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Late Miocene extension in coastal Sonora, México: Implications for the evolution of dextral shear in the proto-Gulf of California oblique rift

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ABSTRACT

The timing, kinematics, and processes responsible for the rapid transition from subduction to oblique rifting and the localization of the Pacific-North America plate boundary in the Gulf of California are not well understood. Well exposed volcanic rocks deposited between ~15 and 10 Ma in the Sierra Bacha (coastal Sonora, México) preserve a record of late Miocene deformation on the eastern rifted margin of the Gulf of California and offer new insights into the timing and kinematic evolution of oblique rifting. Detailed geologic mapping, fault kinematic analysis, U–Pb and 40Ar/39Ar geochronology, and paleomagnetic data reveal that the >2 km-thick composite volcanic section is cut by a series of southwest-dipping, domino-style normal faults and uniformly tilted down-to-the-northeast. Palinspastic cross-section restoration suggests that the region experienced ca. 55–60% northeast-southwest-directed extension between ~11.7 and ~10–9 Ma. Fault kinematic data reflect relatively minor dextral transtension either following or during the later stages of extension. Paleomagnetic results indicating modest clockwise vertical-axis block rotation suggest that dextral shear was concentrated in the southwest of the study area near the modern coastline.

These results support an emerging model in which dextral strain was not ubiquitous across Sonora and did not initiate immediately following the ~12.5 Ma transition from subduction to oblique rifting. Instead, strain east of the Baja California microplate at this latitude evolved from extension-dominated transtension prior to ~8 Ma to dextral shear-dominated transtension by ~7–6 Ma. The onset of dextral shear in coastal Sonora likely resulted from an increase in rift obliquity due to a change in relative plate motion direction at ~8 Ma. The increase in rift obliquity and resultant onset of significant strike-slip faulting played a crucial role in facilitating subsequent plate boundary localization and marine incursion in the northern Gulf of California by ~6 Ma and continental rupture at ~2–1 Ma.

1. Introduction

The transition from distributed extension to localized rifting (e.g., Buck, 1991) and onset of seafloor spreading is a critical step in the process of continental breakup. Modern rifts that preserve an exposed record of rift-related deformation offer valuable insights into the structural evolution of rifted margins and the processes that lead to continental rupture. The Gulf of California (Fig. 1) is a young proto-oceanic oblique rift basin that opened rapidly during late Cenozoic transtension along the Pacific-North America plate boundary (Umhoefer, 2011). This region offers a unique opportunity to explore the kinematics of lithospheric rupture and the structural evolution of a well-exposed obliquely rifted continental margin. While much of the geologic record in the Gulf of California region is accessible and well-studied (e.g., Hausback, 1984; Stock & Hodges, 1989; Lonsdale, 1989; Gans, 1997; Atwater & Stock, 1998; Oskin and Stock, 2003a,b; Fletcher et al., 2007; Lizarralde et al., 2007), the timing, kinematics and processes responsible for the rapid transition from subduction to rifting, continental rupture and seafloor spreading remain incompletely documented.

The Gulf Extensional Province (GEP) is a broad region of continental extension that extends from eastern Baja California to interior México (Fig. 1; Stock and Hodges, 1989) and is thought to be related to the Gulf of California rift. Major extension in the GEP initiated during latest middle Miocene time following the cessation of subduction west of Baja California, which ended at ca. 12.3 Ma west of southern Baja California and slightly earlier farther north (Spencer & Normark, 1979; Mammerickx & Klitgord, 1982; Stock & Hodges, 1989; Stock and Lee,

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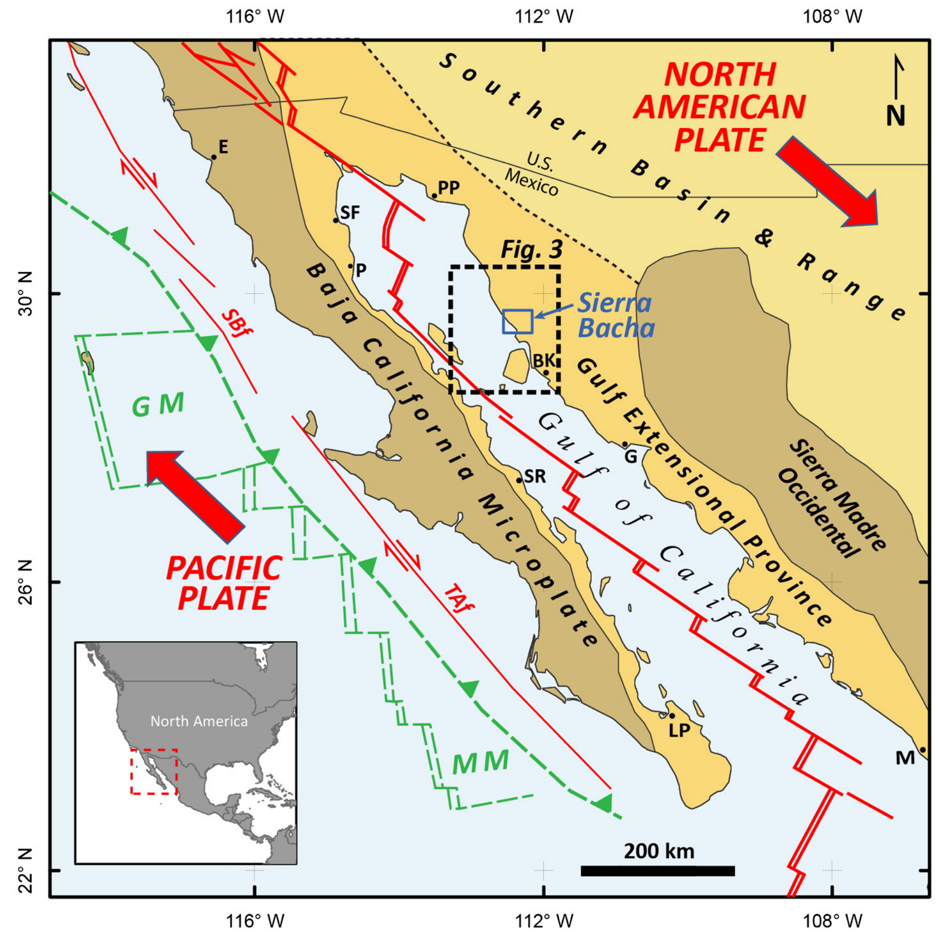

Fig. 1. Regional tectonic map of the Pacific-North America plate boundary in northwestern México and the southwestern United States. Green dashed lines represent inactive plate boundaries, including the former trench related to Farallon-North America subduction and stalled Pacific-Farallon spreading ridges and related microplates. Subduction of the Farallon plate and related microplates ended by ca. 12.5–12 Ma, leading to plate boundary reorganization from ca. 12.5 to 6 Ma. Solid red lines indicate the modern plate boundary, which accommodates modern oblique rifting and opening of the Gulf of California. Abbreviations: BK — Bahía Kino, E — Ensenada, G — Guaymas, GM — Guadalupe microplate; LP — La Paz, M — Mazatlan, MM — Magdalena microplate; P — Puertecitos, PP — Puerto Peñasco, SF — San Felipe, SR — Santa Rosalía, SBf — San Benito fault, TAf — Tosco-Abreojos fault. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1994; Atwater & Stock, 1998; Fletcher et al., 2007). Extension in the GEP was spatially and temporally isolated from late Oligocene to early Miocene extension in the Southern Basin and Range province (Henry, 1989; Nourse et al., 1994; Lee et al., 1996; Gans, 1997; Henry & Aranda-Gomez, 2000; González-León et al., 2010). Latest Miocene localization of plate boundary strain led to marine incursion into the northern Gulf of California at ca. 6.3 Ma and established the modern phase of oblique spreading (Oskin and Stock, 2003a, b; Bennett et al., 2015). The time period between ~12.5 and 6 Ma, and the region that eventually became the modern Gulf of California, are collectively referred to as the “proto-Gulf of California” (e.g., Karig & Jensky, 1972; Stock & Hodges, 1989). Contrasting kinematic models have been proposed for the timing, style and distribution of proto-Gulf deformation in northwestern México (e.g., Stock and Hodges, 1989; Fletcher et al., 2007), but they do not directly address the structural processes responsible for plate boundary strain localization, which is required for successful rupture of continental lithosphere.

Field studies (e.g., Umhoefer and Stone, 1996; Aragón-Arreola et al., 2005; Bennett et al., 2013a) and experimental modeling (Withjack and Jamison, 1986; Tron and Brun, 1991; Agostini et al., 2009; Brune, 2014; Heine and Brune, 2014) show that strike-slip faults are more effective at localizing strain in the upper crust than normal faults because isostatic buoyancy forces related to tectonic unloading are not generated by lateral displacement on steep to vertical strike-slip faults (e.g., Wernicke and Axen, 1988; Buck, 1991; Zoback, 1991; Buck et al. 1999). Thus the strike-slip component of transtension is mechanically favored to localize strain in highly oblique rift settings such as the Gulf of California. A valid test of this hypothesis for the Gulf of California requires detailed knowledge of the kinematics, distribution, timing and rates of deformation immediately preceding plate boundary localization. Evidence of late Miocene dextral shear along the margins of the proto-Gulf of California (Gans, 1997; Seiler et al., 2010; Herman, 2013; Bennett et al., 2013a; Bennett et al., this volume) highlights the need for data from proto-Gulf age structures to assess the role that strike-slip faults may have played in continental breakup and formation of the Gulf of California.

This paper presents the results of new geologic mapping, fault kinematic analysis, geochronology, and paleomagnetic analysis of middle to late Miocene rocks in the Sierra Bacha[2] of coastal Sonora, México, along the eastern rifted margin of the northern Gulf of California (Fig. 1). The study area is strategically located immediately northeast of the Coastal Sonora fault zone, a major NW-striking dextral fault zone that experienced transtensional faulting and block rotations between ~8–7 and 6–5 Ma (Bennett et al., 2013a). Well exposed, proto-Gulf age (ca. 12.5–6 Ma) and older volcanic and sedimentary rocks in the Sierra Bacha allow us to investigate the transition from subduction to oblique rifting in northwestern México. We characterize the timing,

[2] On most topographic maps of this region, the name “Sierra Bacha” refers only to the coastal range in the northwestern study area, and in some cases the name “Sierra Tordilla” is used interchangeably. For the purpose of this study, all references to the “Sierra Bacha” herein refer to the coastal range and adjacent inland areas to the east and southeast.

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