., Kent, G., Schouten, H., and Harding, A., 2002, Fine-scale seismic structure of young upper crust at 17°20'S on the fast spreading East Pacific Rise: *Journal of Geophysical Research*, v. 107, no. B8, 2158, doi:10.1029/2001JB001688.
- Johnson, M., Backus, D., Eros, J., and Lopez-Perez, R., 2005, Pliocene to recent carbonate deposits, Islas Carmen and Monserrat, Gulf of California [abs.], in Gonzalez Yajimovich, O., ed., VII International Meeting on the Geology of the Baja California Peninsula, Ensenada, Baja California.
- Larson, R., 1972, Bathymetry, magnetic anomalies, and plate tectonic history of the mouth of the Gulf of California: *Geological Society of America Bulletin*, v. 83, p. 3345–3360, doi:10.1130/0016-7606(1972)83[3345:BMAAPT]2.0.CO;2.
- Lizarralde, D., Axen, G.J., Brown, H.E., Fletcher, J.M., González-Fernández, A., Harding, A.J., Holbrook, W.S., Kent, G.M., Paramo, P., Sutherland, F., and Umhoefer, P.J., 2007, Variable styles of rifting in the Gulf of California: *Nature*, v. 448, p. 466–469, doi:10.1038/nature06035.
- Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California, in Winterer E.L., et al., 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. 87–125.
- Lonsdale, P., 1995, Segmentation and disruption of the East Pacific rise in the mouth of the Gulf of California: *Marine Geophysical Researches*, v. 17, p. 323–359, doi:10.1007/BF01227039.
- Lonsdale, P., and Kluesner, J., 2010, Routing of terrigenous clastics to oceanic basins in the southern Gulf of California, inherited from features of the pre-spreading protogulf: *Eos (Transactions, American Geophysical Union)*, fall meeting, abs. T33C-2265.
- McCloy, C., Ingle, J.C., and Barron, J.A., 1988, Neogene stratigraphy, foraminifera, diatoms, and depositional history of Maria Madre Island, Mexico: Evidence of early Neogene marine conditions in the southern Gulf of California: *Marine Micropaleontology*, v. 13, p. 193–212, doi:10.1016/0377-8398(88)90003-5.
- McDougall, K., 2006, Marine incursions: Implications for crustal thinning and regional strain: National Science Foundation MARGINS RCL-Cortez Workshop: <http://rcl-cortez.nsf-margins.org/Presentations.html>.
- McDougall, K., Poore, R.Z., and Matti, J.C., 1999, Age and environment of the Imperial Formation near San Gorgonio Pass, California: *Journal of Foraminiferal Research*, v. 29, p. 4–25.
- McKenzie, D., 1978, Some remarks on the development of sedimentary basins: *Earth and Planetary Science Letters*, v. 40, p. 25–32, doi:10.1016/0012-821X(78)90071-7.
- McTeague, M.S., 2006, Marginal strata of the east central San Jose del Cabo Basin, Baja California Sur, Mexico [Ph.D. thesis]: Flagstaff, Northern Arizona University, 152 p.
- Menzies, M., Klemperer, S., Ebinger, C., and Baker, J., 2002, Characteristics of volcanic rifted margins, in Menzies, M., et al., eds., *Volcanic rifted margins: Geological Society of America Special Paper 362*, p. 1–14.
- Michaud, F., Sosson, M., Royer, J., Chabert, A., Bourgois, J., Calmus, T., Mortera, C., Bigot-Cormier, F., Bandy, W., and Pontoise, B., 2004, Motion partitioning between the Pacific plate, Baja California and the North American plate: The Tosco-Abrejos fault revisited: *Geophysical Research Letters*, v. 31, L08604, doi:10.1029/2004GL019665.
- Michaud, F., Royer, J.Y., Bourgois, J., Dymont, J., Calmus, T., Brandy, W., Sosson, M., Mortera-Gutierrez, C., Sichler, B., Rebolledo-Viera, M., and Pontoise, B., 2006, Oceanic-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.
- Mutter, J., Talwani, M., and Stoffa, P., 1982, Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by “subaerial sea-floor spreading”: *Geology*, v. 10, p. 353–357, doi:10.1130/0091-7613(1982)10<353:OOSRIO>2.0.CO;2.
- Nagy, E., and Stock, J., 2000, Structural controls on the continent-ocean transition in the northern Gulf of California: *Journal of Geophysical Research*, v. 105, no. B7, p. 16,251–16,269, doi:10.1029/1999JB900402.
- Nava-Sanchez, E., Gorsline, D., and Molina-Cruz, A., 2001, The Baja California peninsula borderland: Structural and sedimentological characteristic: *Sedimentary Geology*, v. 144, p. 63–82, doi:10.1016/S0037-0738(01)00135-X.
- Nedimovic, M.R., Carbotte, S.M., Diebold, J.B., Harding, A.J., Canales, J.P., and Kent, G.M., 2008, Upper crustal evolution across the Juan de Fuca Ridge flanks: *Geochemistry Geophysics Geosystems*, v. 9, Q09006, doi:10.1029/2008GC002085.
- Orozco-Esquivel, T., Lopez-Martinez, M., Lonsdale, P., Ferrari, L., Cornejo-Jimenez, C., Pinero-Lajas, D., and Duque-Trujillo, J., 2010, Tearing apart of an Early Miocene silicic province in the southern Gulf of California: *Geological Society of America Abstracts with Programs*, v. 42, no. 5, p. 296.
- Oskin, M., and Stock, J., 2003a, Pacific–North America plate motion and opening of the upper Delfin basin, northern Gulf of California, Mexico: *Geological Society of America Bulletin*, v. 115, p. 1173–1190, doi:10.1130/B25154.1.
- Oskin, M., and Stock, J., 2003b, Marine incursion synchronous with plate-boundary localization in the Gulf of California: *Geology*, v. 31, p. 23–26, doi:10.1130/0091-7613(2003)031<0023:MISWPB>2.0.CO;2.
- Oskin, M., Stock, J., and Martin-Barajas, A., 2001, Rapid localization of Pacific–North America plate motion in the Gulf of California: *Geology*, v. 29, p. 459–462, doi:10.1130/0091-7613(2001)029<0459:RLOPNA>2.0.CO;2.
- Persaud, P., Stock, J., Steckler, M., Martin-Barajas, A., Diebold, J., Gonzalez-Fernandez, A., and Mountain, G., 2003, Active deformation and shallow structure of the Wagner, Consag, and Delfin basins, northern Gulf of California, Mexico: *Journal of Geophysical Research*, v. 108, no. B7, 2355, doi:10.1029/2002JB001937.
- Plattner, C., Malservisi, R., Dixon, T.H., LaFemina, P., Sella, G.F., Fletcher, J., and Suarez-Vidal, F., 2007, New constraints on relative motion between the Pacific plate and Baja California microplate (Mexico) from GPS measurements: *Geophysical Journal International*, v. 170, p. 1373–1380, doi:10.1111/j.1365-246X.2007.03494.x.
- Schwennicke, T., and Plata-Hernández, E., 2003, Stratigraphy of the Comondú Group near Timbáchichi, Baja California Sur, Mexico: *Geological Society of America Abstracts with Programs*, v. 35, no. 4, p. 28.
- Stock, J., and Hodges, K., 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, doi:10.1029/TC008i001p0099.
- Stock, J.M., and Lee, J., 1994, Do microplates in subduction zones leave a geological record?: *Tectonics*, v. 13, p. 1472–1487, doi:10.1029/94TC01808.
- Sutherland, F.H., 2006, Continental rifting across the southern Gulf of California [Ph.D. thesis]: San Diego, University of California, 189 p.
- Umhoefer, P., Dorsey, R., Willsey, S., Mayer, L., and Renne, P., 2001, Stratigraphy and geochronology of the Comodu group near Loreto, Baja California Sur, Mexico: *Sedimentary Geology*, v. 144, p. 125–147, doi:10.1016/S0037-0738(01)00138-5.
- Umhoefer, P.J., Mayer, L., and Dorsey, R.J., 2002, Evolution of the margin of the Gulf of California near Loreto, Baja California Peninsula, Mexico: *Geological Society of America Bulletin*, v. 114, p. 849–868, doi:10.1130/0016-7606(2002)114<0849:EOTMOT>2.0.CO;2.
- Umhoefer, P.J., Schwenicke, T., Del Margo, M.T., Ruiz-Geraldo, G., Ingle, J.C., Jr., and McIntosh, W., 2007, Transtensional fault-termination basins: An important basin type illustrated by the Pliocene San Jose Island basin and related basins in the southern Gulf of California, Mexico: *Basin Research*, v. 19, p. 297–322, doi:10.1111/j.1365-2117.2007.00323.x.
- Umhoefer, P., Arrowsmith, R., Kent, G., Driscoll, N., Martínez-Gutiérrez, G., Malservisi, R., Plattner, C., Busch, M., Maloney, S., and Buchanan, B., 2008, Neotectonics across an active oblique-divergent plate margin, SW Gulf of California: *Eos (Transactions, American Geophysical Union)* fall meeting, abs. T11A-1854.
- Unruh, J., Humphrey, J., and Barron, A., 2003, Transtensional model for the Sierra Nevada frontal fault system, eastern California: *Geology*, v. 31, p. 327–330, doi:10.1130/0091-7613(2003)031<0327:TMFTSN>2.0.CO;2.
- Walsh, J., Waterson, J., and Yielding, G., 1991, The importance of small-scale faulting in regional extension: *Nature*, v. 351, p. 391–393, doi:10.1038/351391a0.
- Wang, Y., Forsyth, D.W., and Savage, B., 2009, Convective upwelling in the mantle beneath the Gulf of California: *Nature*, v. 462, p. 499–501, doi:10.1038/nature08552.
- Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: *Canadian Journal of Earth Sciences*, v. 22, p. 108–125, doi:10.1139/e85-009.
- Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, in Burchfiel, B.C., Zoback, M.L., and Lipman, P.W., eds., *The Cordilleran Orogen: Contemporaneous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America*, v. G-3, p. 553–582.
- Wesnousky, S.G., Bormann, J.M., Kreemer, C., Hammond, W.C., and Brune, J.N., 2012, Neotectonics, geodesy, and seismic hazard in the Northern Walker Lane of western North America: Thirty kilometers of crustal shear and no strike-slip?: *Earth and Planetary Science Letters*, v. 329–330, p. 133–140, doi:10.1016/j.epsl.2012.02.018.
- White, R., Spence, G., Fowler, S., McKenzie, D., Westbrook, G., and Bowen, A., 1987, Magmatism at rifted continental margins: *Nature*, v. 330, p. 439–444, doi:10.1038/330439a0.
- Wilson, D.S., McCrory, P.A., and Stanley, R.G., 2005, Implications of volcanism in coastal California for the Neogene deformation history of western North America: *Tectonics*, v. 24, TC3008, doi:10.1029/2003TC001621.
- Yeats, R., and Haq, B., 1981, Deep-sea drilling off the Californias: Implications of Leg 63, in *Initial reports of the Deep Sea Drilling Project, Volume 63: Washington, D.C., U.S. Government Printing Office*, p. 949–961.