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Breaching of strike-slip faults and successive flooding of pull-apart basins to form the Gulf of California seaway from ca. 8–6 Ma

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ABSTRACT

The geologic record of the formation of marine basins during continental rifting is uncommonly preserved. Using GIS-based paleotectonic maps, we show that marine basin formation in the Gulf of California–Salton trough oblique rift (Mexico and the United States) occurred in a stepwise manner as crustal thinning lowered elevations within the Gulf of California Shear Zone, and subsidence along strike-slip and transtensional faults linked isolated pull-apart basins. At 8 Ma, the earliest marine conditions in the Gulf of California were restricted to an embayment at its southern mouth. Farther north, the plate boundary was a set of continental strike-slip faults and linked pull-apart basins, similar to the modern Walker Lane in Nevada and California. By ca. 7 Ma, a series of marine incursions breached across strike-slip faults to the Pescadero and Farallon basins. Marine waters then breached a 75–100 km-long transtensional fault zone between the Farallon and Guaymas basins, with intermittent flooding that led to accumulation of extensive evaporite deposits in the Guaymas basin. Marine incursion north of the Guaymas basin via breaches across the Guaymas and Tiburón strike-slip faults and transtensional zones resulted in flooding of the northern >500 km of the oblique rift by 6.5–6.3 Ma. Thus, strike-slip and transtensional faulting promoted localization of plate boundary strain and guided punctuated marine flooding of the Gulf of California seaway. Inception of the narrow, 1500-km-long Gulf of California at ca. 6.3 Ma was followed by complete continental rupture in the Guaymas basin at ca. 6.0 Ma.

INTRODUCTION

Continental lithospheric rupture and formation of a new ocean basin represent one of the most fundamental tectonic and physiographic transitions on Earth (McKenzie, 1978). Transformative effects of these events include the development of marine depositional environments, reorganizations of topography, climate patterns, and drainage networks (Weissel and Seidl, 1998), and biodiversification through the introduction of marine ecosystems and isolation and evolution of species (e.g Dolby et al., 2015). The stratigraphic record of the transition from early rifting to seafloor spreading is often concealed beneath thick sedimentary sequences along subsided passive margins, or exhumed and destroyed along convergent plate boundaries. Therefore, the processes that occur during initial stages of rifting and seaway development are difficult to constrain and poorly understood.

Many continental rift systems open oblique to the trend of the incipient plate boundary. Models of highly oblique divergent plate boundaries predict that continental rupture is preceded by a focused thinning/rifting stage that involves a series of pull-apart basins (Brune et al., 2012). Conceptually, oblique rifting should lead to stepwise expansion of a nascent ocean basin by linking pull-apart basins (Fig. 1). We define this process of flooding of marine waters into an adjacent basin as breaching (Figs. 1B and 1C). We suggest that breaching of strike-slip fault-controlled topographic sills is a fundamental process in the formation of a narrow seaway that, due to focused crustal thinning and subsidence, leads to continental rupture on geologically short time scales (Umhoefer, 2011).

In the Gulf of California (GOC, Mexico), dextral-oblique rifting between the North America and Pacific plates (Baja California microplate) (Fig. 2) initiated after ca. 12.5 Ma (Lonsdale, 1989; Dorsey and Umhoefer, 2012; Bennett and Oskin, 2014) following ca. 25–15 Ma extension along and east of the future GOC (Ferrari et al., 2002). By ca. 8 Ma, an initial marine embayment had formed in the southernmost GOC, and by ca. 6.3 Ma, a narrow marine seaway was fully developed from the mouth of the GOC in the south to the Salton Trough in the north (California, USA; Bennett et al., 2015). Seafloor spreading

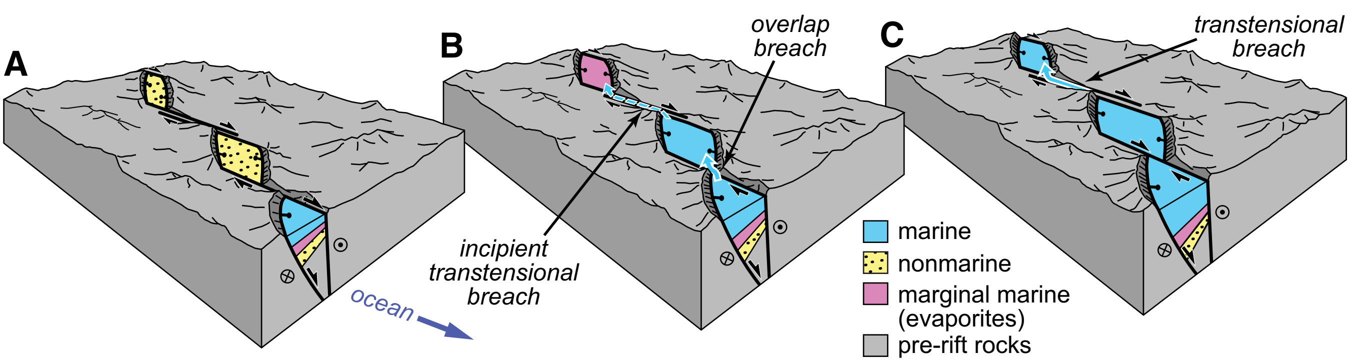

Figure 1. Conceptual block model illustrating progressive seaway encroachment along en-echelon, pull-apart basins. A: Marine inundation will occur first in the basin most proximal to the continental margin (bottom), while topographic barriers generated by isostatic and fault uplift inhibit flooding of the adjacent nonmarine basins. Continued faulting and basin lengthening allows marine waters to "breach" the topographic barriers to adjacent basins due to basin overlap (B) and/or localized subsidence along transtensional fault zones (C).

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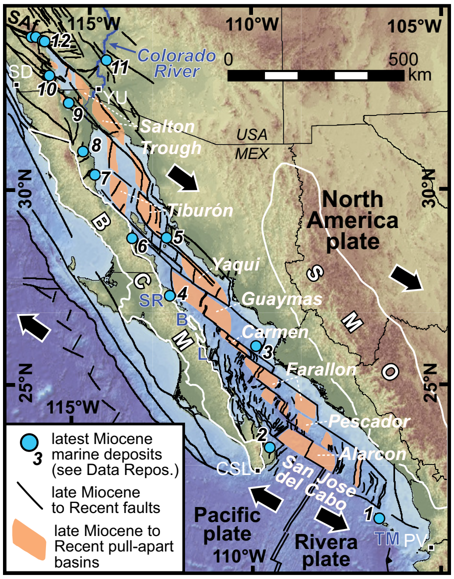

Figure 2. Physiographic map and tectonic setting of the modern Gulf of California plate boundary. Abbreviations: B—Bahía Concepción; BCM—Baja California microplate; CSL—Cabo San Lucas; L—Loreto basin; PV—Puerto Vallarta; SAf—San Andreas fault; SD—San Diego; SMO—Sierra Madre Occidental; SR—Santa Rosalia basin; TM—Tres Marias Islands; YU—Yuma. Data Repos.—Data Repository (see footnote 1). Numbered blue dots refer to locations of published studies (see the Data Repository) that provide age constraints for the earliest marine strata in the Gulf of California.

initiated first within the Guaymas basin in the central GOC at ca. 6.0 Ma (Lizarralde et al., 2007) and developed later in the southern GOC from ca. 3.7–1 Ma (Lonsdale, 1989; Sutherland et al., 2012). Seafloor spreading is inhibited in the northern GOC by thick deltaic sediments of the Colorado River, though rifting did proceed to rupture of continental basement after 2 Ma (Martín-Barajas et al., 2013).

In this paper, we integrate onshore and offshore data from the GOC into a set of GIS-based paleotectonic maps (see the methods in the GSA Data Repository[1]), which, when combined with prior studies of the age and conditions of earliest marine deposits, illustrate how marine incursions rapidly progressed along the axis of oblique rifting from 8 to 6 Ma, and only a few hundreds of thousand years before continental rupture. The short time that passed between full seaway development (ca. 6.3 Ma) and earliest seafloor spreading (ca. 6 Ma) suggests that the tectonic processes that led to marine incursion were also intimately related to continental rupture.

TRANSTENSIONAL BREACHING CONCEPT

If an oblique continental rift and its pull-apart basins are near the ocean, marine waters may flood the nearest basin once the connections to the ocean subside below sea level (Fig. 1A). Marine waters will flood adjacent pull-apart basins as the strike-slip faults lengthen and basins become linked. In detail, breaching from one basin to the next can occur in two basic ways (Figs. 1B and 1C): (1) from the overlapping of basins across a simple strike-slip fault system, or (2) through a more complex narrow zone of transtensional faulting that undergoes localized subsidence. Shallow sill depth combined with fluctuating relative sea level may lead to pulses of flooding that alternate with evaporitic conditions during the transition to marine conditions (Fig. 1B).

DEVELOPMENT OF THE GULF OF CALIFORNIA SEAWAY

The earliest marine deposits at the mouth of the GOC on the Tres Marias islands (McCloy et al., 1988) and in the San José del Cabo basin (Martínez-Gutiérrez, and Sethi, 1997) have been dated at 9(?)–8 Ma based on marine microfossils (Figs. 3A and 3B). Based on our reconstruction, we show a terrestrial basin for the adjacent Alarcón basin at this time, but this is uncertain and marine waters may have occupied this basin. The east-dipping San José del Cabo fault formed the western margin of the mouth of the GOC, while west-dipping structures likely formed the southeastern margins of the greater San José del Cabo basin near the Tres Marias islands (Fig. 3B). Along strike to the north, thermochronological and geomorphological data support the onset of rift-related exhumation and terrestrial sedimentation in the transtensional Loreto basin at ca. 8–7 Ma (Figs. 3C and 3D) (Mark et al., 2014). East of this basin, our reconstruction suggests that the Pescadero and Farallon pull-apart basins were not overlapping and therefore they were probably terrestrial (Figs. 3A and 3B). Between 8 and 7 Ma, the model suggests that the Alarcón, Pescadero, and Farallon basins were breached across simple strike-slip fault systems (Figs. 3C and 3D).

By ca. 7 Ma, we infer from our model that a series of marine incursions breached the 75–100-km-long transtensional fault barrier between the Farallon and Guaymas basins, along the future Farallon and Carmen transforms (Fig. 3D). Episodic breaching of this narrow transtensional belt is supported by an extensive, up to 2-km-thick salt deposit in the southeast Guaymas basin (Miller and Lizarralde, 2013). The presence of thick evaporites suggests that the Farallon–Guaymas barrier, and perhaps the Guaymas basin itself, resided at or just below sea level for an extended period of time. Correlative evaporites and marine strata in the onshore Santa Rosalia basin (Miller and Lizarralde, 2013) are dated at 7.09–6.93 Ma (Holt et al., 2000). We conclude that part of the Farallon to southeast Guaymas transtensional belt eventually developed into the small Carmen basin in the modern GOC (Fig. 3D).

Continued strike-slip and transtensional faulting along the incipient Guaymas and Tiburón transform faults led to breaching of the intervening Yaqui and Tiburón basins and then abrupt marine flooding from the Tiburón basin to the Salton Trough and lower Colorado River valley by 6.5–6.3 Ma (Figs. 3E and 3F) (e.g., Martín-Barajas et al., 1997, 2001; McDougall et al., 1999; Dorsey et al., 2007, 2018; Bennett et al., 2015). Based on the relatively short length of the Guaymas transform, breaching of the Yaqui basin may have occurred by direct overlap with the Guaymas basin or transtensional subsidence. Conversely, the marine connection from the Yaqui to Tiburón basins was concentrated along a much longer narrow, transtensional fault zone that developed into the Tiburón transform fault, similar to the proposed connection from the Farallon to Guaymas basins. Once marine waters breached the Tiburón transform barrier, the basins were connected along >500 km to the Salton Trough (Fig. 3F), which suggests that the northern pull-apart basins were already overlapped by 6.5–6.3 Ma. This along-strike contrast in common transtensional fault-basin geometry in the southern to central GOC compared to the overlapping basins in the northern GOC is due to rifting that was less oblique and more extensional in the northern GOC (Dorsey and Umhoefer, 2012). The rapid marine incursion at 6.5–6.3 Ma in the northern GOC and Salton Trough was during a fall of global sea level (Dorsey et al. 2018), which favors breaching as a mechanism rather than a sea level rise. At the time of full development of the GOC seaway ca. 6.3 Ma, the majority of Pacific–North America plate motion localized into the GOC (Oskin et al., 2001), and the Guaymas basin rapidly evolved to full continental rupture by ca. 6.0 Ma (Lizarralde et al., 2007).

DISCUSSION AND CONCLUSIONS

The geometry and obliquity of a rift controls the spacing and topographic isolation of basins along its length. Highly oblique rift segments, which are characterized by relatively long strike slip-faults, may act as barriers to marine incursion. The bathymetry of the GOC (Fig. 2) suggests that a chain of isolated pull-apart basins formed along its axis prior to continental rupture (Lonsdale, 1989), and our reconstructions are consistent with that conclusion (Fig. 3A).

We suggest that the initial spacing of early pull-apart basins and the length of strike-slip faults were first-order controls on the breaching process in the GOC, and ultimately determined which of the two breaching mechanisms

[1]GSA Data Repository item 2018250, reconstruction methods, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

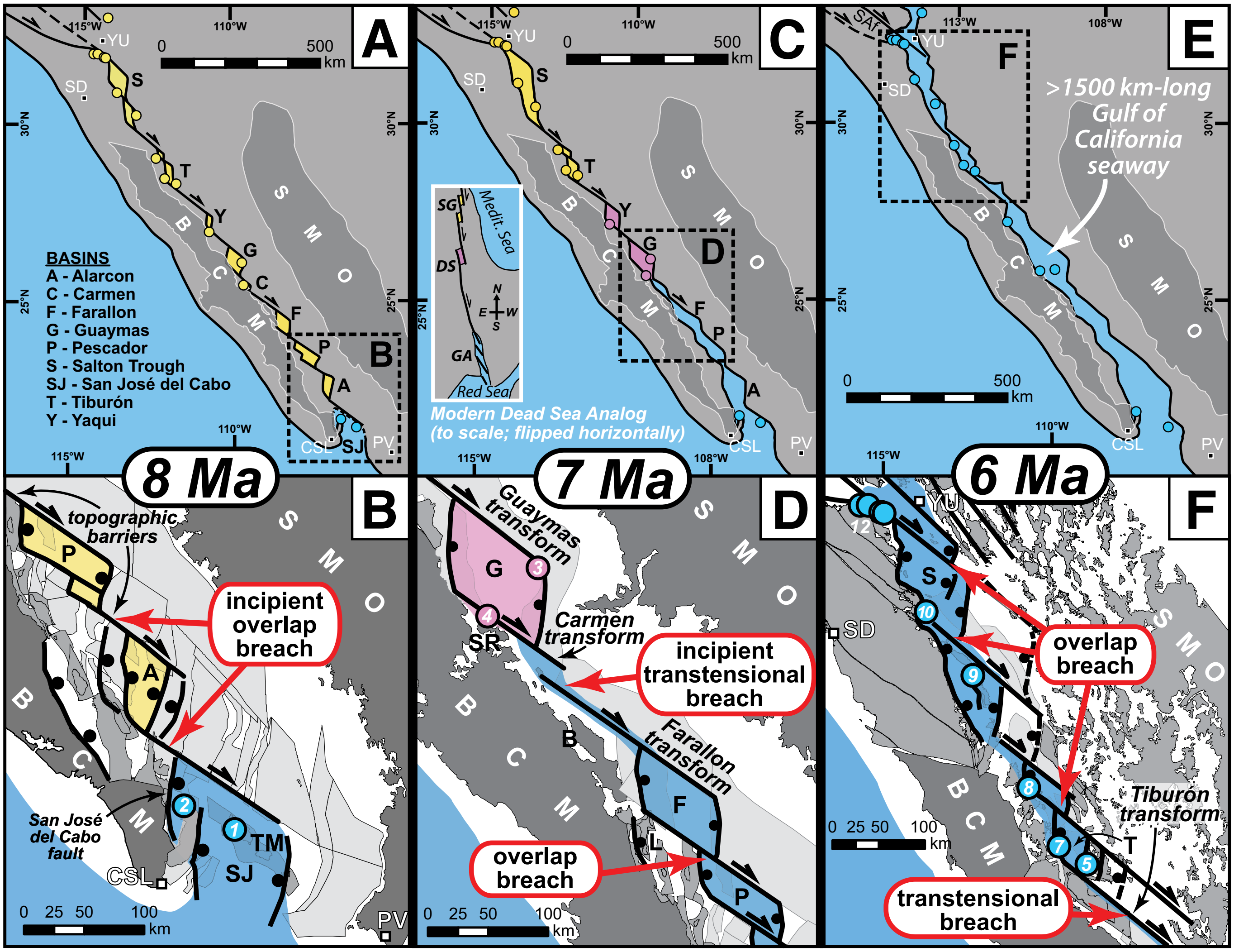

Figure 3. GIS-based reconstructions at 8, 7, and 6 Ma showing terrestrial (yellow), evaporitic (pink), and marine (blue) basins and locations of data in colored circles in the Gulf of California (see the Data Repository [see footnote 1]). Detailed maps (B, D, F) of key breaching areas for each reconstruction show rigid microplates (dark gray), and faulted onshore (medium gray) and offshore (light gray) continental crust. Abbreviations as in Figure 2; panel C inset: Medit.—Mediterranean; DS—Dead Sea; GA—Gulf of Aqaba; SG—Sea of Galilee.

occurred in a particular location. Breaching by basin overlap is favored by short strike-slip faults and closely spaced basins (Fig. 1B). Breaching along complex, narrow transtensional fault zones is favored by other geometries common in the GOC, such as (1) widely spaced basins with a long linking strike-slip fault with complex steps and bends, (2) small changes in the azimuth of a strike-slip fault that foster formation of a narrow transtensional fault zone, and (3) widening of pull-apart basins over time (e.g., Gürbüz, 2010). Inherited geologic features likely controlled the initial pattern of strike-slip faults including variations in trend of the long-lived Cordilleran convergent margin (Gastil et al., 1981), segmentation in the Oligocene-early Miocene extensional belt along and east of the future GOC (Ferrari et al., 2002), and variability in the precursor Comondú volcanic arc (Drake et al., 2017). Pre-GOC extension also must have lowered the elevation of the region and shortened the time to breaching and marine flooding.

Within the GOC oblique-rift system, the transition from disconnected, en echelon, nonmarine pull-apart basins to rapid marine seaway incursion followed by onset of seafloor spreading occurred rapidly over a period of ~2 m.y., from ca. 8–6 Ma. These events took place during, and were triggered by, an increase in transtensional deformation rates in the GOC rift (Seiler et al., 2011; Bennett et al., 2016). The final stage of marine incursion at ca. 6.3 Ma north of the Guaymas basin occurred only a few hundreds of thousands of years before the Guaymas basin proceeded to continental rupture at ca. 6.0 Ma (Lizarralde, et al., 2007), highlighting the role of strike-slip faulting and pull-apart basins in the lithospheric rupture process. Intriguingly, seafloor spreading in the Guaymas basin occurred in isolation for 3–4 m.y., while oblique rifting to the south and north continued as a series of pull-apart and transtensional basins (Dorsey and Umhoefer, 2012).

The GOC seaway at 6.3 Ma (Fig. 3E) was a remarkable paleogeographic feature with an exceptional aspect ratio: ~1500 km long and only a few tens of kilometers wide at the basins, and possibly only a few kilometers wide at the breaching zones. Yet marine microfossils and sedimentary facies along the length of the early GOC seaway indicate that it was a normal marine environment from south to north. The rapid change of elevation that accompanied formation of this narrow marine seaway in a transtensional setting likely produced a landscape with several small catchments feeding the early GOC seaway for its first ~1 m.y., prior to downward integration of the large Colorado River system into the developing marine seaway at ca. 5.3 Ma (Dorsey et al., 2018). Such a long, narrow seaway would be two to three times as long as both the Walker Lane and Gulf of Aqaba–Dead Sea–Sea of Galilee fault zones (Fig. 3C), if they were flooded today.

The topography, structure, and along-strike variety of depositional settings of the highly oblique Gulf of Aqaba–Dead Sea fault zone offer many favorable comparisons to the processes that we interpret formed the late Miocene GOC seaway. The terminal Gulf of Aqaba today is similar to the 8–7 Ma southern GOC. Lying below sea level, ~100 km north of the Gulf of Aqaba, the highly evaporitic Dead Sea basin straddles a long transtensional fault zone where the ~100-km-long Jordan River connects the Dead Sea to the freshwater lake of the Sea of Galilee in the north, broadly similar to our 7 Ma GOC reconstruction (Fig. 3C). If the Dead Sea was flooded by marine water today, the narrow valley from there to the Sea of Galilee (~100 km) would also flood quickly, much like the marine incursion that flooded the northern ~500 km of the GOC at 6.3 Ma. We therefore conclude that oblique-rift plate boundaries are prone to rapid flooding of long (hundreds of kilometers), narrow marine seaways that may evolve into ocean basins by continued oblique divergence and continental rupture.

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