Chapter 10

Influence of sediment input and plate-motion obliquity on basin development along an active oblique-divergent plate boundary: Gulf of California and Salton Trough

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ABSTRACT

Transtensional basins have formed along the Pacific-North America plate boundary in the Gulf of California and Salton Trough region during Late Cenozoic time. Axial basins occupy a 50–60 km wide belt along the main plate boundary, and change from sediment-starved oceanic spreading centers in the south that are oriented perpendicular to long NW-striking transform faults, to oblique N-trending pull-apart (stepover) basins in the north that contain thick sediments and lack evidence for normal oceanic crust. Marginal basins are found along the flanks of the Gulf-Trough corridor and consist mainly of supradetachment basins (only in the north), transtensional fault-termination basins, and classic orthogonal rift basins.

A review of previous studies suggests that three main parameters govern the structural style, composition, and total thickness of sedimentary basins in this setting: (1) the rift angle (α), defined as the acute angle between the overall trend of the plate boundary and the direction of relative plate motion; (2) proximity to voluminous input of sediment from the Colorado River and other smaller drainages in the north; and (3) the degree of strain partitioning. Detachment faults and supradetachment basins are well documented in the northern Gulf and Salton Trough where $\alpha \geq 30^\circ$, whereas no detachment faults are recognized in the central and southern Gulf of California ($\alpha < 20^\circ$). We suggest that faster extension associated with a higher rift angle is the main factor responsible for creation of supradetachment basins in the northern region.

Voluminous input of sediment derived primarily from the Colorado River exerts a first-order control on crustal thickness and composition, lithospheric mechanics, and rift architecture. In the sediment-starved southern Gulf of California, the plate boundary has completed the transition from continental rifts to seafloor spreading centers with normal ocean crust and magnetic lineations. The Guaymas spreading center in the central Gulf has young oceanic crust with an upper layer of sediments and shallow intrusions. In contrast, sediment-filled and overfilled basins in the north are characterized by thick new transitional crust that is formed by input and magmatic modification of sediment, which fills the new space created by lithospheric rupture and oblique divergence. Thus the rate of sediment input appears to determine whether or not continental rifting progresses to the ultimate formation of a new ocean basin floored by normal basaltic crust.

Keywords: Gulf of California; oblique-divergent plate boundary; rift architecture; transtensional basins; Colorado River

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INTRODUCTION

The Gulf of California and Salton Trough region (Fig. 10.1) provides an excellent setting within which to study processes of basin development along an oblique-divergent plate boundary. In this region the plate boundary is actively deforming at a high rate (51 mm/yr; Plattner et al., 2007), onshore basins are well exposed and accessible, and offshore basins are broadly characterized by recent marine geophysical studies (though detailed study of offshore basins is largely still lacking). The tectonic lowland that occupies this plate boundary, referred to here as the "Gulf-Trough corridor," contains a series of Late Cenozoic transtensional basins that have formed in response to oblique dextral motion between the Pacific and North America plates (Fig. 10.1). During the past 8–12 My, the crust has deformed in a range of different extensional and transtensional structural styles that control basin geometry, subsidence rates, and filling patterns. Voluminous input of sediment from the Colorado River in the north, and lesser input from smaller drainages east of the central Gulf-Trough corridor, also exerts a first-order control on basin evolution and crustal composition, thickness, and rheology. In this chapter we summarize some salient aspects of

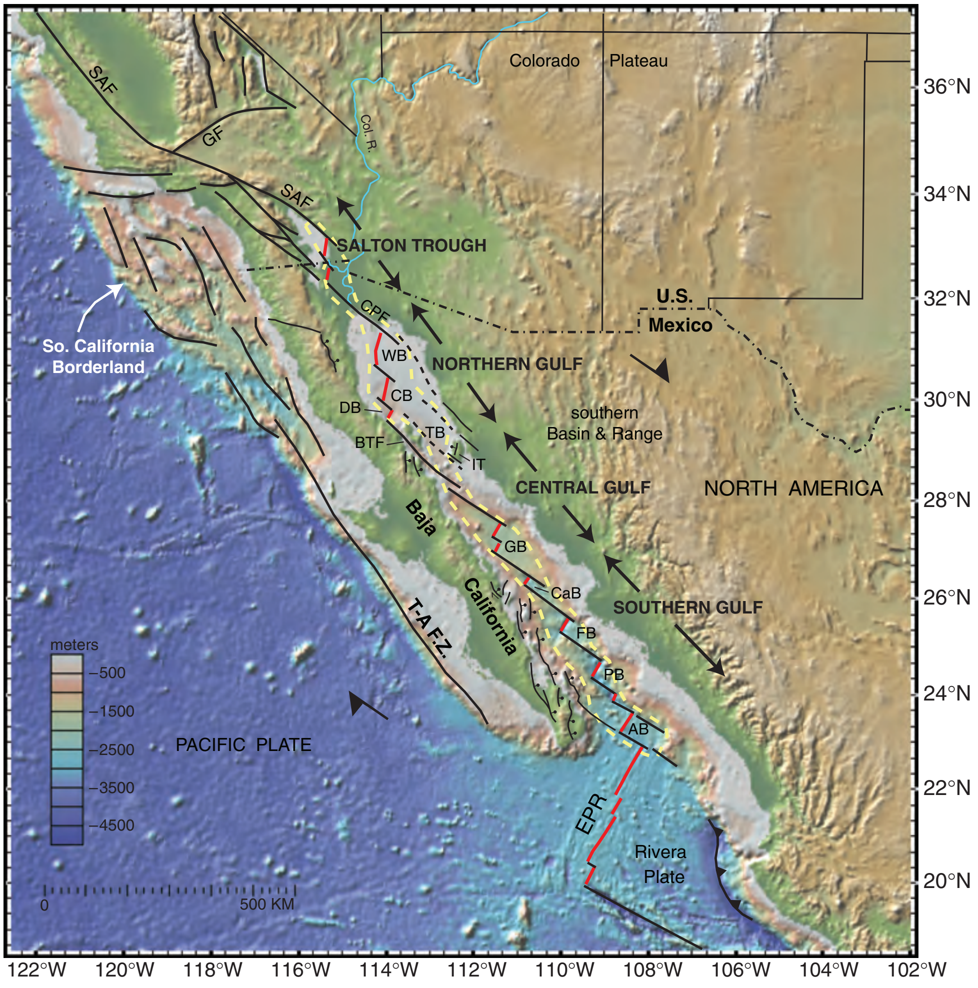

Fig. 10.1. Map of topography, bathymetry, and faults in the Gulf of California and Salton Trough region. Transtensional basins in the Gulf-Trough corridor are formed in response to oblique-divergent motion along the Pacific–North America plate boundary. The systematic decrease in water depth from south to north along the plate boundary is due primarily to voluminous input of sediment from the Colorado River in the north. Dashed yellow line shows approximate location of axial basins. Abbreviations: AB, Alarcón basin; BTF, Ballena transform fault; CaB, Carmen basin; CB, Consag basin; CPF, Cerro Prieto fault; DB, Delfin basin; EPR, East Pacific Rise FB, Farallon basin; GB, Guaymas basin; GF, Garlock fault; IT, Isla Tiburón; PB, Pescadero basin; SAF, San Andreas fault; T.A.F.Z., Tosco-Abreojos fault zone; TB, Tiburón basin; WB, Wagner basin.

sedimentary basins along the Gulf-Trough corridor, and explore how variations in sediment input and structural style affect the size, geometry, behavior, and development of these basins.

This survey suggests that two main parameters control the behavior and evolution of basins along the Gulf-Trough corridor: (1) the acute angle (α) between the overall trend of the plate boundary and the direction of relative plate motion; and (2) input of sediment from the Colorado River and other drainages in the north. Assuming an average relative plate motion of ~310°, a small change in the rift trend causes the rift angle to increase from ~17–18° in the southern and central Gulf to ~33–35° north of 30° N latitude (Fig. 10.1). Systematic variations in these two parameters – rift angle and sediment supply – exert first-order controls on structural style, basin geometry, crustal thickness, and the degree to which the plate boundary and its basins have completed the transition from continental rifts to seafloor spreading centers with normal ocean crust.

A secondary but important aspect of structural style that influences basin development is the extent to which deformation along the margins of the plate boundary is strain-partitioned. For this chapter, we define strain partitioning as a kinematic style in which oblique strain is partitioned (segregated) into strike-slip offset on NW-striking transform faults and dip-slip offset on north- to NW-striking normal faults. Non-partitioned strain is defined as integrated transtensional deformation accommodated by slip on a network of linked dextral, normal, and sinistral faults and variably oriented oblique-slip faults.

BASIN TERMINOLOGY

Several types of strike-slip and extensional sedimentary basins are present in the Gulf of California and Salton Trough region. Sketches in Figure 10.2 illustrate the geometries and terminology that we use to describe basin types in this chapter. Ocean spreading centers form by divergence, subsidence, and creation of new basaltic crust at releasing stepovers between active transform faults. Pull-apart basins, also known as rhombochasms or stepover basins (Nilsen and Sylvester, 1995), form in areas of dilation and extension as a result of slip through a releasing stepover on a master strike-slip fault system (e.g., Burchfiel and Stewart, 1966). Fault-termination basins form in areas of complex transtensional deformation and dilation where slip on a master strike-slip fault decreases toward its termination on branching faults (Umhoefer et al., 2007). Although simplified cross sections resemble those of half-graben rift basins (Fig. 10.2), fault-termination basins are characterized by their complex map pattern, multiple sediment sources, short total lifetime (~2–3 My), Gilbert-type fan deltas, buttress unconformities, rapid lateral and vertical facies changes, and complex fault control on basin subsidence (Umhoefer et al., 2007). Half-graben (orthogonal) rift basins are defined as basins that form by extension on dip-slip normal faults, with tilt dominantly in one direction toward a master basin-bounding high-angle normal fault (e.g., Leeder and Gawthorpe, 1987). Supradetachment basins also result from orthogonal extension with tilt dominantly in one direction, but the basin-bounding fault is a low-angle normal fault, or detachment fault (Friedmann and Burbank, 1995).

TECTONIC SETTING AND STRUCTURAL OVERVIEW

The Gulf of California and Salton Trough occupy the oblique-divergent boundary between the Pacific and North American plates (Fig. 10.1). Most of the plate motion at this latitude is accommodated in the Gulf-Trough corridor by transform faults and linked short spreading centers that carry a slip rate of ~43–47 mm/yr (Plattner et al., 2007). An additional 4–6 mm/yr is accommodated on the offshore Tosco-Abreojos fault zone located southwest of the Baja California peninsula (Plattner et al., 2007) (Fig. 10.1), which links north to a complex network of faults in the southern California continental borderland (Nicholson et al., 1994; Dixon et al., 2000). Regional transtension has rifted Baja California obliquely away from mainland Mexico over the past ~12.5 million years (e.g., Atwater and Stock, 1998; Oskin and Stock, 2003a). Recent seismic reflection and refraction studies provide new insights into rift architecture, crustal thickness and composition, and structural controls on basin formation in the Gulf of California (e.g., Aragón-Arreola et al., 2005; González et al., 2005; Aragón-Arreola and Martín-Barajas, 2007; Lizarralde et al., 2007). Complementary onshore studies document more precisely the timing of basin formation and stratigraphic

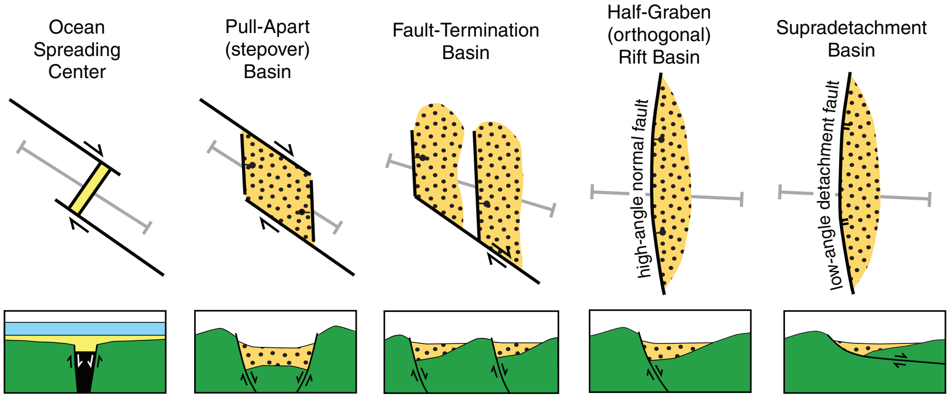

Fig. 10.2. Sketches illustrating main basin types found in the Gulf of California and Salton Trough region, and terminology used in this chapter.

response to crustal deformation (e.g., Umhoefer et al., 1994, 2007; Axen and Fletcher, 1998; Dorsey and Umhoefer, 2000; Dorsey et al., 2007).

It is widely agreed that Pacific-North America plate motion became localized along the axis of the present-day Gulf-Trough corridor at ca. 6 Myr (Oskin et al., 2001), but the distribution and kinematics of plate-boundary deformation between 12.5 and 6 Myr are uncertain and debated. According to one model, late Miocene plate motion was partitioned into strike-slip offset on the Tosco-Abreojos fault zone southwest of Baja California and east-west to WSW-ENE extension in what is now the Gulf of California and surrounding areas (Spencer and Normark, 1979; Stock and Hodges, 1989). This model involves ca. 300 km of northwest motion between the Baja California peninsula and mainland Mexico. A second model proposes that deformation since ∼12.5 Myr has occurred in a single phase of regionally integrated dextral-oblique shear across a wide belt from the southwest side of the Baja California peninsula to mainland Mexico, and involves ca. 450–500 km of offset across the Gulf of California (Gans, 1997; Fletcher et al., 2007). These contradictory models remain unresolved but do not significantly affect the features and processes discussed below.

Sedimentary basins in the Gulf-Trough corridor can be divided into two main types: axial basins and marginal basins. Axial basins occupy a 50–60 km wide belt along the main plate-boundary faults (Fig. 10.1), and show a systematic decrease in water depth and increase in the thickness of basin fill from south to north. Axial basins in the southern Gulf consist of short, sediment-starved oceanic spreading centers in deep water (2000–3000 m) that trend northeast, perpendicular to long transform faults. In the central Gulf, the Guaymas basin lies in up to ∼1600 m water depth and has moderate sedimentation. In the northern Gulf and Salton Trough, axial basins are situated in shallow marine (<500 m) and nonmarine settings. They define oblique pull-apart geometries, or rhombochasms, in which NW-striking transform faults are linked by N- to NNE-trending normal faults and stepover basins that contain thick sediments and lack evidence for seafloor spreading or normal oceanic crust at depth.

Marginal basins are located outside the zone of the axial basins and occupy the flanks of the Gulf of California and Salton Trough (Fig. 10.1). Some marginal basins occupy relatively shallow water and structural levels, some are exposed onland as a result of structural reorganizations that terminated deposition, and some onland basins are still actively subsiding. We recognize three main structural styles in the marginal basins: (1) transtensional fault-termination basins, which form along or near the tips of strike-slip faults (e.g., Umhoefer et al., 2007); (2) orthogonal rift basins, which form in the hanging wall of high-angle normal faults; and (3) supradetachment basins, which form in the upper plate of low-angle normal faults (e.g., Friedmann and Burbank, 1995) (Fig. 10.2). Supradetachment basins are found only along the margins of the northern Gulf and Salton Trough where the rift angle is ∼33–35°, and they are absent in the central and southern Gulf (rift angle 17–18°).

Basins associated with northwest-striking dip-slip normal faults (high or low angle) record strain partitioning in which the extensional component of relative plate motion is accommodated by NE-directed extension, roughly perpendicular to the plate boundary. Examples of this style include the Yaqui Basin in the central Gulf (Aragón-Arreola et al., 2005; Fig. 10.4), the Cañada David detachment fault and its hanging-wall basin in the Salton Trough (Axen et al., 2000; Fig. 10.5), and the San Pedro Martír fault and flanking basin in northern Baja California (Stock and Hodges, 1989; Fig. 10.5). In contrast, fault-termination basins form in areas of non-partitioned strain where regional transtension is accommodated by integrated oblique-slip faults and complex overlapping fault networks.

SUMMARY OF BASINS

Southern Gulf of California

The Alarcón, Pescador, and Farallon axial basins in the southern Gulf of California (Fig. 10.3) are interpreted to be centers of sea floor spreading, although only the Alarcón rise has been studied with modern seismic data (Sutherland, 2006; Lizarralde et al., 2007). The axial basins are relatively short (10–45 km) spreading centers connected by long (~60–140 km) transform faults (Fig. 10.3). The axis of the Alarcón basin center is a true spreading ridge and is ~2.5 km deep at the spreading center; other basins are ~5–8 km wide

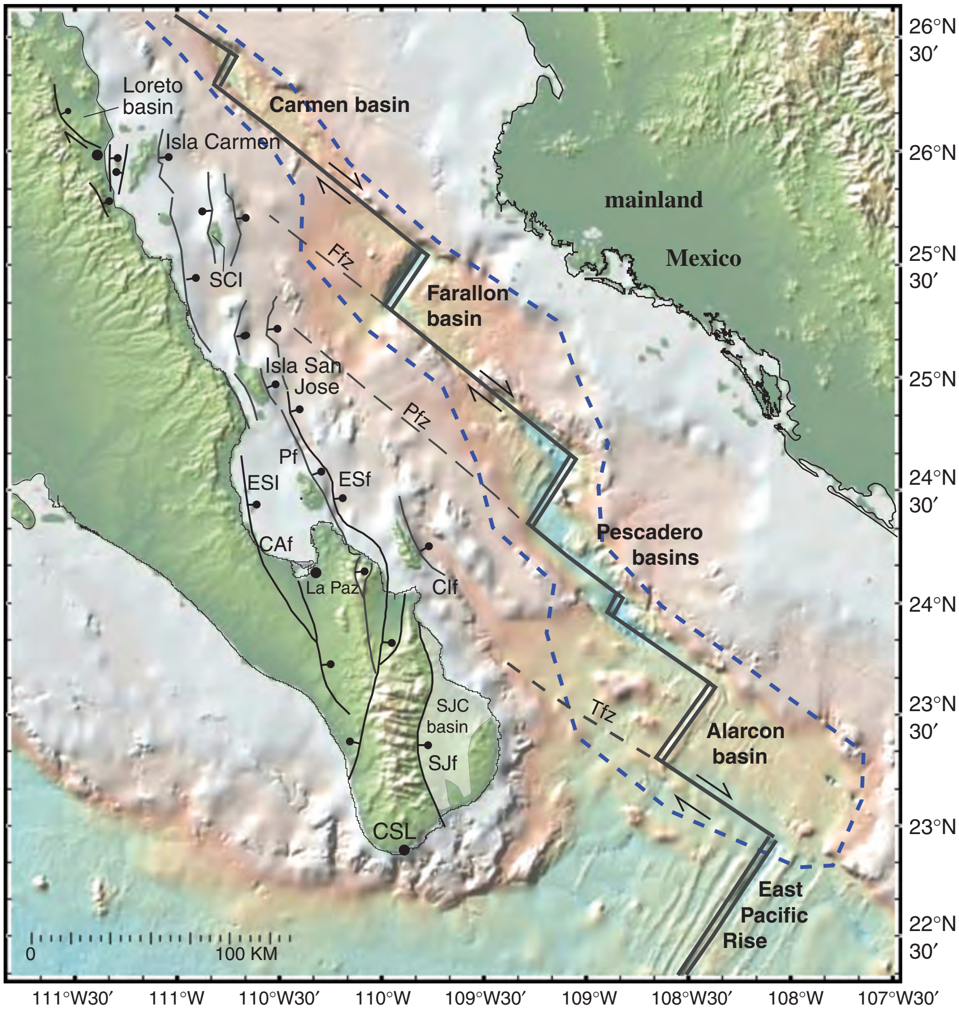

Fig. 10.3. Map of faults and basins in the southern Gulf of California region. Axial basins are short sediment-starved oceanic spreading centers oriented northeast, perpendicular to long NW-striking transform faults. Dashed blue line shows approximate boundary between axial and marginal basins. Abbreviations: CAf, Carrizal fault; CIf, Cerralvo Island fault; CSL, Cabo San Lucas; ESI, Espiritu Island; Ffz, Farallon fracture zone; Pf, Partida fault; Pfz, Pescadero fracture zone; SCI, Santa Catalina Island; SJC basin, San Jose del Cabo basin; SJf, San Jose fault; Tfz, Tamayo fracture zone.

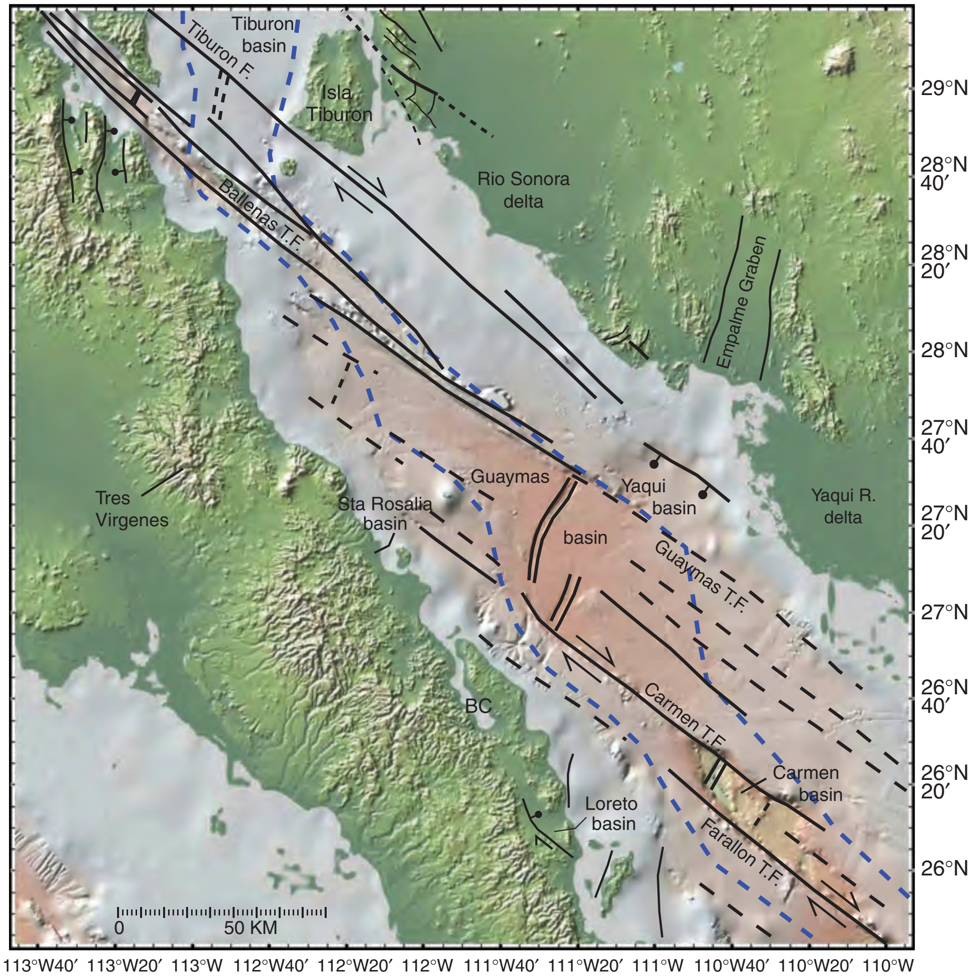

Fig. 10.4. Map of faults and basins in the central Gulf of California region. The main axial basin in this realm is the Guaymas basin, a moderately sedimented marine basin with a NE-trending oceanic spreading central bounded by long NW-trending transform faults. Dashed blue line shows approximate boundary between axial and marginal basins. BC, Bahía Concepcion.

troughs that attain depths of up to 3.0–3.5 km below sea level. The Alarcón rise contains about 6 km of oceanic crust that consists of ∼5 km of lower crust and 1 km of upper crust including a thin sedimentary layer (Sutherland, 2006; Lizarralde et al., 2007). Analysis of magnetic anomalies, crustal structure from a velocity model, tomography, and multichannel seismic (MCS) data suggest an early stage of asymmetric spreading from 3.0 to 2.4 Myr that failed to localize. At 2.4 Myr a small ridge jump led to initiation of symmetric seafloor spreading that continues today at the modern rate of 46–47 mm/yr (Sutherland, 2006; Plattner et al., 2007).

The Alarcón rift segment includes the axial Alarcón basin and flanking conjugate margins and is bounded by the Pescadero and Tamayo fracture zones (Fig. 10.3). This rift segment experienced about 350 km of continental extension (calculated for a cross section oriented parallel to the present-day relative plate motion), and thus is defined as a wide rift (Lizarralde et al., 2007). A series of semi-starved basins with sediments 500 to 1500 m thick are found along the Alarcón rift segment. Most of these basins are simple half grabens, though at least two basins are more complex and may be transtensional basins (Sutherland, 2006). MCS data reveal ∼500–700 m to much thinner sequences of syn-rift strata overlain by thicker post-rift sequences (Sutherland, 2006; Brown, 2007). The basins and related faults indicate that faulting ended a few million years ago outside the axial basin system in the southern Gulf of California, except for a few slowly active basins in the Los Cabos to La Paz region as discussed below. Recognition of several nearly north trending faults and rift basins that rest on thin continental crust (~7 km) suggests that early axial basins may have been pull-apart basins linked to northwest striking strike-slip faults (Lonsdale, 1989; Sutherland, 2006; Brown, 2007).

A group of orthogonal rift basins along the southwest margin of the southern Gulf, from the San Jose del Cabo basin to the La Paz area, are present in the hanging walls of slowly active normal faults (Fig. 10.3). Most of these basins are still active and have late Quaternary deposits at the surface, revealing little of their older history. The San Jose del Cabo basin (SJC; Fig. 10.3) exposes Middle Miocene to Quaternary deposits and is a complex half graben that changed from terrestrial to marine at ~8 Myr (Carreño, 1992; McTeague, 2006) and

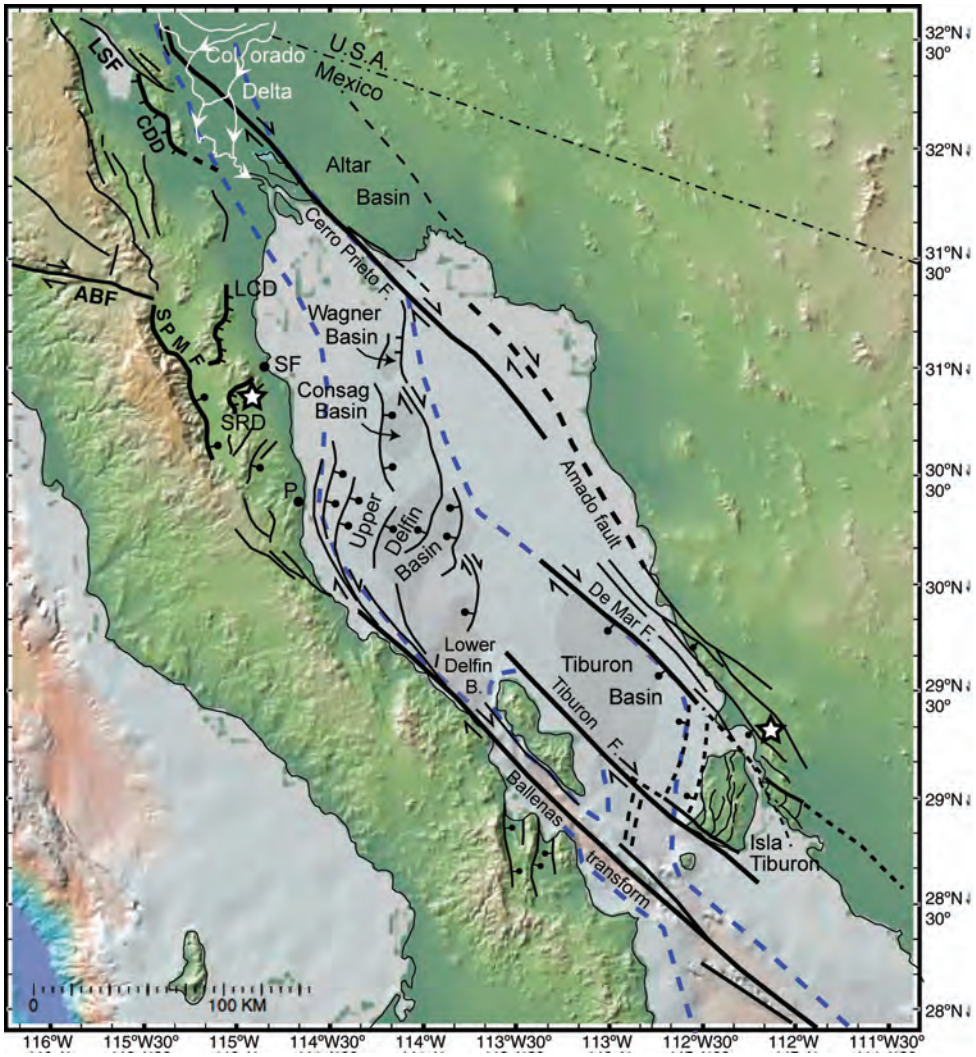

Fig. 10.5. Map of major faults and basins in the northern Gulf of California, redrafted from Aragón-Arreola and Martín-Barajas (2007), Persaud et al. (2003), and Oskin and Stock (2003b, 2003c). The northern Gulf contains several N- to NNE-trending oblique pull-apart basins bounded by transform faults. Active diffuse deformation in the Delfin basin occurs on closely spaced oblique-slip faults, and there is no evidence for existence of oceanic crust at depth (Persaud et al., 2003). Much of the crust is sedimentary due to the high rate of input from the Colorado River. Abbreviations: ABF, Agua Blanca fault; CDD, Canada David detachment; LCD, Las Cuevitas detachment fault; P, Puertecitos; SF, San Felipe; SPMF, San Pedro Martir fault; SRD, Santa Rosa detachment fault. White stars indicate exposures of pre-Miocene fluvial conglomerate with distinctive fusilinid-bearing limestone clasts that provides evidence for ~300 km of dextral offset between NE Baja California and mainland Mexico due to opening of the northern Gulf of California since about 6.5 Myr (Gastil et al., 1973; Oskin and Stock, 2003b). Dashed blue line shows approximate boundary between axial and marginal basins.

back to terrestrial sedimentation (Martinez-Guitierrez and Sethi, 1997; McTeague, 2006). Syn-rift normal faulting and sedimentation have been documented on the east side of the basin (McTeague, 2006).

Transtensional fault-termination basins along the western margin of the central and southern Gulf are characterized by multiple sediment sources, short total lifetime (~2–3 My), Gilbert-type fan deltas, buttress unconformities, stratigraphically complex fault blocks, rapid lateral and vertical facies changes, and complex local fault control on basin subsidence (Umhoefer et al., 2007). On San Jose Island (Fig. 10.3), the ~1 km-thick section reveals stratigraphic patterns intermediate between those of orthogonal rift and pull-apart basins, and records a complex history of sedimentation along linked normal and oblique-slip faults (e.g., Fig. 10.2). Farther north, the Pliocene Loreto basin formed a west-tilted asymmetric wedge in response to westward tilting on the oblique dextral-normal Loreto fault (Fig. 10.3; Umhoefer et al., 1994; Dorsey and Umhoefer, 2000). Most of the basin filling took place during a short episode of rapid fault slip, subsidence, and accumulation of marine Gilbert-type fan deltas between ~2.46 and 2.36 Myr (Umhoefer et al., 1994; Dorsey and Umhoefer, 2000; Mortimer et al., 2005).

The contrast in basin style between the La Paz to San Jose del Cabo area (classic half-graben rift basins) and the San Jose Island to Loreto area (transtensional fault-termination basins) can be explained by a difference in degree of strain partitioning between the marginal basins and the main plate boundary faults. In the highly partitioned La Paz to Cabo domain, the basin style and paleoseismology (Busch et al., 2011; Maloney et al., 2007) and recent earthquakes (Fletcher and Munguía, 2000) all suggest dominantly E-W to NE-SW extension on N- to NW-striking normal faults. This deformation is isolated and partitioned from transform faults and seafloor spreading centers that have been active in the Alarcón basin since at least 2.4 Myr (Lonsdale, 1989; Sutherland, 2006; Lizarralde et al., 2007). In contrast, the integrated style of faulting and basin formation in the San Jose Island to Loreto marginal domain suggests a more direct, complex connection to axial Gulf faults and basins during Pliocene time, with low rates of faulting since then (Mayer and Vincent, 1999). This suggests a closer mechanical link (i.e., non-partitioned strain) between the plate margin in the San Jose Island-Loreto domain and related axial basins and transform faults to the southeast in the Alarcón and Pescador basins.

Central Gulf of California

The Guaymas basin is intermediate in terms of bathymetry and stratigraphic thickness between sediment-starved basins in the south and filled basins in the north, and is the northernmost axial basin with NE-trending oceanic spreading centers bounded by long NW-trending transform faults (Figs. 10.1 and 10.4). The basin lies in up to ~1600 m of water and contains ~3 km of sediments (Aragón-Arreola et al., 2005), and thus is shallower with much thicker sedimentary fill than the axial basins to the south. Basinal sediments consist mainly of pelagic and hemipelagic marine claystone, diatomaceous ooze, and thin-bedded mud-rich turbidites derived from rivers in western Sonora (Curray et al., 1982; Einsele and Niemitz, 1982). Turbiditic sandstones are dominated by fine-grained feldspar and volcanic rock fragments with subordinate quartz, indication that the siliciclastic component of the basin fill is derived from rivers in mainland Mexico to the east, not the Colorado River to the north (Einsele and Niemitz, 1982).

Lizarralde et al. (2007) suggested that, in addition to mantle fertility, the high rate of basaltic magmatism and thicker crust in the Guaymas basin may be due to thick basin-filling sediments that act to inhibit hydrothermal circulation and enhance extraction of melt from the upper mantle. They identified the Guaymas basin as a narrow rift, in which the total map width of extended continental crust is less than 200 km. Sediments of the Guaymas basin are underlain by 6–8 km of gabbroic crust, which is thicker than the 5-km-thick oceanic crust at the Alarcón rise. The age of onset of mafic crust formation has been variably estimated at ~3.6 to 2 Myr (Lonsdale, 1989) or ~6 Myr (Lizarralde et al., 2007).

Marginal basins in the central Gulf region display evidence for both strain-partitioned and non-partitioned structural behavior. Multichannel seismic reflection lines in the Yaqui marginal basin on the Sonoran continental shelf (Fig. 10.4) reveal a history of NE-SW extension and formation of NW-trending, NE-tilted half-graben rift basins that accumulated up to 4 km of sediment from latest Miocene to Pliocene time (Aragón-Arreola et al., 2005). This structural style represents an example of strain partitioning, as defined above, in which the extensional component of plate-boundary strain is accommodated by dip-slip offset on normal faults, with little or no mechanical linkage to axial transform faults and basins. Activity in these basins and bounding faults ended ~2–3 Myr and shifted west into the main Guaymas basin (Aragón-Arreola et al., 2005; Aragón-Arreola and Martín-Barajas, 2007). It thus appears that the Pliocene westward shift in faulting and basin formation may have coincided with the end of strain partitioning in the central Gulf region.

The late Miocene Santa Rosalia basin formed on the west margin of the Gulf (immediately west of Guaymas axial basin) in response to early rifting and oblique slip on NNW-striking dextral-normal faults (Wilson, 1948; Ochoa et al., 2000). The presence of small complex fault blocks, marginal-marine Gilbert deltas, and buttress unconformities suggests that this may be a transtensional fault-termination basin similar to better-documented examples farther south (cf. Fig. 10.2). The age of the oldest marine deposits in the Santa Rosalia basin was determined from paleomagnetism and ^{40}Ar/^{39}Ar dating to be ~7.1 Myr (Holt et al., 2000). Thus an extensive seaway related to oblique rifting was present in the central Gulf region by this time, about 0.6 to 1.0 My prior to marine incursion in the northern Gulf and Salton Trough (McDougall et al., 1999; Oskin and Stock, 2003a; Dorsey et al., 2007).

Northern Gulf of California

Axial basins in the northern Gulf of California display sharp contrasts with central and southern axial basins (Figs. 10.1 and 10.5). Seafloor bathymetry is significantly shallower, with water depths $\leq$ 200 m in most areas. The sedimentary fill is much thicker than in basins to the south, with thickness estimates ranging from 6.5–7.0 km (Aragón-Arreola and Martín-Barajas, 2007) to ~10 km (Gonzalez et al., 2005). Evidence that Colorado River-derived sediment dominates the basin fill in the northern Gulf is provided by physical continuity with the Colorado River delta, diagnostic heavy mineral assemblage (Van Andel, 1964), presence of reworked Cretaceous foraminifers in sediments up to ~4.5 km deep, and correlation of stratigraphic sequences in the subsurface Altar basin (Pacheco et al., 2006). The base of the crust beneath the northern Gulf is 15 to 20 km below sea level (González et al., 2005). Seismic P-wave velocities and velocity gradients suggest that the crust in this area consists of felsic greenschist-facies metasedimentary rocks, similar to metasedimentary rocks imaged at depth in the Salton Trough (Fuis et al., 1984). However, it is not known whether the lower crust in this area consists of metamorphosed Colorado River sediments with basaltic intrusions, as is implied by comparison to the Salton Trough (Fuis et al., 1984), or older granitic crust that has been strongly thinned and exhumed from the sides of the oblique rift zone (González et al., 2005).

Axial basins in the northern Gulf define a composite pull-apart geometry in which four north-trending extensional sub-basins – the Wagner, Consag, and Upper and Lower Delfin basins – link the Ballenas transform fault in the south to the Cerro Prieto fault in the north (Fig. 10.5; Lonsdale, 1989; Persaud et al., 2003; Aragón-Arreola and Martín-Barajas, 2007). Strain is transferred off the tip of the Ballenas transform fault into a complex network of horsetail splays that dissect the lower and upper Delfín basins in a broad zone of distributed transtensional deformation. Subsidence in offshore basins on the eastern side of the Gulf was greatly reduced at ~2–3 Myr, when activity on the basin-bounding faults shifted to the currently active western margin of the Gulf (Aragón-Arreola et al., 2005; Aragón-Arreola and Martín-Barajas, 2007).

The age of marine sediments in the axial northern basins is poorly known due to the low abundance, poor preservation, and inconsistent ages of microfossils in cuttings obtained from an exploratory well drilled by the Mexican oil company PEMEX. Some authors favor an in-situ interpretation for the older microfossils and, thus, a middle to late Miocene age for deposits deeper than ~1.5–2.0 km (Aragón-Arreola and Martín-Barajas, 2007; Helenes et al., 2009). This interpretation is inconsistent with a reconstruction of well dated middle to late Miocene volcanic rocks by Oskin and Stock (2003b), who showed that coastal Sonora and Isla Tiburón were adjacent to the Baja California peninsula at 6.4 Ma, and the northern Gulf of California has opened by oblique extension since 6.4 Ma. It also conflicts with the documented presence of reworked Cretaceous foraminifers, a robust indicator of sediment derived from the Colorado Plateau (thus requiring an age of <6 Ma), at depths up to 4.5 km in the Altar basin (Pacheco et al., 2006). These findings support an alternative interpretation that marine sediments in the Tiburón basin are mostly Plio-Pleistocene and the Miocene microfossils are reworked.

Marginal basins in the northern Gulf include transtensional, rift and supradetachment basins that range in age from late Miocene to modern (Fig. 10.5). The NNW-trending San Pedro Martír fault in northeastern Baja California is an active dip-slip listric normal fault with at least 5 km of displacement at the western boundary of the Gulf Extensional Province (Gastil et al., 1973, 1975; Stock and Hodges, 1989). Slip on the San Pedro Martír fault began between 11 and 6 Myr and continues today (Stock and Hodges, 1989). Two currently inactive detachment faults east of the San Pedro Martír fault bound Late Cenozoic supradetachment basins. The Santa Rosa basin formed in the hanging wall of the Santa Rosa detachment fault (Fig. 10.5) and accumulated nonmarine conglomerate and sandstone between ~12.5 and 6 Ma, concurrent with other late Miocene rift basins in the surrounding area (Bryant, 1986; Oskin and Stock, 2003c). The Las Cuevitas detachment fault dips 15–35° east and experienced oblique-dextral movement of its hanging wall to the east and ESE (Black and Axen, 2003; Black, 2004). Subsidence on the Las Cuevitas detachment started in latest Miocene time, controlled marine incursion at ~6 Ma, and accommodated deposition of marine diatomite that passes laterally into fault-proximal breccia and arkosic sandstone (Boehm, 1984; Black and Axen, 2003; Black, 2004).

Fault-bounded marginal basins are also exposed on Isla Tiburón and adjacent coastal Sonora northeast of the Gulf (Fig. 10.5). Faulted upper Miocene nonmarine deposits on mainland Sonora include NE-dipping sedimentary and volcanic rocks that record NE-SW extension and formation of broad rift basins between ~12 and 6 Myr (Gastil and Krumenacher, 1977; Oskin and Stock, 2003c). Latest Miocene conglomerate in coastal Sonora accumulated in nonmarine transtensional basins bounded by NW-striking dextral faults and NNE-striking normal faults, including one low-angle detachment fault, during strong dextral shear that started ~6.5–7.0 Myr (Dorsey et al., 2008; Bennett, 2009). Lower Pliocene marine deposits exposed on southwest Isla Tiburón rest on middle to upper Miocene volcanic rocks and record marine incursion in response to initiation or acceleration of Pacific-North America plate motion along the Gulf-Trough corridor at ca. 6.5–6.0 Myr (Oskin and Stock, 2003a–2003c).

Salton Trough

The Salton Trough is a large transtensional basin that straddles the active plate boundary at the northwest end of the Gulf of California (Fig. 10.6). Sediment from the Colorado River has dominated the basin fill since early Pliocene time, constructing a subaerial delta that presently isolates the Salton Sea from the Gulf of California (Merriam and Bandy, 1965; Winker, 1987). Colorado River sediment is metamorphosed at shallow depths by rapid burial, active magmatism, and high heat flow (Muffler and White, 1969; Elders and Sass, 1988), and is rapidly converted to metamorphic rock beneath the Salton Sea (Fuis et al., 1984; Schmitt and Vazquez, 2006; Dorsey, 2010). Seismic and gravity data suggest that the entire thickness of sub-sediment basement under axial basins of the Salton Trough, from about 5 to 12 km depth, consists of young, post-6 Myr crust that has formed by filling of the oblique rift zone with sediment from above and mafic intrusions from below (Fuis and Kohler, 1984; Fuis et al., 1984; Fuis and Mooney, 1991). Several exploratory wells in the subsurface Altar basin (Fig. 10.5) encountered pre-Tertiary granitic basement at depths of 4 to 5 km (Pacheco et al., 2006), revealing the high degree of structural complexity and variability of basin depth along the plate boundary in this area.

The southwestern Salton Trough exposes Late Cenozoic marginal basins that formed in the hanging wall of two low-angle detachment faults: the east-dipping West Salton detachment fault (WSDF) in the north (Axen and Fletcher, 1998; Dorsey et al., 2011) and the west-dipping Cañada David detachment (CDD) in the south (Fig. 10.6; Axen, 1995; Axen et al., 2000; Martín-Barajas et al., 2001). Late Miocene extension led to deposition of rift-related alluvial fans in the northern area between about 8 and 6.5 Ma, followed by marine incursion into the Salton Trough region at ~6.3 Myr (McDougall et al., 1999; Dorsey et al., 2007; McDougall, 2008). During early Pliocene time the Colorado River delta prograded south and displaced marine environments into the Gulf of California (Dibblee, 1954, 1984; Winker, 1987; Winker and Kidwell, 1996; Axen and Fletcher, 1998; Dorsey et al., 2011). A similar history is recorded in sedimentary rocks exposed around Laguna Salada south of the international border (Fig. 10.6; Axen et al., 2000; Martín-Barajas et al., 2001).

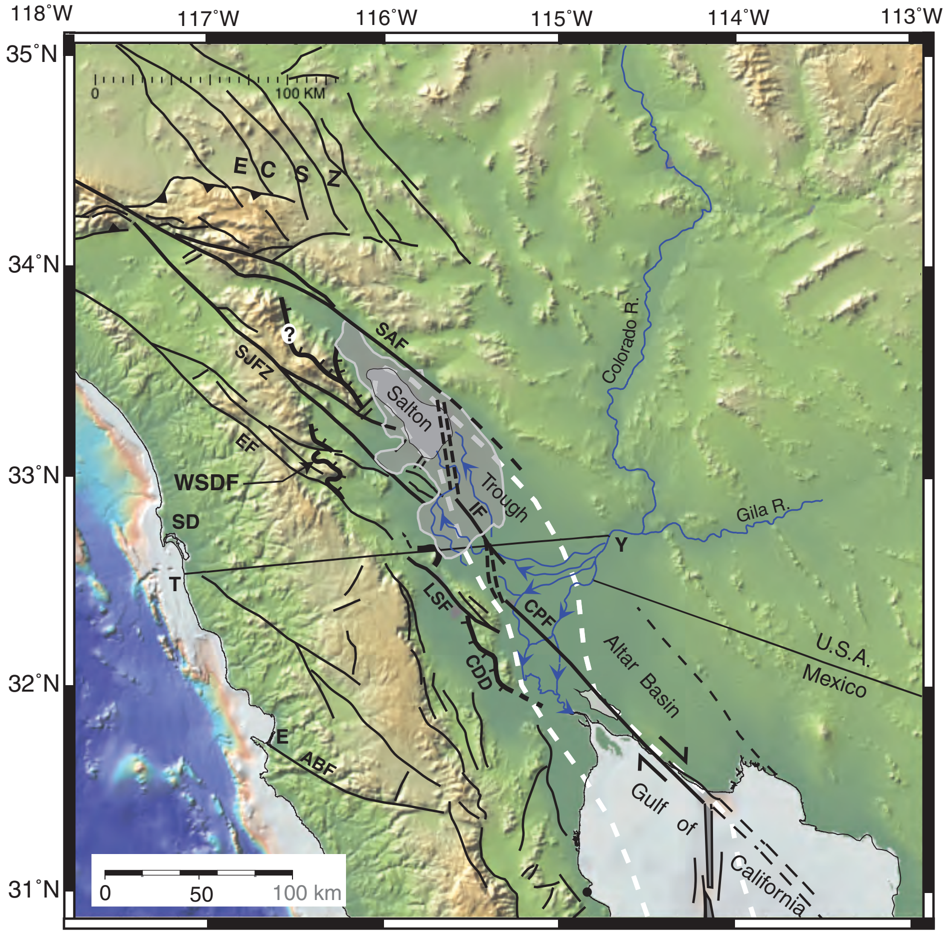

Fig. 10.6. Map of faults and basins in the Salton Trough and northernmost Gulf of California. Dashed white line shows approximate location of axial basins Abbreviations: ABF, Agua Blanca fault; CDD, Canada David detachment; CPF, Cerro Prieto fault; E, Ensenada; ECSZ, eastern California shear zone; EF, Elsinore Fault; IF, Imperial fault; LSF, Laguna Salada fault; SAF, San Andreas fault; SD, San Diego; SJFZ, San Jacinto fault zone; SSPMF, Sierra San Pedro Martir fault; T, Tijuana; WSDF, West Salton detachment fault; Y, Yuma. *Source*: Redrafted from Axen and Fletcher (1998) and Dorsey et al. (2011).

The kinematics of northwest-striking detachment faults in the southwestern Salton Trough is variable and somewhat ambiguous. Axen and Fletcher (1998) found that slip on the WSDF was to the NE to ENE, suggesting regional-scale strain partitioning in which the divergent component of plate-boundary strain was taken up by orthogonal, NE-directed extension. However, recent analysis of fault striae in the WSDF zone suggests a wide range of scatter with overall upper-plate transport to the east or ESE (Steely et al., 2009). Similarly, the CDD shows large scatter in fault striae orientations, with overall top-to-the west fault motion (Axen and Fletcher, 1998). Thus, although the supradetachment basins in the southwestern Salton Trough resemble basins that form in regions of orthogonal extension and low-angle normal faulting, it appears that their bounding detachment faults experienced oblique, dextral-normal offset with little or no strain partitioning relative to the plate boundary.

The Salton Trough region experienced a major tectonic reorganization at about 1.1–1.4 Ma, when Plio-Pleistocene detachment faults and supradetachment basins were terminated, dissected and uplifted by initiation of the San Jacinto, Elsinore, and Laguna Salada strike-slip fault zones (Fig. 10.6; Morton and Matti, 1993; Dorsey and Martín-Barajas, 1999; Lutz et al., 2006; Kirby et al., 2007; Steely et al. 2009). This reorganization was accompanied by a change from dominantly transtensional to dominantly dextral wrench deformation in the western Salton Trough, and it coincides with the onset of uplift and inversion of the southwestern parts of the former supradetachment basins. Thus the present-day topography and basin-forming processes in the Salton Trough are significantly different than their Plio-Pleistocene counterparts.

DISCUSSION

Influence of rift angle

Analog clay models have shown that oblique rifts with a rift angle (α) less than 20° are dominated by deformation on strike-slip faults, whereas those with $\alpha > 20°$ are dominated by complex networks of linked strike-slip, normal, and oblique-slip faults, and the overall trend and complexity of the fault zone is determined by the degree of rift obliquity (Fig. 10.7; Withjack and Jamison, 1986; Tron and Brun, 1991; Clifton et al., 2000). Numerical models also generate wrench-dominated deformation at $\alpha < 20°$ and extension dominated deformation at $\alpha > 20°$ (Tikoff and Teyssier, 1994). Fault geometries in the Gulf of California and Salton Trough region generally support this prediction. An array of transtensional faults in the Loreto area (southern Gulf region; $\alpha \sim 17$–$18°$) resembles the pattern expected for the $\alpha = 15°$ analog model of Withjack and Jamison (1986) after modifications that are predicted to result from fault zone evolution and finite strain (Umhoefer and Stone, 1996). Off-axis (marginal) portions of the northern Gulf region ($\alpha = 33$–$35°$) contain more large normal faults and are affected by greater amounts of extensional strain than the southern Gulf region, as predicted by theoretical and analog modeling studies.

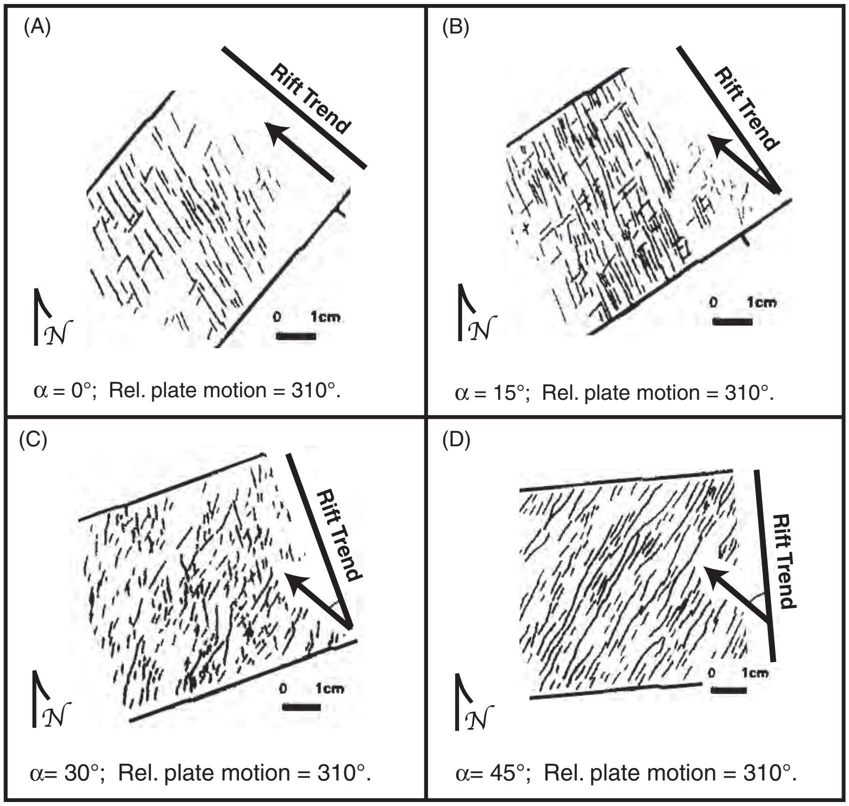

Fig. 10.7. Fault patterns created by oblique rifting in analog clay model for different values of rift angle (α). Arrow represents the direction of relative plate motion, held constant at 310° in this reproduction. For settings where $\alpha = 0°$ (pure strike-slip) and 15° (A, B), strain is accommodated mainly on strike-slip faults oriented sub-parallel to the rift trend. For $\alpha = 30°$ (C), transtensional deformation occurs in a complex network of linked strike-slip, normal, and oblique-slip faults. For rift angles $\geq 45°$ (D), deformation occurs mainly on normal faults oriented perpendicular to the direction of plate motion, and the rift trend varies as a function of α (Withjack and Jamison, 1986). The southern Gulf has a rift trend of 17° to 20° (close to diagram B), and the northern gulf to Salton Trough has an overall rift trend of about 30° (close to diagram C). *Source*: Modified from Withjack and Jamison (1986).

In addition, here we highlight an aspect of fault geometry that has not been discussed in previous studies of oblique rifting: presence or lack of low-angle normal faults (detachment faults). During development of the oblique-divergent plate boundary in the past 6–12 My, five large detachment faults in the Salton Trough and NE Baja California, and one smaller detachment in coastal Sonora, formed the faulted boundaries of marginal basins in the northern region, a zone of extension-dominated transtension where $\alpha = 33–35°$. In addition, the San Pedro Martír fault is inferred to shallow downward into a low-angle normal fault at depth (Gastil et al., 1975), and González et al. (2005) suggested that the northern Gulf axial basins are underlain by a regional-scale core complex and subhorizontal detachment fault. In contrast, not a single detachment fault or supradetachment basin has been identified in the entire central to southern Gulf of California region ($\alpha < 20°$), a region of wrench-dominated transtension.

We suggest that the presence or lack of detachment faults and supradetachment basins in this setting is determined by the rift angle. It is generally understood that detachment faults form in regions of high heat flow and rapid continental extension (Buck, 1991; Friedmann and Burbank, 1995; Lavier and Buck, 2002). The condition of high heat flow is satisfied because the plate boundary was established along the axis of the early to middle Miocene magmatic arc (Stock and Hodges, 1989). We propose that formation of detachment faults in the Gulf-Trough region requires a critical rate of extension that is exceeded in the north and not in the south, because of the difference in rift angle. The rate of relative motion between Baja California and mainland Mexico (47–43 mm/yr from south to north; Plattner et al., 2007) is similar along the length of the Gulf-Trough corridor, but the ratio of strike-slip to extensional strain changes from south to north as a function of rift obliquity. A purely strike-slip margin ($\alpha = 0$) would undergo purely strike-slip strain with no extension, while a purely orthogonal rift ($\alpha = 90°$) would accommodate all of the plate motion by extension on normal faults. In the southern and central Gulf where $\alpha < 20°$, strike-slip-dominated transtensional deformation takes place either by distributed strain on linked oblique-slip and strike-slip faults (non-partitioned style; San Jose Island to Loreto region), or by partitioned strain characterized by rapid slip on NW-striking strike-slip faults and slow extension on normal faults (La Paz to Los Cabos region; Fletcher and Munguía, 2000). In the northern Gulf and Salton Trough where $\alpha > 30°$, extension makes up a greater percentage of the total bulk strain for both strain-partitioned and non-partitioned deformation styles. We suggest that the resulting higher rate of crustal extension in the north produces faster slip rates on normal faults, possibly > 1–2 mm/yr, thus exceeding the threshold rate required to form low-angle normal faults and supradetachment basins in warm thick crust (i.e., Friedmann and Burbank, 1995).

Influence of sediment input

Voluminous input of Colorado River sediment clearly is responsible for filling and overfilling of basins in the Salton Trough and northern Gulf of California. Subtle topography in the nonmarine delta presently isolates the Salton Sea (~70 meters below sea level) from marine waters of the Gulf of California (e.g., Merriam and Bandy, 1965; Winker, 1987). In addition to the obvious impact on surficial features and environments, rapid sediment input in this setting also directly affects crustal thickness and composition, lithospheric rheology, mechanics of extension, and rift architecture. Geophysical studies indicate that pre-Cenozoic continental lithosphere in the northern Gulf and Salton Trough has fully ruptured by dilation beneath the fault-bounded basins, and new crust is being constructed at depth from young syn-rift sediment and mantle-derived intrusions (Moore, 1973; Fuis et al., 1984; Nicolas, 1985; Gonzalez et al., 2005). The large volume of Colorado River-derived sediment in these basins, estimated at $2.2–3.4 \times 10^5\,\text{km}^3$, has built a new generation of transitional crust in the past 5–6 My at rates similar to rates documented for island arcs and sea-floor spreading centers (Dorsey, 2010). The rapid input of sediment also affects upper mantle thermal structure and changes in buoyancy forces in ways that enhance localization of strain and favor an early transition to narrow-rift mode (Lizarralde et al., 2007; Bialas and Buck, 2009).

In the sediment-starved southern Gulf of California, the plate boundary has completed the transition from continental rift basins to seafloor spreading centers characterized by normal mafic ocean crust and magnetic lineations. In contrast, filled and overfilled basins in the northern Gulf and Salton Trough are characterized by thick new crust created by input and modification of

Colorado River sediment, which fills the space created by lithospheric rupture and plate divergence (Moore, 1973; Fuis et al., 1984; Nicolas, 1985). The degree to which basins have completed the transition from continental rifts to oceanic spreading centers changes dramatically from south to north along the plate boundary, despite the fact that the basins all initiated around the same time and there has been about the same amount of offset across the main plate boundary since ~6.1–6.4 Myr (Oskin et al., 2001; Oskin and Stock 2003b). The northern basins are not oceanic because rapid input of sediment generates new crust that prevents normal basaltic ocean crust from forming in the zone of plate divergence. Although the pre-existing continental lithosphere has ruptured completely in the north, extension has not progressed to the predicted seafloor spreading center with normal oceanic crust, and instead has produced a thick new transitional crust composed of Colorado River-derived sediments and mantle-derived intrusions.

The above summary highlights the first-order control that sediment input has on the thickness and composition of crust in oblique-divergent basins of the Gulf-Trough corridor. In fact, it appears that the rate of sediment input in this setting determines whether or not rifting is able to completely remove continental crust and form a new ocean basin floored by mafic crust.

CONCLUSIONS

Sedimentary basins in the Gulf of California and Salton Trough region display a wide range of structural styles related to transtensional deformation along the oblique-divergent Pacific-North America plate boundary. Basin-filling patterns vary systematically as a function of distance from the mouth of the Colorado River, which has delivered a large volume of sediment to this region during the past 5–6 My. Axial basins in the southern Gulf consist of short, sediment-starved oceanic spreading centers that trend northeast, perpendicular to long transform faults, whereas axial basins in the north are mainly oblique pull-apart basins that contain thick sedimentary fill and lack evidence for sea floor spreading or normal mafic ocean crust at depth.

It appears that three main parameters govern the behavior and evolution of basins along the Gulf-Trough corridor: (1) the acute angle between the overall trend of the plate boundary and the direction of relative plate motion (rift angle, α); (2) input of sediment from the Colorado River in the north; and (3) degree of strain partitioning. Detachment faults are found only in the northern Gulf and Salton Trough where the rift angle is greater than 30°, and they are absent in the central and southern Gulf where $\alpha < 20°$. We suggest that the faster extension rates produced by the higher rift angle in the north are responsible for formation of low-angle detachment faults and supradetachment basins, which are believed to require extension rates greater than ca. 1–2 mm/yr.

The spatially variable supply of sediment to basins in the Gulf-Trough corridor exerts a profound control on crustal thickness and composition, lithospheric rheology, mechanics of crustal extension, and overall rift architecture. In the sediment-starved southern Gulf, the plate boundary has completed the transition from continental rift basins to seafloor spreading centers with mafic ocean crust and magnetic lineations. In the northern Gulf and Salton Trough, where sediment supply is sufficient to keep basins filled and overfilled, creation of new transitional crust by sediment input has prevented the formation of normal ocean crust and seafloor spreading centers. It thus appears that the rate of sediment input controls whether or not continental rifting progresses to the expected formation of a new ocean basin floored by mafic crust. This process may be important at other obliquely divergent margins where sediment is rapidly delivered to transtensional basins from one or more large continental river systems.

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REFERENCES

Aragón-Arreola, M., Morandi, M., Mártin-Barajas, A., Deldago-Argote, L., and Gonzalez-Fernandez, A. (2005) Structure of the rift basins in the central Gulf of California: kinematic implications for oblique rifting. Tectonophysics, 409, 19–38.

Aragón-Arreola, M. and Martín-Barajas, A. (2007) Westward migration of extension in the northern Gulf of California, Mexico. Geology, 35, 571–574.

Atwater, T., and Stock, J.M. (1998) Pacific North America plate tectonics of the Neogene southwestern United States: An update: International Geology Review, 40, 375–402.

Axen, G.J. (1995) Extensional segmentation of the Main Gulf Escarpment, Mexico and the United States: Geology, 23, 515–518.

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, 40, 217–244.

Axen, G.J., Grove, M., Stockli, D., Lovera, O.M., Rothstein, D.A., Fletcher, J.M., Farley, K., Abbott, P.L. (2000) Thermal evolution of Monte Blanco Dome; low-angle normal faulting during Gulf of California rifting and late Eocene denudation of the eastern Peninsular Ranges. Tectonics, April 2000 19, 197–212.

Bennett, S.E.K. (2009) Transtensional rifting in the late proto-Gulf of California near Bahía Kino, Sonora, Mexico. [M.S. thesis]: University of Norgth Carolina, 121 pp

Bialas, R.W., and Buck, W.R. (2009) How sediment promotes narrow rifting: Application to the Gulf of California. Tectonics, 28 doi: 10.1029/2008TC002394

Black, N. (2004) Structure and hanging wall stratigraphy of the Las Cuevitas detachment, Central Sierra, San Felipe, Baja California, Mexico. [M.S. thesis]: UCLA, 102 pp.

Black, N., and Axen, G. (2003) Structure and hanging wall stratigraphy of the Las Cuevitas detachment, central Sierra San Felipe, Baja California: Geological Society of America Abstracts with Programs, 35 (4), 10.

Boehm, M.C. (1984) An overview of the lithostratigraphy, biostratigraphy, and paleoenvironments of the late Neogene San Felipe marine sequence, Baja California, Mexico. In: V.A. Frizzell, Jr. (Ed.) Geology of Baja California Peninsula. Field Trip Guidebook, Pac. Sect., Soc. Econ. Paleontol. Mineral., 39, 253–265.

Brown, H.E. (2007) Crustal rupture, creation, and subduction in the Gulf of California, Mexico and the role of gas hydrate in the submarine Storegga Slide, offshore Norway [Ph.D. thesis]: University of Wyoming, Laramie, 159 pp.

Bryant, B.A. (1986) Geology of the Sierra Santa Rosa Basin, Baja California, Mexico [M.S. thesis]: San Diego, San Diego State University, 75 p.

Buck, W.R. (1991) Modes of continental lithospheric extension. Jour. Geoph. Research, 96, 20161–20178.

Burchfiel, B.C., and Stewart, J.H. (1966) Pull-apart origin of the central segment of Death Valley, California. Geological Society of Americ Bulletin, 77, 439–442.

Busch, M.M., Arrowsmith, J.R., Umhoefer, P.J., Coyan, J.A, Maloney, S.J., and Gutiérrez, G.M. (2011) Geometry and evolution of rift-margin, normal-fault-bounded basins from gravity and geology, La Paz - Los Cabos region, Baja California Sur, Mexico. Lithosphere, 3, 110–127.

Carreño, A.L. (1992) Neogene microfossils from the Santiago Diatomite, Baja California Sur, Mexico: Paleontología Mexicana, 59, 1–38.

Clifton, A.E., Schlische, R.W., Withjack, M.O., and Ackermann, R.V. (2000) Influence of rift obliquity on fault-population systematics: results of experimental clay models. Journal of Structural Geology, 22, 1491–1509.

Curray, J.R., Moore, D.G., et al. (1982) Guaymas Basin: sites 477, 478, and 481. Initial Reports of the DSDP, 64, 211–415.

Dibblee, T.W. (1954) Geology of the Imperial Valley region, California, Geology of Southern California, California Division of Mines Bulletin, 170, 21–28.

Dibblee, T.W. (1984) Stratigraphy and tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills, and vicinity. In Rigsby, C.A. (ed.) The Imperial Basin – tectonics, sedimentation, and thermal aspects. Los Angeles, Pacific Section S.E.P.M., 31–44.

Dixon, T., F. Farina, C. DeMets, F. Suarez Vidal, J. Fletcher, B. Marquez-Azua, M. Miller, O. Sanchez, and P. Umhoefer (2000) New kinematic models for Pacific-North America motion from 3 Myr to present, II: Tectonic implications for Baja and Alta California, Geophys. Res. Lett., 27, 3961–3964.

Dorsey, R.J. (2010) Sedimentation and crustal recycling along an active oblique-rift margin: Salton Trough and northern Gulf of California. Geology, 38, 443–446.

Dorsey, R.J. and Martín-Barajas, A. (1999) Sedimentation and deformation in a Pliocene-Pleistocene transtensional supradetachment basin, Laguna Salada, Northwest Mexico. Basin Research, 11, 205–222.

Dorsey, R.J. and Umhoefer, P.J. (2000) Tectonic and eustatic controls on sequence stratigraphy of the Pliocene Loreto basin, Baja California Sur, Mexico. Geolgical Society of America Bulletin, 112, 177–199.

Dorsey, R.J., Fluette, A., McDougall, K.A., Housen, B.A., Janecke, S.U., Axen, G.J., and Shirvell, C.R. (2007) Chronology of Miocene-Pliocene deposits at Split Mountain Gorge, southern California: A record of regional tectonics and Colorado River evolution. Geology, 35, 57–60.

Dorsey, R.J., Peryam, T.C., Bennett, S., Oskin, M.E., and Iriondo, A. (2008) Preliminary Basin Analysis of latest Miocene Nonmarine Deposits Near Bahia Kino, Coastal Sonora: A New Record of Crustal Deformation During Initial Opening of the Northern Gulf of California. Eos Trans. AGU, 89 (53) Fall Meeting Supplement, Abstract, T11A–1851.

Dorsey, R.J., Housen, B.A., Janecke, S.U., Fanning, M., and Spears, A.L.F. (2011) Stratigraphic record of basin development along a transtensional plate boundary: Late Cenozoic Fish Creek-Vallecito basin, southern California. Geological Society America Bulletin, 123, 771–793.

Einsele, G., and Niemitz, J.W. (1982) Budget of post-rifting sediments in the Gulf of California and calculation of the denudation rate in neighboring land areas. Initial Reports of the DSDP, 64 (2), 571–592.

Elders, W.A., and Sass, J.H. (1988) The Salton Sea scientific drilling project. Journal of Geophysical Research, 93 (B11), 12953–12968.

Fletcher, J.M., and Munguía, L. (2000) Active continental rifting in southern Baja California, Mexico: Implications for plate motion partitioning and the transition to seafloor spreading in the Gulf of California. Tectonics, 19, 1107–1123.

Fletcher, J.M., 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, 119, 1313–1336.

Friedmann, S.J., and Burbank, D.W. (1995) Rift basins and supradetachment basins: Intracontinental extensional end members. Basin Res., 7, 109–127.

Fuis, G.S., and Kohler, W.M. (1984) Crustal structure and tectonics of the Imperial Valley region, California, in Rigsby, C., ed., The Imperial Basin—tectonics, sedimentation, and thermal aspects, field trip guidebook. Los Angeles, Pacific Section SEPM, Society for Sedimentary Geology, 40, 1–13.

Fuis, G.S., and Mooney, W.D. (1991) Lithospheric structure and tectonics from seismic refraction and other data, in The San Andreas Fault System, California. U.S. Geol. Surv. Profess. Pap., 1515, 207–236.

Fuis, G.S., Mooney, W.D., Healy, J.H., McMechan, G.A., and Lutter, W.J. (1984) A seismic refraction survey of the Imperial Valley Region, California. Journal of Geophysical Research, 89, 1165–1189.

Gans, P.B. (1997) Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwest Mexico. Tectonics, 16 (3), 388–408.

Gastil, R.G., Lemone, D.V., and Stewart, W.J. (1973) Permian fusulinids from near San Felipe, Baja California: AAPG Bulletin, 57, 746–747.

Gastil, R.G., Phillips, R.P., and Allison, E.C. (1975) Reconnaissance geology of the State of Baja California. Boulder, CO, Geological Society of America Memoir 140, 170 p.

Gastil, R.G., and Krummenacher, D. (1977) Reconnaissance geology of coastal Sonora between Puerto Lobos and Bahia Kino. Geological Society of America Bulletin, 88, 189–198.

González-Fernandez, A., Danobeitia, J.J., Deldago-Argote, L., Michaud, F., Cordoba, D., and Bartolome, R. (2005) Mode of extension and rifting history of upper Tiburón and upper Delfin basins, northern Gulf of California. Journal of Geophysical Research, 110, 1–17.

Helenes, J., Carreño, A.L., and Carrillo, R.M. (2009) Middle to late Miocene chronostratigraphy and development of the northern Gulf of California. Marine Micropaleontology, 72, 10–25.

Holt, J.W., Holt, E.W., and Stock, J.M. (2000) An age constraint on Gulf of California rifting from the Santa Rosalía basin, Baja California Sur, Mexico. Geological Society of America Bulletin, 112 (4), 540–549.

Kirby, S.M., Janecke, S.U., Dorsey, R.J., Housen, B.A., Langenheim, V., McDougall, K., and Steely, A.N. (2007) Pleistocene Brawley and Ocotillo formations: Evidence for initial strike-slip deformation along the San Felipe and San Jacinto fault zones, southern California. Journal of Geology, 115, 43–62.

Lavier, L.L., and Buck, W.R. (2002) Half graben versus large-offset low-angle normal fault: Importance of keeping cool during normal faulting. Journal of Geophysical Research, 107 doi: 10.1029/2001JB000513.

Leeder, M.R., and Gawthorpe, R.L. (1987) Sedimentary models for extensional tilt-block/half-graben basins, in Coward, M.P. and Dewey J.F., eds., Continental extensional tectonics. Geological Society Special Publication 28, pp. 139–152.

Lizarralde, D., Axen, G.J., Brown, H.E., Fletcher, J.M., Antonio González-Fernández, A., Harding, A.J., Holbrook, W.S., Kent, G.M., Paramo, P., Sutherland, F. and Umhoefer, P.J. (2007) Variation in styles of rifting in the Gulf of California. Nature, 448, 466–469.

Lonsdale, P. (1989) Geology and tectonic history of the Gulf of California, in Winterer, E.L., Hussong, D., and Decker, R.W., eds., The Eastern Pacific Ocean and Hawaii, vol. N Boulder, CO, Geological Society of America, Geology of North America, 499–522.

Lutz, A.T., Dorsey, R.J., Housen, B.A., and Janecke, S.U. (2006) Stratigraphic record of Pleistocene faulting and basin evolution in the Borrego Badlands, San Jacinto fault zone, southern California. Geological Society of America Bulletin, 118, 1377–1397.

Maloney, S.J., Umhoefer, P.J., Arrowsmith, J.R., Gutiérrez, G.M., Santillanez, A.U., Rittenour, T.R. (2007) Late Pleistocene-Holocene faulting history along the Northern El Carrizal Fault, Baja California Sur, Mexico: earthquake recurrence at a persistently active rifted margin. Eos Trans. AGU88(52) Fall Meet. Suppl., Abstract T41A-0358.

Martínez-Gutiérrez, G., and Sethi, P.S., 1997, Miocene-Pleistocene sediments within the San José del Cabo Basin, Baja California Sur, Mexico, in Johnson, M.E., and Ledesma-Vázquez, J., eds., Pliocene carbonates and related facies flanking the Gulf of California, Baja California, Mexico. Special Paper, 318. Boulder, CO, Geological Society of America, 141–166.

Mayer, L. and Vincent, K.R. (1999) Active tectonics of the Loreto area, Baja California Sur, Mexico. Geomorphology, 27, 243–255.

McDougall, K.A. (2008) Late Neogene marine incursions and the ancestral Gulf of California. In: Reheis, M., Herschler, R., and Miller, D. (eds.) Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River Region: Geologic and Biotic Perspectives. Geological Society of Americ Special Paper 439, 355–373.

McDougall, K.A., Poore, R.Z., Matti, J.C. (1999) Age and paleoenvironment of the Imperial Formation near San Gorgonio Pass, Southern California. Journal of Foraminiferal Research, 29, 4–25.

McTeague, M.S. (2006) Marginal strata of the east central San Jose del Cabo basin, Baja California Sur, Mexico. Master's thesis, Northern Arizona University, Flagstaff, 152 pp.

Merriam, R.H. and Bandy, O.L. (1965) Source of upper Cenozoic sediments in the Colorado delta region. Journal of Sedimentary Petrology, 35, 911–916.

Moore, D.G. (1973) Plate-edge deformation and crustal growth, Gulf of California structural province. Geological Society of America Bulletin, 84, 1883–1905.

Mortimer, E., Gupta, S., and Cowie, P.A. (2005) Clinoform nucleation and growth in coarsegrained deltas, Loreto basin, Baja California Sur, Mexico: A response to episodic accelerations in fault displacement. Basin Research, 17, 337–359.

Morton, D.M. and Matti, J.C. (1993) Extension and contraction within an evolving divergent strike-slip fault complex: the San Andreas and San Jacinto fault zones at their convergence in southern California, in Powell, R.E., Weldon, R.J., II, and Matti, J.C., eds., The San Andreas fault system: displacement, palinspastic reconstruction, and geologic evolution: Memoir – Geological Society of America. Boulder, CO, Geological Society of America, 178, 217–230.

Muffler, J.L.P. and White, D.E. (1969) Active metamorphism of the upper Cenozoic sediments in the Salton Sea geothermal field and the Salton trough, southern California: Geological Society of America Bulletin, 80, 157–182.

Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., Luyendyk, B.P. (1994) Microplate capture, rotation of the Western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system, Geology, 22, 491–495.

Nicolas, A. (1985) Novel type of crust produced during continental rifting. Nature, 315, 112–115.

Nilsen, T.H., and Sylvester, A.G. (1995) Strike-slip basins, In: Busby, C.J. and Ingersoll, R.V. (Eds.) Tectonics of sedimentary basins. Oxford, Blackwell Science, 425–457.

Ochoa-Landín, L., Ruiz, J., Calmus, T., Pérez-Segura, E., and Escandón, F. (2000) Sedimentology and stratigraphy of the upper Miocene Boleo Formation, Santa Rosalía, Baja California, Mexico. Revista Mexicana de Ciencias Geológicas, 17 (2), 83–96.

Oskin, M., Stock, J., and Martín-Barajas, A. (2001) Rapid localization of Pacific-North America plate motion in the Gulf of California. Geology, 29, 459–462.

Oskin, M., and Stock, J.M. (2003a) Marine incursion synchronous with plate-boundary localization in the Gulf of California. Geology, 31, 23–26.

Oskin, M., and Stock, J.M. (2003b) Pacific-North America plate motion and opening of the Upper Delfín basin, northern Gulf of California. Geological Society of America Bulletin, 115, 1173–1190.

Oskin, M., and Stock, J.M. (2003c) Cenozoic volcanism and tectonics of the continental margins of the Upper Delfín basin, northeastern Baja California and western Sonora, in Kimbrough, D.L., Johnson, S.E., Paterson, S., Martín-Barajas, A., Fletcher, J.M., and Girty, G., eds., Tectonic evolution of northwestern Mexico and the southwestern USA: Geological Society of America Special Paper 374. Boulder, CO, Geological Society of America, 421–428.

Pacheco, M., Martín, A., Elders, W., Espinosa, J., Helenes, J., and Segura, A. (2006) Stratigraphy and structure of the Altar basin of NW Sonora: Implications for the history of the Colorado River delta and the Salton Trough, Revista Mexicana de Ceiencias Geologicás, 23, 1–22.

Persaud, P., Stock, J.M., Steckler, M.S., Martin-Barajas, A., Diebold, J.B., Gonzalez-Fernandez, A., and Mountain, G.S. (2003) Active deformation and shallow structure of the Wagner, Consag, and Delfin basins, northern Gulf of California, Mexico: Journal of Geophysical Research, 108 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. Geophys. J. Int., 170, 1373–1380. doi: 10.1111/j.1365-246X.2007.03494.x.

Schmitt, A.K., and Vazquez, J.A. (2006) Alteration and remelting of nascent oceanic crust during continental rupture: Evidence from zircon geochemistry of rhyolites and xenoliths from the Salton Trough, California. Earth and Planetary Science Letters, 252, 260–274.

Spencer, J.E., and Normark, W.R. (1979) Tosco-Abreojos fault zone: A Neogene transform plate boundary within the Pacific margin of south Baja California, Mexico: Geology, 7, 554–557.

Steely, A.N., Janecke, S.U., Dorsey, R.J. and Axen, G.J. (2009) Early Pleistocene initiation of the San Felipe fault zone, SW Salton Trough, during reorganization of the San Andreas fault system. Geological Society of America Bulletin, 121, 663–687.

Stock, J.M., and Hodges, K.V. (1989) Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific Plate: Tectonics, 8, 99–115.

Sutherland, F.H. (2006) Continental rifting across the southern Gulf of California. PhD thesis, University of California, San Diego, 173 pp.

Tikoff, B., and Teyssler, C. (1994). Strain modeling of displacement: field partitioning in transpressional orogens. Journal of Structural Geology, 16, 1575–1588.

Tron, V., Brun, J.P. (1991). Experiments on oblique rifting in brittle–ductile systems. Tectonophysics 188, 71–84.

Umhoefer, P.J., Dorsey, R.J., and Renne, P.R. (1994) Tectonics of the Pliocene Loreto basin, Baja California Sur, Mexico, and evolution of the Gulf of California. Geology, 22, 649–652.

Umhoefer, P.J., and Stone, K.A. (1996) Description and kinematics of the SE Loreto basin fault array, Baja California Sur, Mexico: a positive field test of oblique-rift models. Journal of Structural Geology, 18 (5), 595–614.

Umhoefer, P.J., Schwennicke, 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, 19, 297–322.

Van Andel, T. (1964) Recent marine sediments of Gulf of California, in Van Andel, T. and Shor, G.G., eds., Marine Geology of the Gulf of California: American Association of Petroleum Geologists, Memoir 3, p. 216–310.

Wilson, I.F. (1948) Buried topography, initial structures, and sedimentation in Santa Rosalia area, Baja California, Mexico: American Association of Petroleum Geologists Bulletin, 32, 1762–1807.

Winker, C.D. (1987) Neogene stratigraphy of the Fish Creek – Vallecito section, southern California: implications for early history of the northern Gulf of California and Colorado delta. Ph.D. dissertation, University of Arizona, Tucson, 494 p.

Winker, C.D., and Kidwell, S.M. (1996) Stratigraphy of a marine rift basin: Neogene of the western Salton Trough, California. In Abbott, P.L., and Cooper, J.D. (eds.) Field conference guidebook and volume for the annual convention, San Diego, CA, May, 1996 Bakersfield, CA, Pacific Section, American Association of Petroleum Geologist, 295–336.

Withjack. M.O. and Jamison, W.R. (1986) Deformation produced by oblique rifting. Tectonophysics, 126, 99–124.