

Westward migration of extension in the northern Gulf of California, Mexico

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ABSTRACT

Interpretation of industry seismic lines indicates that the eastern margin of the northern Gulf of California contains the inactive Adair-Tepoca and Upper Tiburón basins. The western margin is active and includes the Wagner, Consag, Upper Delfín, and Lower Delfín basins. These basin systems are separated by a wide basement high across which the upper strata in the inactive basins correspond to the middle and lower strata in the active basins, recording the westward migration of strain and subsidence during late Pliocene time. Our results illustrate the formation of an abandoned rift margin along the eastern Gulf of California.

Keywords: Gulf of California, oblique rifting, rift kinematics, seismic reflection, rift basins.

INTRODUCTION

The Gulf of California is a well-developed transtensional plate margin linked to the rupture of Baja California from southwestern North America (Fig. 1). In middle Miocene time, extensional deformation affected the Gulf Extensional Province (Stock and Hodges, 1989; Gans, 1997; Axen and Fletcher, 1998), but sometime during the middle to late Miocene, the strain localized into the highly oblique Gulf of California rift, which is now dominated by large transform faults linked by pull-apart basins (Lonsdale, 1989; Stock and Hodges, 1989; Oskin et al., 2001). However, little is known about how strain evolved during the history of focused rifting. Based on processing and interpretation of seismic profiles, we compiled a structural map of the northern Gulf of California (the northern Gulf), documenting structures related to the initial stage of focused rifting. We show that the crustal strain and subsidence migrated westward to form the modern rift configuration. Finally, we propose that the eastern Gulf forms an abandoned rift margin.

GEOLOGIC FRAMEWORK

Evolution of the Gulf of California is related to transfer of the Baja California from the North America to the Pacific plate. This process started ~12 m.y. ago and imposed a northwestward motion on Baja California that triggered the localization of most of the Pacific–North America plate motion into the Gulf Extensional Province (Stock and Hodges, 1989; Henry and Aranda-Gomez, 2000; Umhoefer et al., 2002). Around the northern Gulf, the early marine sedimentation occurred during latest middle Miocene time (Delgado-Argote et al., 2000; Gastil et al., 1999; Helenes and Carreño, 1999; McDougall et al., 1999; Helenes et al., 2005), but it is unclear if deposition was related to oblique or orthogonal extension. Nevertheless, the marine environment became established by 6.5–6.3 Ma, synchronous with the full localization of oblique strain into the Gulf (Oskin et al., 2001; Oskin and Stock, 2003).

Previous works documented that the eastern margin of the Gulf contains several inactive basins, including the Upper Tiburón, Lower Tiburón, and Yaqui basins; it is interpreted that these basins were formed as

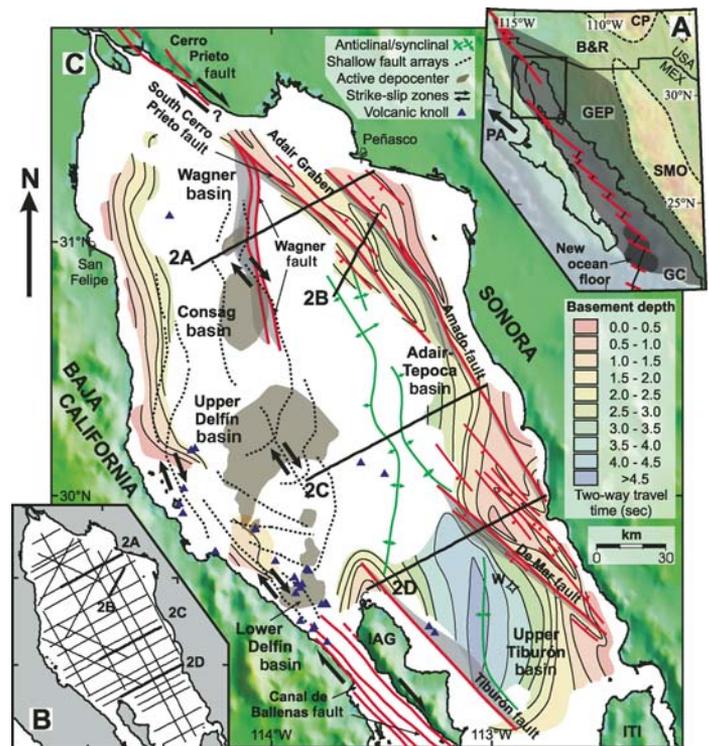


Figure 1. A: Regional tectonic framework of western North America and northwestern Mexico (after Stock and Hodges, 1989; Lonsdale, 1989; Fenby and Gastil, 1991). Arrow shows relative motion of Pacific–North America plates. B: Layout of processed seismic lines. C: Structural map of northern Gulf of California. Eastern margin contains inactive basins and faults, while western margin includes active basins of modern rift. Pattern of active depocenters and shallow fault arrays is from Persaud et al. (2003). Faults outside data coverage are from Fenby and Gastil (1991). PA—Pacific plate; GC—Gulf of California; GEP—Gulf Extensional Province; B&R—Basin and Range Province; SMO—Sierra Madre Occidental; CP—Colorado Plateau; ITI—Isla Tiburón; IAG—Isla Ángel de la Guarda.

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incipient spreading centers (Phillips, 1964; Fenby and Gastil, 1991; Lonsdale, 1989) abandoned ~3 m.y. ago (Stock, 2000). However, these studies lacked the data to resolve the structural pattern of the inactive basins, such that the database used here may help to clarify these conclusions.

The crustal structure displays contrasts across the northern Gulf. Toward the east, the crust is continental and thicker than in the west, where it is likely formed by a mix of continental, igneous, and sedimentary rocks (Phillips, 1964; Persaud et al., 2003; González-Fernández et al., 2005). Moreover, the shoulders of the northern Gulf differ in the amount and age of extension and volcanism; in central Sonora, the extension produced basin-and-range-type deformation and the exhumation of metamorphic core complexes during late Oligocene–middle Miocene time, coeval with arc-related volcanism (Nourse et al., 1994; Gans, 1997; Martín-Barajas, 2000). In contrast, extension in Baja California was accrued in high- to moderate-angle normal faults, and some detachment faults, and started in late-middle Miocene time after cessation of arc volcanism (Axen, 1995; Lee et al., 1996). Moreover, discrete postsubduction volcanism has occurred along the coastal plain of Baja California (Sawlan, 1991; Martín-Barajas, 2000). Thus, extensional strain is older and of larger magnitude in the eastern than in the western margin of the northern Gulf.

DATABASE

Our database contains ~3600 km of multichannel seismic reflection data (Fig. 1B) surveyed by PEMEX during 1978 and 1979 (Aragón-Arreola, 2006). These 48-fold data were acquired with a 48-channel, 2400-m-long streamer, a 21.98 L (1341 cu. in.) air gun array, and a shot interval of 25 m. Recording time was 6.1 s, with a sampling rate of 2 ms. Our processing included filtering, semblance velocity analysis, spherical spreading and normal move-out corrections, predictive deconvolution, stacking, and post-stack time migration. Depths are given in seconds of two-way travel-time; some absolute depths were estimated using the calculated interval velocities, such that they should be taken as rough estimates due to the lack of well constraints. Our geologic map (Fig. 1C) also presents the geologic information shown by Persaud et al. (2003) for the active basins.

RESULTS: STRUCTURE OF THE NORTHERN GULF OF CALIFORNIA

The main structural fabric of the northern Gulf consists of NW-SE–striking faults of moderate dip (Fig. 1) with >1 s of throw (>1 km). The larger faults offshore Sonora include the west-dipping Amado fault and the conjugate De Mar and Tiburón faults (Fig. 2¹; see GSA Data Repository²); these faults do not cut the uppermost strata, and are now inactive. The major faults display an en echelon array with intervening basins that mimics the active structural fabric of the Gulf (Fenby and Gastil, 1991; Lonsdale, 1989), which suggests that they had accommodated significant dextral shear. Our data show that the active Cerro Prieto fault extends into the northern Gulf; however, its southernmost segment is inactive and draped by undeformed strata (Figs. 2A, 2B). The data also reveal that numerous minor faults develop in the shallow section of the major structures.

Several NW-striking secondary faults were identified near the coast of Sonora. These structures display <1 s of throw and define horsts and grabens of moderate relief that are draped by sediments. One of these faults paired with the Amado fault, and bounds the ~10-km-wide Adair graben, which extends >50 km (Figs. 1, 2A, and 2B). In the north-central Gulf, the Wagner fault zone branches out from the Cerro Prieto fault and dips to the west at a moderate angle that tends to shallow with depth, suggesting listric fault geometry. The strata overlying the Wagner fault define fault-propagation

folds and are cut by multiple ~N-S–striking subsidiary faults that lie along the axis of the Wagner and Consag basins (Figs. 1 and 2A). Farther south, in the Upper Delfín and Lower Delfín basins, the shallow sediments are cut by dense fault arrays that crown and splay away from the northern strands of the Canal de Ballenas fault (Persaud et al., 2003; Aragón-Arreola, 2006).

The data clearly image the acoustic basement in the northeastern Gulf (Fig. 1). Here the basement is depicted as a sharp reflector that outlines the rhombochasmic Adair-Tepoca and Upper Tiburón basins. The Adair-Tepoca basin has a stratal thickness of as much as ~3.8 s (~4.8 km) and is bounded by the Amado fault and several minor faults to the east, a structural high to the west (see below), and terminates northward into the Adair graben (Figs. 1, 2A, and 2B). This basin contains two seismic sequences; the lower is formed by growth strata and aggradation patterns that accrete eastward against the basin-bounding faults, suggesting the syntectonic evolution of faulting and sedimentation (B in Figs. 2A, 2B). The upper sequence is formed by nearly parallel strata that onlap to the east and drape the basement relief (C in Figs. 2A, 2B).

The Upper Tiburón basin has a stratal thickness of as much as ~4.8 s (~6.0 km) and is bounded by the De Mar fault to the east and the Tiburón fault to the west (Figs. 1 and 2D). This basin contains three seismic sequences; the lower is formed by a hammock reflector pattern cut by the basin-bounding faults (A in Fig. 2D). The middle sequence is built by growth strata that accrete on the basin-bounding faults, revealing the syntectonic sedimentation (B in Fig. 2D). The upper sequence is formed by nearly parallel strata that onlap and drape the shallow (<1.5 s) and faulted basement offshore Sonora; toward the top this sequence includes local unconformities, but they do not separate changes in the stratal pattern (C in Figs. 2A, 2B).

The lateral continuity of seismic reflectors across the northeastern Gulf reveals the correlation of sequences B and C of the Adair-Tepoca and Upper Tiburón basins. The sequence C forms condensed sections that drape the Amado, De Mar, and Tiburón faults and fills the basement relief offshore Sonora. The data also show that reflectors of sequence C are locally truncated at the sea bottom, but do not record active faulting (Fig. 2C), indicating that this region is now structurally inactive.

The basement in the central-west margin of the northern Gulf is poorly defined, but suggests a broad rhombochasmic depression limited by the Cerro Prieto and Canal de Ballenas faults. This depression contains the Wagner, Consag, and Upper and Lower Delfín basins (Fig. 1) that form a set of shallow sags oriented N-NE (Persaud et al., 2003). Here the stratal thickness is poorly estimated, but exceeds 4.0 s (~4–5? km; Figs. 2A, 2C). The reflectors can be traced across contiguous sags and display multiple truncations, suggesting that the active basins tend to coalesce. Our data also show growth strata within the Wagner and Consag basins that form aggradation patterns against the Wagner fault (Fig. 2A), indicating syntectonic sedimentation.

The boundary between the active and inactive basins consists of a broad anticline. This flat-topped, ~20-km-wide, doubly hinged structure trends NNW-SSE and extends ~120 km from the Tiburón to the Cerro Prieto fault (Figs. 1, 2B, and 2C); the data suggest that this anticline is cored by a basement high. This anticline is built by condensed sequences cut by numerous small-throw faults. A conspicuous feature is that the B-C sequence boundary in the inactive basins can be traced across the entire anticline and deepens to the west into the active basins (Figs. 2A, 2C). These seismic relationships indicate that once subsidence and sedimentation shifted from the eastern to the west basins.

DISCUSSION

We interpret that the lower sequence in the Upper Tiburón basin (A in Fig. 2D [see footnote 1]) was deposited in a sag-shaped depression with no obvious association to any major fault. In contrast, sequence B in the Adair-Tepoca and Upper Tiburón basins comprises growth strata associated with the Amado, De Mar, and Tiburón faults, which are parallel to the main

¹Figure 2 is provided on a separate insert.

²GSA Data Repository item 2007130, Figures DR1–DR4, seismic profiles prepared for large-format printout, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

structural fabric of the Gulf of California rift (Fig. 1). The syntectonic evolution of sequence B reveals that the major faults accrued >1 km of throw, and possibly large strike-slip motion, based on the en echelon pattern (Fig. 1). The recognition of linked seismic sequences in the Adair-Tepoca and Upper Tiburón basins associated with growth faults suggests that sequence B records the onset of focused extension in the northern Gulf, while sequence A represents pre-rift deposition probably linked to the proto-Gulf Stage (Stock and Hodges, 1989; Henry and Aranda-Gomez, 2000).

Our results indicate that sequence C records the abandonment of the eastern basins. This sequence drapes and is posttectonic to the major faults; in addition, the unconformities and stratal truncation within this sequence (Figs. 2B, 2D) suggest erosional stages probably tied to the cease of tectonic activity. Moreover, the correlation of the B-C sequence boundary from the Adair-Tepoca and Upper Tiburón basins into the Wagner, Consag, and Upper Delfín basins (Figs. 2A, 2B, 2C) supports that strain and associated subsidence waned in the eastern basins as they relocated to the west. This sequence boundary was traced down to ~3.0 s into the Wagner and Consag basins (Figs. 2A, 2B); thus, most of the stratigraphic section in the active basins postdates the shift of deformation.

Here we infer prerift and synrift deposition, and the migration of strain and subsidence, but we lack time constraints for these events. The reconstruction of conjugate margins in the Upper Delfín basin segment suggests that rifting began ca. 6–7 Ma (Oskin et al., 2001; Oskin and Stock, 2003). However, microfossil data from an ~4800 m well drilled by PEMEX in the Upper Tiburón basin (W in Fig. 1) show that the upper ~3500 m postdate the late-middle Miocene; the lower section that mostly correlates with sequence A lacks biostratigraphic control due to poor faunal preservation (Helenes et al., 2005). Thus, the prerift sequence A predates or is at least late-middle Miocene age, which suggests that it was deposited during the proto-Gulf stage (Stock and Hodges, 1989; Henry and Aranda-Gomez, 2000). The upper 800 m in well W that correlate with sequence C were deposited in Pliocene–Pleistocene time (Helenes et al., 2005), suggesting that migration of strain occurred in that time. Thus, our interpretation agrees with reconstructions in which, ca. 3.3–2.0 Ma, the Upper Tiburón basin and Tiburón fault became inactive as the Lower Delfín basin and Canal de Ballenas fault initiated (Nagy and Stock, 2000; Stock, 2000).

The shift of subsidence in narrow basins has been explained by the lateral contrast of heat flow caused by attenuation of continental crust during rifting (Sandiford et al., 2003). In addition, large sediment piles likely play a roll in the lithospheric weakening, because sediments thermally insulate the lower crust (Lavie and Steckler, 1997). This insulation favors the lateral heat transfer that may trigger the migration of deformation in the vicinity of rift basins (Sandiford et al., 2003). The northern Gulf meets both conditions: it contains kilometeric sedimentary columns and its western shoulder records volcanic activity since the early Miocene (Sawlan, 1991; Martín-Barajas, 2000). Moreover, the onshore volcanism and the numerous volcanic knolls in the active basins (Fig. 1) also suggest a sustained heat source near Baja California.

The Wagner, Consag, and Upper and Lower Delfín basins are in a large stepover of the Canal de Ballenas and Cerro Prieto faults; here, subsidence is diffusely controlled by shallow fault arrays that branch out from the major faults (Lonsdale, 1989; Nagy and Stock, 2000; Stock, 2000; Persaud et al., 2003). However, our data reveal that the likely listric Wagner fault roots the shallow deformation and yields the formation of thick growth strata; thus, this fault is likely the main control of subsidence in the Wagner and Consag basins (Figs. 1 and 2A). We argue that vertical propagation of the Wagner fault results in the distributed faulting that controls the modern depocenter of these basins. Furthermore, subsidence of the Upper Delfín and Lower Delfín basins is related to horsetail structures splaying away the Canal de Ballenas fault (Fig. 1; Persaud et al., 2003). We speculate that these shallow faults may also be linked to the propagation of deep structures, similar to the Wagner fault.

The pattern of inactive basins is a conspicuous feature along the eastern Gulf of California rift (Fig. 3). North of the Adair-Tepoca and Upper Tiburón basin system, the Altar and East Mesa basins contain deltaic successions that onlap late Miocene marine deposits; these basins are above the base level and are now inactive (Pacheco-Romero et al., 2006). In the central Gulf, the Yaqui basin is an inactive half-graben abandoned during late Pliocene time (Aragón-Arreola et al., 2005). Farther south, the eastern margin contains the inactive San Blas, Tamayo, Nayarit, and Tres Mariás troughs (Brown et al., 2006; Sutherland et al., 2006). We propose that the inactive basins along the eastern Gulf of California constitute an abandoned rift margin that is forming an incipient drift margin.

CONCLUSIONS

Our results indicate that focused extension in the northern Gulf of California occurred through a process of localization and relocation of strain that resulted in two diachronous basin systems controlled by large dextral-oblique faults. The inactive margin includes the Adair-Tepoca and Upper Tiburón basins, controlled by the Amado, de Mar, and Tiburón faults. During middle to late Pliocene time, the strain localized to the west, giving rise to the Wagner, Consag, and Upper and Lower Delfín basins, which are controlled by the Wagner fault and the fault arrays that branch away the Cerro Prieto and Canal de Ballenas faults. The pattern of inactive fault-basin systems in the east is present along the entire length of the Gulf and forms an abandoned rift margin, while active rifting is located in the western Gulf.

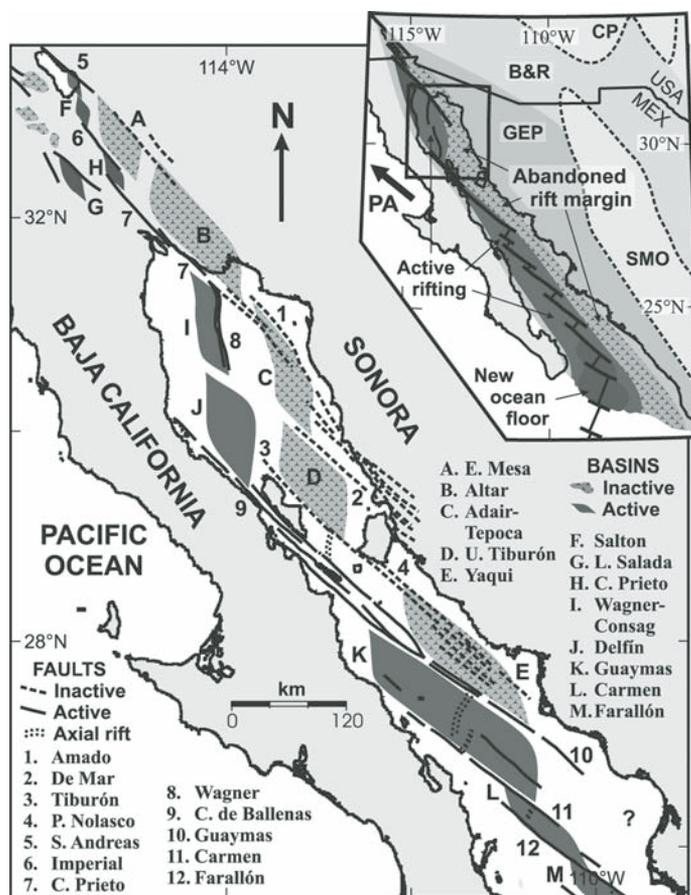


Figure 3. Eastern Gulf of California contains abandoned rift basins, while active rifting occurs in the western Gulf (Lonsdale, 1989; Fenby and Gastil, 1991; Persaud et al., 2003; Aragón-Arreola et al., 2005; this study). Eastern Gulf constitutes abandoned rift margin (see inset). Abbreviations as in Figure 1.

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