

Why did the Southern Gulf of California rupture so rapidly?—Oblique divergence across hot, weak lithosphere along a tectonically active margin

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ABSTRACT

Rifts in the interior of continents that evolve to form large oceans typically last for 30 to 80 m.y. and longer before complete rupture of the continent and onset of sea-floor spreading. A distinct style of rifts form along the active tectonic margins of continents, and these rifts more commonly form marginal seas and terranes or continental blocks or slivers that are ruptured away from their home continent. The Gulf of California and the Baja California microplate make up one of the best examples of the latter setting and processes. In the southern Gulf of California, sea-floor spreading commenced only ~6–10 m.y. after the formation of the oblique-divergent plate boundary at ca. 12.5 Ma. Three main factors caused this rapid rupture: (1) an inherited long, narrow belt of hot, weak crust from a volcanic arc that was active immediately before formation of the oblique-divergent plate boundary and that lay between two strong batholith belts; (2) relatively rapid plate motion resulting in high strain rates; and (3) a dominant role of strike-slip faulting in the highly oblique-divergent setting that formed large pull-apart basins with rapid and focused crustal thinning in a linked en-echelon system. Accentuating factor 1 is that the formation of slab windows associated with microplate capture west of the Baja California peninsula may have further weakened the crust. These causes of rapid rupture of continental lithosphere are mostly linked to the fact that the Gulf of California developed along a long-lived tectonically active margin of a continent with a convergent or oblique-convergent setting since at least the Jurassic, but not a margin that was thickened in a major contractional orogen. This combination of causes and factors suggests that rifts that form at active margins are fundamentally different than continental interior rifts, and that these differences can produce vastly different rifting histories. The formation and northwestward motion of the Baja California microplate also show that “terranes” formed in an oblique-divergent setting can form and move long distances over relatively short geologic time intervals.

INTRODUCTION

The rupture of continental lithosphere is one of the most fundamental tectonic processes. Complete rupture of a continent requires the familiar progression from early rifting to extreme continental lithosphere thinning to continental breakup that forms oceanic spreading in a nascent ocean (e.g., Veevers, 1981). The development of a rift, and whether it progresses to

breakup, is mainly dependent on the thermal structure, crustal thickness, and crustal strength of the lithosphere when rifting begins (e.g., Buck, 2007), as well as forces at the base of the lithosphere and far-field plate interactions (Ziegler and Cloetingh, 2004).

Continental rupture at its two extremes creates either large ocean basins or small and narrow marginal seas depending largely on the tectonic setting of the rift. Rupture of a continent that creates large oceans most commonly initiates as rifts in old, cold continental lithosphere or within former large collisional belts in the interior of large continents, part of the process known as the Wilson Cycle (Wilson, 1966). Rupture to create narrow marginal seas commonly occurs in active continental margins and results in the formation of micro-continents or continental terranes. Examples of these marginal sea settings are the modern Andaman Sea and Gulf of California and the Mesozoic of the Alps (Kelts, 1981; Weissert and Bernoulli, 1985; Channell and Kozur, 1997). The creation and later translation and accretion of terranes is one of the processes that leads to the formation of so-called accretionary or Cordilleran-type orogens (Helwig, 1974; Coney et al., 1980; Moores and Twiss, 1995).

The process of rifting active continental margins can occur in two distinctly different settings that create vastly different results. Most attention and research has been done in rifts within active margins that were previously contractional orogens, such as the Basin and Range or Aegean Sea, in which the crust was thickened before rifting. In the western United States, before the Basin and Range extensional event, the crust was ~70 km thick in the Sierra Nevada arc (Ducea, 2001) and >50 km thick in the hinterland of the thrust belt (Coney and Harms, 1984). In both of these examples, after tens of millions of years of extension, continental crust has not fully ruptured, but it has thinned appreciably to 20–30 km (Thompson and Burke, 1974; Wernicke, 1992; Klemperer and Ernst, 2003; Sodoudi et al., 2006).

The Aegean Sea is also an example of slab rollback that drove extension in the backarc but has not resulted in continental rupture after a few tens of millions of years. Slab rollback in the Tyrrhenian Sea did produce continental rupture and formation of oceanic crust (Nicolosi et al., 2006), but only after extension occurred for ~30 m.y. (Malinverno and Ryan, 1986). Therefore, from the Mediterranean region, it appears that slab rollback is an alternative process to the oblique divergence explored in this paper, which may produce rupture of continental lithosphere—but in these examples rupture was a slow process. However, there may be conditions in which slab rollback produces more rapid rupture of continental lithosphere.

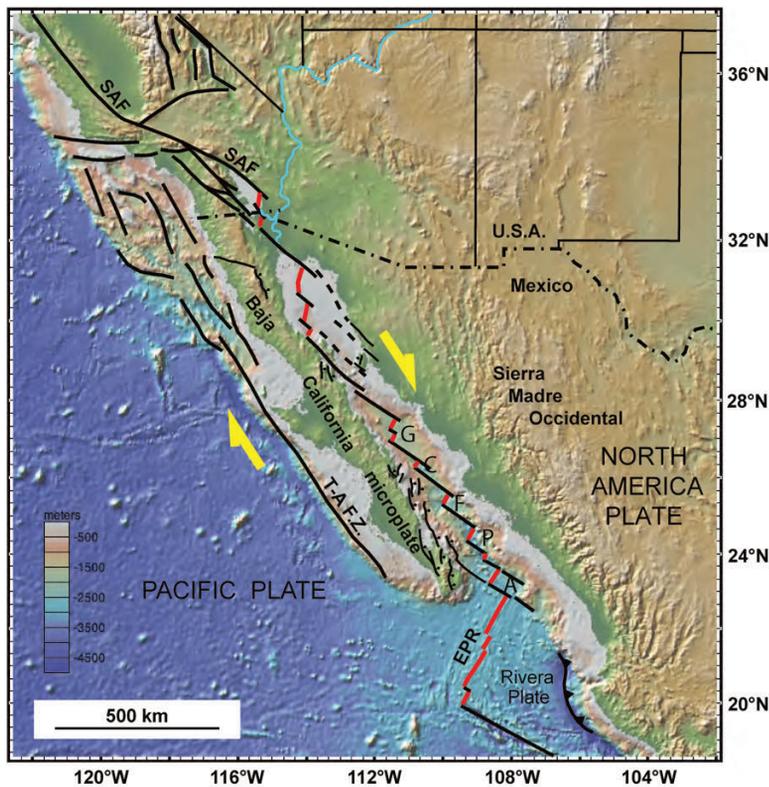


Figure 1. Tectonic map of the Pacific–North America plate boundary of the Gulf of California–Salton trough region (modified from Dorsey and Umhoefer, 2011). Thin black lines are faults; red lines are spreading centers in the southern Gulf of California and complex pull-apart basins in the northern Gulf of California and Salton trough. Abbreviations from north to south: SAF—San Andreas fault; G—Guaymas spreading center; C—Carmen spreading center; F—Farallon spreading center; P—Pescadero spreading center; A—Alarcón spreading center; T-A F.Z.—Tosco-Abreajos fault zone; EPR—East Pacific Rise. Normal faults on the Baja California peninsula and islands are selected young and active faults.

In contrast to these rifts formed on ancient contractional orogens, other rifts along active continental margins form on volcanic arcs in regions with previous neutral or extensional tectonics, such as the Gulf of California. The Gulf of California is an example of a region in which a young oblique rift formed on a volcanic arc with an extensional backarc. The Pacific–North America plate boundary in the Gulf of California (Fig. 1) is one of the best modern examples of rupture of continental lithosphere to form a narrow continental fragment or terrane outboard of a narrow sea (Wilson, 1966; Lonsdale, 1989; Umhoefer and Dorsey, 1997). Among rifts and passive margins worldwide, one of the distinguishing traits of the Gulf of California is how rapidly it evolved to active sea-floor spreading and formation of oceanic crust. In the past decade, new research has started to quantify the style and the timing of that rupture process (e.g., Lizarralde et al., 2007). In the southern Gulf of California, sea-floor spreading commenced ~6–10 m.y. after the formation of the oblique-divergent plate boundary at 12–12.5 Ma (Lonsdale, 1989; Stock and Hodges, 1989; Stock and Lee, 1994). This contrasts greatly to rifts in the interior of continents that develop into large oceans and have a typical duration of 30–80 m.y. and longer.

This paper summarizes recent advances in understanding when and where the southern Gulf of California plate boundary developed to the stage of sea-floor spreading and explores possible reasons for this rapid rupture of the continental lithosphere. This example of continental rupture and formation of a terrane (the Baja California microplate; Fig. 1) shows the critical role of the history of the inherited lithosphere upon which a rift develops, rapid plate divergence, and strike-slip faulting in the rapid rupture of continents. This paper also highlights the stark difference between rifting of continent interiors versus

rifting of tectonically active continental margins. The formation of the Baja California microplate also demonstrates how rapidly terranes or microplates can form and translate long distances along their mother continent; in 20–25 m.y., Baja California will likely have translated 1000 km.

TECTONIC SETTING AND RAPID RUPTURE OF SOUTHERN GULF OF CALIFORNIA

The Gulf of California and the Salton Trough form the oblique-divergent boundary between the Pacific and North America plates from 22° to 34°N latitude (Fig. 1). Most of the plate motion in the southern Gulf of California is accommodated in the gulf axis system by linked transform faults and short spreading centers (Lonsdale, 1989). Relative plate motion between the Baja California microplate and North America in the southern gulf is ~45–47 mm/yr (Plattner et al., 2007). An additional 4–6 mm/yr is accommodated on the offshore Tosco-Abreajos fault zone (borderland fault system) southwest of the Baja California peninsula (Fig. 1) (Dixon et al., 2000; Plattner et al., 2007). Regional transtensional faulting has rifted Baja California obliquely away from mainland Mexico over the past ~12.5 m.y. (e.g., Atwater and Stock, 1998). Pacific–North America plate motion became localized along the axis of the present-day plate boundary by at least 6 Ma (Oskin et al., 2001; Oskin and Stock, 2003a and 2003b), but the distribution of plate-boundary deformation between 12.5 and 6 Ma is uncertain and debated. In one model, Miocene plate motion was partitioned into strike-slip faulting in the borderland system and east-west extension in the Gulf of California (Spencer and Normark, 1979; Stock and Hodges, 1989); Pliocene to Recent faulting became more transtensional as the main oblique-divergent plate boundary moved into the Gulf of California. This

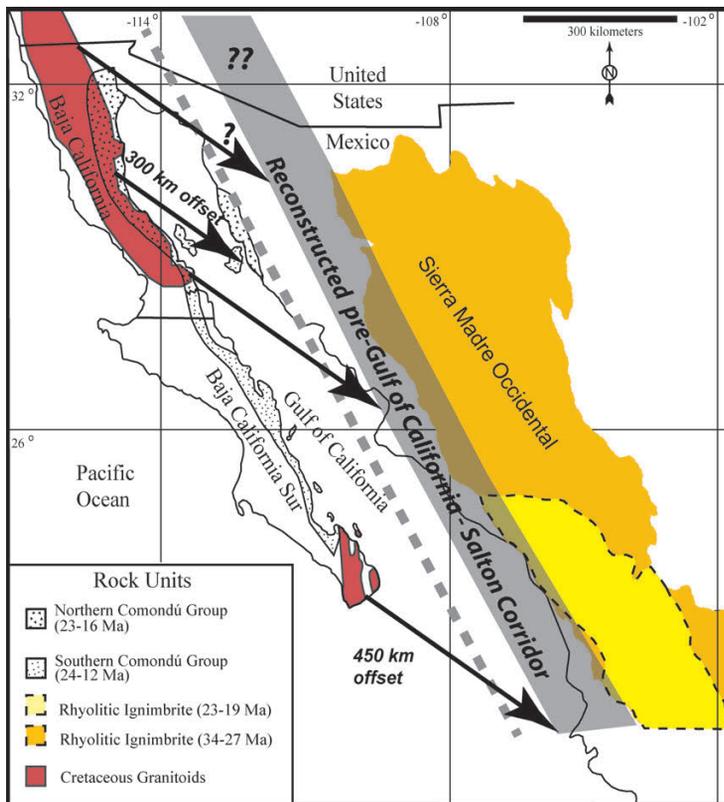


Figure 2. A simple cartoon of the narrow corridor (gray) between the Baja California peninsula and the Sierra Madre Occidental middle Cenozoic volcanic belt that results if there was a total of ~450 km offset across the Gulf of California since 12–14 Ma (Gans, 1997; Sutherland, 2006; Fletcher et al., 2007; Lizarralde et al., 2007). Note that with that 450 km of offset the lower to middle Miocene volcanic arc of the Comondú Group, and the early oblique-divergent plate boundary, formed along the reconstructed gray corridor. The dashed gray line is the width of the Gulf of California–Salton trough corridor if the total offset was the more modest 300 km as indicated by the shorter arrow across the northern Gulf (Stock and Hodges, 1989; Oskin and Stock, 2003b). Smaller granite exposures in mainland Mexico, on the islands in the Gulf, and in the gap between the northern and southern Baja California granites are not shown.

model results in ~300 km of northwesterly motion of the Baja California microplate relative to North America mainly since 6 Ma (Oskin et al., 2001). A second model proposes that Miocene dextral-oblique shear has separated the Baja California microplate from mainland Mexico since ca. 12.5 Ma, producing a total of ~450–500 km offset across the Gulf of California between the Baja California microplate and North America (= mainland Mexico) (Gans, 1997; Fletcher et al., 2007). This model results in the same ~300 km of northwesterly motion of the Baja California microplate relative to North America mainly since 6 Ma, but requires an additional northwest-directed offset of ~150–200 km before 6 Ma. These contradictory models remain unresolved, but evidence from a crustal scale seismic survey in the southern gulf favors the larger offset model for that region (Sutherland, 2006; Lizarralde et al., 2007).

The spreading centers in the southern gulf (Fig. 1) formed at variable times from ca. 6 Ma to ca. 2 Ma. The Guaymas spreading center in the central gulf formed ca. 6 Ma based on the width of the new igneous crust as determined from a seismic refraction profile from Lizarralde et al. (2007). In the mouth of the gulf, the northern East Pacific Rise has a more complex history in which part of that system formed a spreading center ca. 5.5 Ma (Lonsdale, 1989; Brown, 2007). The Alarcón spreading center began forming proto-oceanic crust ca. 3–3.5 Ma (DeMets, 1995), and true sea-floor spreading at present rates started at 2.4 Ma (Sutherland, 2006; Umhoefer et al., 2008). The East Pacific Rise and Alarcón Rise both have magnetic anomalies on the oceanic crust (Lonsdale, 1989; DeMets, 1995), while the Guaymas basin is a complex of sills and sediment cover that obscures simple magnetic anomalies (Lizarralde et al., 2007). The Pescador, Farallon, and Carmen(?) spreading centers may have formed ca. 2 Ma based on a proposed link to the

Loreto basin (Dorsey and Umhoefer, 2000; Mortimer et al., 2005) and the width of the bathymetrically low basin surrounding the spreading centers (Lonsdale, 1989). By comparing these ages of initiation of sea-floor spreading to the estimate of 12.5 Ma for commencement of the Pacific–North America oblique-divergent plate boundary in this region (Stock and Lee, 1994; Atwater and Stock, 1998), it is clear that the time from onset of rifting to complete rupture of continental lithosphere (referred to below as “time-to-rupture”) in the southern gulf was only ~6–10 m.y.

DURATION OF TYPICAL RIFT STAGES FOR LARGE OCEANS

The time-to-rupture for the Gulf of California was much more rapid than rupture of continent interiors to form large oceans. Rifts in the interior of continents that evolve to form oceans typically last for 30 to 80 m.y. before complete rupture of the continent and onset of sea-floor spreading, and some rift stages last much longer (Ziegler and Cloetingh, 2004). For example, the Newark rift basin in the eastern United States records >30 m.y. of sedimentation that began rifting before ca. 230 Ma (Olsen et al. 1996, 2004) and has the Central Atlantic Magmatic Province basalts dated at 201 Ma (Schoene et al., 2010) in its upper parts. The oldest documented true oceanic crust and sea-floor spreading in the east-central Atlantic is ca. 185 Ma (Withjack et al., 1998; Bird et al., 2007), while there was a proto-Atlantic stage from 200–185 Ma, during which sea-floor spreading may have initiated (Schettino and Turco, 2011). Therefore, the rift stage in the central Atlantic lasted ~35–45 m.y. The southern Atlantic had a rift stage that lasted for ~30 m.y. Rifting in the southernmost ocean north of the Falkland plateau and Scotia Sea started ca. 155 Ma (Jokat et al., 2003), whereas

sea-floor spreading started ca. 125 Ma (Müller et al., 1997). The rifting stage between Africa and Antarctica lasted at least 30 m.y. before breakup (Jokat et al., 2003). Likewise, the Australian margins have rift stages that lasted 30–40 m.y. (Brown et al., 2003). Rifting in the southern Red Sea occurred over 20–25 m.y.; extension in Yemen and Ethiopia started ca. 28–26 Ma (Menzies et al., 1997; Garfunkel and Beyth, 2006), and the oldest ocean crust is 4–6 Ma (Cochrane, 1983). The eastern Gulf of Aden had a shorter rifting stage of 17 m.y.; rifting started at 35 Ma, and initial sea-floor spreading occurred at 18 Ma (d'Acromont et al., 2006).

WHY DID THE SOUTHERN GULF OF CALIFORNIA RUPTURE RAPIDLY?

The factors that affect rift localization and the subsequent rupture of continental lithosphere include the thermal structure, crustal thickness, and strength of the lithosphere (e.g., Buck, 2007), as well as forces near the asthenosphere-lithosphere boundary and far-field plate interactions (Ziegler and Cloetingh, 2004). These factors have been investigated largely from numerical and analog modeling. Here I will explore the main factors that may have created rapid rupture in the Gulf of California, and in the following section, I will discuss a paradox of this history compared to recent modeling results.

It is clear that the southern Gulf of California developed from initial rifting to sea-floor spreading much more rapidly than typical continental rifts. There appear to be three major factors that caused this rapid time-to-rupture: (1) the presence of a narrow zone of hot, weak crust between belts of strong crust because of the long history as an active tectonic margin; (2) moderately rapid relative plate motion; and (3) obliquity of plate motion with a major role of strike-slip faulting.

The first factor that favors rapid rupture is the inherited crustal structure when oblique divergence commenced. An older arc with presumed hot, weak crust formed between two strong, older batholith belts. When Baja California is reconstructed in a simple fashion 450 km back to the southeast (the large-offset model), there remains a long, narrow belt (1800 × 150 km) that was occupied by the pre-gulf volcanic arc from ca. 20–12 Ma (gray belt, Fig. 2) (Hausback, 1984; Sawlan, 1991; Ferrari et al., 2007). The eastern part of this belt west of the Sierra Madre Occidental underwent widespread extension during this time before the oblique-divergent plate boundary formed in the future Gulf of California (Henry, 1989; Gans, 1997; Ferrari et al., 2007) and arguably thinned the crust. Arc volcanism was active in the southern gulf until immediately before the change to oblique divergence at 12.5 Ma (Umhoefer et al., 2001). The volcanic arc and extension formed between two provinces underlain by strong batholithic crust. In the west, a Cretaceous batholith occupies the length of the Baja California peninsula (Fig. 2; small exposures are discontinuous between the large northern and southern belts). In the east, the Sierra Madre Occidental is a vast 34–27 Ma rhyolitic caldera province with an axial zone that has a thick crust of 55 km and is likely underlain by a silicic batholith and mafic lower crust (Ferrari et al., 2007). These initial conditions of a thermally weak arc crust of normal thickness would greatly promote rifting, but the weak crust may also delay localization and rupture (after Buck, 2007). Intuitively, the two relatively strong batholith belts on either side

of the narrow arc would work against the rift widening past the batholith margins, and indeed the present boundaries of the gulf extensional province lie along the edges of the batholiths (Figs. 1 and 2). Therefore, I suggest it is the combination of the narrow, weak arc crust between the strong batholiths that was the first key factor in rapid rupture.

McCrory et al. (2009) suggested another factor that may have further thermally weakened the arc crust in the few million years before oblique convergence. They proposed that the slab window related to the capture of microplates west of southern Baja California during the volcanic arc (Stock and Lee, 1994) would have heated the region from the accretionary prism to the arc, further decreasing the strength of the crust within the arc.

The second cause of rapid rupture is suggested to be the moderately rapid relative motion across this plate boundary. The Pacific and North America plates have moved 630 km since 12.5 Ma at a rate of 51 km/m.y. (Atwater and Stock, 1998; Plattner et al., 2007). The Late Cenozoic history of separation across the gulf itself is debated as summarized in the “Tectonic Setting” section. Using the model for 450 km offset across the southern gulf and a rate of 47 mm/yr since 6 Ma (present rate between the southernmost Baja California microplate and North America [Plattner et al., 2007] extrapolated back to 6 Ma [Oskin et al., 2001]) gives 282 km of offset since 6 Ma. That yields a remainder of 170 km of offset from 12.5 to 6 Ma at a rate of 26 mm/yr of plate motion across the gulf. Much is uncertain in these estimates of plate motion for the early gulf, but most viable options result in moderately fast rates of relative plate motion, and a substantial increase in across-gulf offset rates at ca. 6 Ma. These rates of plate motion compare to rates of 3 to 6 mm/yr across the East Africa Rift system (Stamps et al., 2008). The key second conclusion is that these rates of motion across the Gulf of California are much higher than those across most active rifts and may have promoted efficient magma generation and strain localization in the axial region of the plate boundary.

The third cause of rapid rupture is suggested to be the obliquity of motion across the plate boundary. Highly oblique divergence can be defined in terms of the rift angle, or the angle between the azimuth of the axis of the plate boundary and the azimuth of the relative plate motion. The southern gulf has a rift angle of ~20°, which results in a transtensional deformation style and means that strike-slip faulting played a major role in divergence before the modern plate boundary formed with its long transform faults and short spreading centers (e.g., Lonsdale, 1989; Umhoefer et al., 2007). The large-offset (450–500 km) and long-lived transtensional model suggests that strike-slip and transtensional faulting were dominant for the whole history of the gulf. The smaller-offset (300 km) model suggests that there was little or no strike-slip faulting from 12.5 to 6 Ma and then an abrupt change to dominantly strike-slip faulting at 6 to 0 Ma.

In the large-offset model, the likely pre-seafloor spreading fault patterns were dominated by en-echelon strike-slip faults that were linked to transtensional systems of normal and strike-slip faults at the gulf margin (Dorsey and Umhoefer, 2000; Umhoefer et al., 2007). Along the gulf axis, the en-echelon strike-slip faults likely produced large pull-apart

basins (Lonsdale, 1989). These fault and basin patterns are locally known along the margin; the patterns are hypothetical in the gulf axis, but modern bathymetry supports rhomboid shaped basins (Figs. 1 and 2), and limited seismic lines support rift and transtensional basins (Sutherland, 2006). The key point for the causes of rapid rupture of lithosphere is that pull-apart basins are the most efficient basin type at localizing rapid thinning of the crust and the most rapidly subsiding basins (Christie-Blick and Biddle, 1985; Pitman and Andrews, 1985; Allen and Allen, 2005; Xie and Heller, 2009).

DISCUSSION AND CONCLUSIONS

Gulf of California as an End-Member Example

The oblique-divergent plate boundary in the southern Gulf of California localized ~90% of plate motion to develop sea-floor spreading by 6–2.4 Ma. This produced an unusually rapid rupture of continental lithosphere that took only 6–10 m.y. Evidence summarized in this paper suggests that three main factors caused this rapid rupture: (1) an inherited long, narrow belt of hot, weak crust from a volcanic arc that was active immediately before formation of the oblique-divergent plate boundary and formed between two strong batholith belts (Fig. 2); (2) relatively rapid plate motion resulting in high strain rates; and (3) a dominant role of strike-slip faulting with highly oblique divergence that likely formed large pull-apart basins with rapid crustal thinning in a linked en-echelon system.

These causes of rapid rupture are mostly linked to the fact that the Gulf of California developed along the tectonically active margin of a continent that experienced multiple episodes of magmatism (and deformation) through much of Phanerozoic time. The precursor volcanic arc clearly demonstrates this case, and the two batholiths on either side of the Gulf of California are products of earlier Tertiary and Cretaceous convergent margin episodes. Moreover, relatively rapid plate motion as seen in this example is unlikely for a rift in a continental interior. This combination of causes and factors suggests that rifts that form at active margins are fundamentally different than continental interior rifts, and that these differences produce vastly different rifting histories. The difference in rifts in these two settings is not just in the setting itself, but in the series of processes that occur in each setting before and during rifting, and the rates of extension across the rift. I suggest that the Gulf of California represents the end member along an active margin where a previous arc existed with an extensional backarc and along which many features developed before the rift started that led to the key factors that favor a short time-to-rupture. The rifting of active margins in which the previous tectonics were a long-lived contractional orogen (Basin and Range or Aegean Sea) that produced thickened continental crust have many factors that work against rapid localization and rupturing of continental lithosphere, especially the initially thick crust across a wide zone.

Gulf of California and Modeling Results

One apparent paradox arises when comparing recent models for extension at the crustal scale and the Gulf of California. As one example, Huisman and Beaumont (2007) used finite-element modeling to explore the effects of the strength of the

crust and fate of extension on the symmetry and mode (narrow versus wide) of the rift. At high rifting velocities it was found that strong viscous coupling in the lower crust suppresses localization and produces a distributed, symmetric style of extension. In addition, weak lower crust appears to result in delayed rupture. These results appear to contradict the observations from the Gulf of California for rapid rupture. But it is important to note that modeling to date involves extension of uniform layers across a relatively wide region as the initial condition. The initial conditions in the Gulf of California were much different than these models. I would suggest that it was this narrow, weak arc lying between strong batholiths, together with the moderately rapid plate motion and strike-slip faulting, that was the critical combination of factors that led to the rapid lithosphere rupture in the Gulf of California.

Implications for Terrane Formation and Translation

The rapid rupture of the southern Gulf of California and formation of the Baja California microplate also has implications for terrane formation and translation. This young and modern example demonstrates that terranes composed of fragments of their former continent can form rapidly and translate long distances in relatively short geologic time spans. For the Baja California terrane, the large-offset model suggests it has moved 450–500 km northwest relative to stable North America in 12.5 m.y. Assuming that the Baja California terrane either continues to move at the present rate (47 km/m.y.) or Pacific–North America plate motion fully localizes in the Gulf of California (51 km/m.y.), the terrane will move a total of 1000 km in ~22–25 m.y. For the smaller-offset model with 300 km offset across the Gulf of California, the Baja California terrane will move 1000 km in ~27 m.y.

If this process of rapid rupture along highly oblique plate boundaries occurs along a plate boundary with rates of plate motion at the high end of current relative plate motions, one can reasonably suggest shorter times for terrane formation and translation of 1000 km. The modern Pacific basin has examples of Nazca–South American relative motion of ~70–75 km/m.y. and Pacific–Australia (north of Australia) highly oblique relative motion of 110–115 km/m.y. (DeMets et al., 2010). Given these rates, one could envision the formation and translation of a terrane like Baja California moving 1000 km in 10–15 m.y. For example, if a terrane formed in 5 m.y. at a rate of motion of about 80 km/m.y. (the same percentage of total relative motion that is localized in the Gulf of California since its inception), it would move 400 km. If the plate motion was then fully localized along the main plate boundary at 115 km/m.y., the terrane would move a total of 1000 km in ~10 m.y. This possibility of the formation and translation of terranes these large distances over relatively short time periods is a challenge for those studying ancient orogens because it demands understanding of the orogenic processes to a few-million-year resolution in order to detect large terrane translations.

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