Geometry and Quaternary slip behavior of the San Juan de los Planes and Saltito fault zones, Baja California Sur, Mexico: Characterization of rift-margin normal faults

Melanie M. Coyan1*, J Ramón Arrowsmith1, Paul Umhoefer2, Joshua Coyan1,4, Graham Kent1, Neal Driscoll1, and Genaro Martínez-Gutiérrez2

1School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe, Arizona 85287, USA
2Department of Geology, Northern Arizona University, Campus Box 4099, Flagstaff, Arizona 86011, USA
3Neveda Seismological Laboratory, University of Nevada, Reno, MS-0174, Reno, Nevada 89557, USA
4Geosciences Research Division, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, California 92093, USA
5Departamento de Geología Marina, Universidad Autónoma de Baja California Sur, La Paz, BCS 23080, Mexico

ABSTRACT

An array of north-striking, left-stepping, active normal faults cuts the southwest margin of the Gulf of California and across the southern tip of the Baja California peninsula. This is the gulf margin fault system of the oblique-divergent plate boundary within the Gulf of California. Detailed geologic and geomorphic mapping along the onshore San Juan de los Planes and Saltito fault zones allowed us to delineate geometric sections and to infer the tectonic history of the fault zones. To achieve a more complete understanding of these individual normal faults within a larger array, we mapped faults to ~10 km offshore using seismic CHIRP (compressed high-intensity radar pulse) profiling. Both onshore faults slip at a low rate and have a low total offset. Along the San Juan de los Planes fault zone, which is entirely onshore, the young, scarp-forming fault reactivated older faults to rupture a broad, low-relief pediment surface with thin Quaternary cover, reflecting a two-stage slip history along this fault zone. The offshore study suggests a northward continuation of the onshore Saltito fault, and a complex fault array north of the La Gata fault on the east side of the San Juan de los Planes basin extending northward to the west Cerralvo fault. Our results suggest relatively low rates of active faulting of <1 mm/yr across the San Juan de los Planes sys-

*Present address: ConocoPhillips, 600 N. Dairy Ashford Street, Houston, Texas 77079, USA; Author was formerly Melanie M. Busch.
4Present address: Chevron, 1500 Louisiana Street, Houston, Texas 77002, USA.

INTRODUCTION

The Gulf of California is undergoing active, transtensional rifting. The majority of rift-related deformation occurs along right-lateral strike-slip faults and short spreading centers within the Gulf of California. However, in the La Paz–Los Cabos region of the Baja California peninsula, an array of active normal faults along the southwestern margin of the gulf also accommodates rift-related deformation to a lesser extent (e.g., Angelier et al., 1981; Fletcher and Munguía, 2000; Umhoefer et al., 2002; Plattner et al., 2007). In general, this gulf margin fault system comprises north- to north-northwest striking, east-dipping and left-stepping normal faults. These faults have low slip rates and low total offset (Maloney, 2009; Busch et al., 2011), but conspicuously control the topography on the southern end of the Baja California peninsula (Fletcher and Munguía, 2000) (Fig. 1). The fault array is situated in an area of transition between the warm, thinned crust in the main rift zone and the thicker, cooler continental crust marginal to the main rift zone. The sustained low slip rate along these faults therefore might be driven by the differing crustal properties between these two zones, or may reflect a gravity-driven process where blocks are collapsing into the gulf proper. Although investigations of the array as a whole have been published (e.g., Fletcher and Munguía, 2000; Munguía et al., 2006; Busch et al., 2011), detailed maps and comprehensive characterizations of the individual fault zones within the array are sparse (exceptions are Martínez-Gutiérrez and Sethi, 1997; Maloney, 2009; Buchanan, 2010).

Establishing a comprehensive understanding of individual faults within the gulf margin fault system has important implications for its development. Detailed investigations of individual faults can provide insight into fault growth and slip history through the delineation of fault segments and the documentation of the rate and distribution of recent slip. Study of these fault zones is required to document their full lengths, including the continuation of the fault zones offshore. Knowledge of the characteristics and slip behaviors of these individual faults is not only important to understanding the early processes involved in oblique-divergent rifting, but also to seismic hazard assessment, which has safety implications for the communities along these active fault zones, including the capital city of La Paz (Baja California Sur, Mexico).

We conducted a detailed investigation of the San Juan de los Planes and Saltito fault zones, two onshore fault zones within the gulf margin normal fault array, and the offshore extensions of these and related faults (Fig. 2). From our investigation, we characterized the geometry and Quaternary slip behavior of the onshore San Juan de los Planes fault and Saltito fault and its offshore extension within the transtensional, rift-margin fault array. In addition, by examining offshore, high-resolution seismic reflection profiles from the CHIRP (i.e., compressed high-intensity radar pulse; a sonar variant was used) system and side-scan sonar, we are able to make general inferences.
about the structural and stratigraphic nature of the offshore components of the Saltito fault. These seismic reflection profiles also indicate offshore faulting north of the San Juan de los Planes basin, including a direct projection of the relatively large down-to-the-west La Gata fault toward the down-to-the-western Cerralvo fault.

In this paper we present high-resolution geologic and geomorphic maps along the San Juan de los Planes and onshore Saltito fault zones that include delineation of the active scarp traces and hanging-wall Quaternary geomorphic surfaces. These maps provide detailed normal fault zone documentation. In addition to our maps, fault-scarp profiles and structural measurements illustrate scarp morphology and allow us to infer the structural history along the fault zones. We compile these field data along with gravity survey data and optically stimulated luminescence (OSL) dating from our previous research along the San Juan de los Planes fault zone (Busch et al., 2011) to achieve a more complete understanding of how these individual normal faults behave within a larger array. We also present the results of our CHIRP survey that extends the fault systems offshore to ~10 km.

GEOLOGIC SETTING

The southwestern gulf margin fault array is one of three fault systems accommodating transtensional rifting along the oblique-divergent plate boundary in the Gulf of California region. The gulf-axis system accommodates most extension and is characterized by right-lateral transform faults separated by shorter spreading centers within the deep central Gulf of California. Offshore, west of the Baja California peninsula, the right-lateral strike-slip borderland system plays a lesser role in regional transtensional rifting along the oblique-divergent plate boundary of the Gulf of California (Stock and Hodges, 1989; Fletcher and Munguía, 2000; Plattner et al., 2007) (Fig. 1).

The Cenozoic tectonic history of Baja California began with eastward subduction of the Farallon plate beneath western North America (Stock and Hodges, 1989). Continued subduction and eventual breakup of the Farallon plate into microplates from 30 to 15 Ma led to the inception of the Mendocino and Rivera Triple Junctions along southern California and northern Baja California (Atwater, 1970; Stock and Hodges, 1989; Stock and Lee, 1994). Between ca. 25 and 12 Ma, series of microplates along Baja California were captured by the Pacific plate. The Tosco-Abreojos right-lateral fault and other faults (the borderland system) (Spencer and Normark, 1979; Stock and Hodges, 1989; Stock and Lee, 1994) developed from the former trench to the shelf bounding Baja California on the west. By 12–6 Ma, north-northwest– and north-striking normal faults developed east of the borderland system, in the region of the present-day Gulf of California (Stock and Hodges, 1989, Hauback, 1984; Umhoefer et al., 2002). The normal fault–dominated system along the present-day Gulf of California region and the borderland strike-slip faults to the west (Stock and Hodges, 1989), or it might have been part of a complex, intragulf transtensional fault system since 12 Ma (Fletcher et al., 2003; Fletcher et al., 2007; Sutherland et al., 2012). In the Stock and Hodges (1989) model, strike-slip faults separated by small pull-apart or rift basins began to form in the present-day Gulf of California at 8–6 Ma, coincident with diminished activity along the borderland system (Lonsdale, 1989; Fletcher and Munguía, 2000; Oskin et al., 2001) and a change to more northwestern motion of the Pacific plate relative to the North American plate (Atwater and Stock, 1998). Between ca. 6 and 2.4 Ma, transform faults and spreading centers formed in the central to southwestern Gulf of California and created new oceanic crust; the southern Alarcón spreading center formed as an incipient spreading center from ca. 3.5 to 2.4 Ma, when full spreading commenced, forming oceanic crust at modern rates (DeMets, 1995; Umhoefer et al., 2008). Seismic data from the PESCADOR seismic experiment cruise (R/V Maurice Ewing; Sutherland et al., 2012; Brothers et al., 2012) suggest that oblique rifting in the gulf began ca. 12 Ma; dextral strike-slip motion along the borderland faults began ca. 8 Ma and continues to the present. In this model, normal faults situated near La Paz highlight ongoing strain partitioning in the gulf in a manner analogous to north-south–striking normal faults along the eastern boundary of the Sierra Nevada–Great Valley microplate, with dextral strike slip to the east within the northern Walker Lane near Lake Tahoe (Dingler et al., 2009). In either case, the Gulf of California continues to be a region of oblique divergence with active continental rifting on its western side (Fletcher and Munguía, 2000; Umhoefer et al., 2002; Mayer and Vincent, 1999; DeMets, 1995).

PREVIOUS STUDIES OF THE GULF MARGIN NORMAL FAULT SYSTEM

Basement rocks of Baja California Sur are made up of Cretaceous metamorphic and plutonic rocks and are best exposed south of La Paz.
The Oligocene–Miocene Comondú Group, which consists of calc-alkaline volcanic and volcaniclastic rocks, overlies the Cretaceous basement. These rocks originated from an Early–Middle Miocene volcanic arc that primarily was located east of present-day Baja California, and subsequently moved westward to the eastern edge of Baja California (Hausback, 1984).

Faults within the gulf margin system control the topography and geomorphology of the southern Baja California peninsula by causing uplift of the Cretaceous basement, engendering a westward dip of the Comondú Group and dividing this region into fault blocks that are ~20–30 km wide. The faults also offset Quaternary alluvial deposits. Principal onshore faults in this system include, from northwest to southeast, the El Carrizal, San Juan de los Planes, La Gata, and San José del Cabo (Fletcher and Munguía, 2000) (Fig. 2). Offshore faults farther north of this system are the northern Carrizal, Espiritu Santo, west Cerralvo, and Cerralvo.

The San José del Cabo fault, the southernmost of the onshore faults, strikes north-south and is nearly 90 km long (Fig. 2). Martínez-Gutiérrez and Sethi (1997) studied the Late Miocene–Pleistocene sediments in the San José del Cabo basin and concluded that it is a half-graben controlled by the San José del Cabo fault, which initiated during the Miocene in association with rifting in the Gulf of California. Based on fission track thermochronology, Fletcher et al. (2000) estimated ~5.2–6.5 km of Neogene exhumation with an average slip rate of 0.4–0.7 mm/yr along the San José del Cabo fault. A reconnaissance gravity survey across the San José del Cabo basin provided an estimated maximum basin depth of 1.6–2.7 km (Busch et al., 2011). The gravity survey revealed irregularities in the basement–basin fill contact suggestive of buried...
relict normal faults within the basin, indicating that basin evolution likely involved early graben and half-graben faulting along these smaller faults that was more complex than earlier models, and later localization of deformation along the east-dipping San José del Cabo fault, which currently bounds the west side of the basin. The San José del Cabo fault is the dominant fault within the onshore gulf margin fault system, as indicated by a deeper basin and higher footwall topography than the La Paz and San Juan de los Planes basins, although there are not sufficient data to evaluate the depth of the offshore basins.

The El Carrizal fault defines the westernmost boundary of the gulf margin system at the latitude of La Paz and controls the western side of the La Paz basin (Maloney, 2009) (Fig. 2). It is a segmented normal fault that strikes northwest-southeast and dips northeast. It has an onshore length of ~70 km and probably continues ~50 km offshore into La Paz Bay (Maloney, 2009). The maximum late Quaternary slip rate along the El Carrizal fault is ~0.1–0.4 mm/yr, as estimated from OSL ages of offset sediment horizons observed in paleoseismic trench sites. Footwall uplift probably increases to the north (Maloney, 2009; Buchanan, 2010). The Centenario fault is within the La Paz basin. Based on gravity measurements across the basin, the northern end of the onshore La Paz basin is a half-graben with two smaller basins separated by a bedrock high. The westernmost of the two smaller basins is controlled by the east-dipping Carrizal fault on its western side, whereas the easternmost basin is controlled by the east-dipping Centenario fault on its western side. The maximum onshore basin depth is 200–500 m, making this the shallowest onshore basin of the major fault-bounded basins within the gulf margin array (Busch et al., 2011).

The San Juan de los Planes fault is the western basin-bounding fault of the San Juan de los Planes basin (Fig. 2). On the east, the basin is bounded by a west-dipping fault, which we refer to as the La Gata fault after Aranda-Gómez and Pérez-Venzor (1997); however, Fletcher and Munguía (2000) called it the San Bartolo fault (after a town south of the southern projection of the fault zone). Gravity surveys across the San Juan de los Planes basin yield maximum depths of 1.0–1.5 km adjacent to a west-dipping intrabasin fault. In addition, there are thicker Quaternary sediments on the immediate hanging wall of the La Gata fault than along the San Juan de los Planes fault, and footwall relief along the La Gata fault zone is higher than that along the San Juan de los Planes fault. These features imply higher activity along the west-dipping faults than along the San Juan de los Planes fault. It is likely that the La Gata fault, along with buried west-dipping faults within the basin, accommodated most of the basin-forming slip, and that the San Juan de los Planes fault has a lower slip rate than the La Gata fault, and/or activity along the San Juan de los Planes fault began later than that along the La Gata fault (Busch et al., 2011).

Bathymetry and seismicity provide evidence that the gulf margin system extends offshore north of the onshore Saltito fault and the San Juan de los Planes basin; significant east-facing bathymetric escarpments are present east of Isla La Partida, Isla Espíritu Santo, and Isla Cerralvo in the Gulf of California. In 1995, a series of earthquakes occurred with epicenters just east of Isla Espíritu Santo and Isla La Partida (Fletcher and Munguía, 2000) (Fig. 2). Detailed bathymetric data are required to assess with greater certainty the offshore fault architecture and links to onshore faults. The results of the 2008 CHIRP study presented here further contribute to our understanding of the structural connection between the onshore and offshore systems.

METHODS

Geologic and Geomorphic Mapping

Detailed geologic and geomorphic swath maps were produced along the San Juan de los Planes and Saltito fault zones southeast and northeast, respectively, of La Paz (Fig. 2). A reconnaissance-style investigation was conducted along the La Gata fault zone, primarily involving observations from aerial photographs. The Saltito fault map presents an ~2-km-wide swath along both the footwall and hanging wall. The San Juan de los Planes fault map covers a north-south swath from the Gulf of California in the north to south of San Antonio, a zone ~40 km long and ranging from 1 to 4 km wide. Base maps were high-resolution, color aerial photographs. All mapping was completed at a scale of 1:10,000. Mapped features include the active fault-scarp trace, inactive fault zones >~5 m wide, and bedrock contacts. The topography around this fault zone is marked by low relief, gently sloping geomorphic surfaces on both the hanging wall and footwall that we mapped as Qyax, where x varies with relative surface age. We have largely interpreted the position and extent of these surfaces from high-resolution aerial photographs while simultaneously inspecting them in the field to confirm the accuracy of our aerial-photograph interpretations. Soil properties (described in Busch, 2011) were used to correlate surfaces along the fault and to understand age relationships among surfaces (e.g., Birkeland et al., 1991).

Fault-Scarp Profiles

Along active fault zones, the height of the fault scarp indicates the magnitude of recent displacement along the fault. We therefore constructed fault-scarp profiles across faulted geomorphic surfaces to document scarp height and slope morphology. Scarp profiles were constructed by measuring the change in slope angle over short intervals of slope distance perpendicular to the local strike of the scarps (e.g., Wallace, 1977). We used a clinometer to measure slope angle and a tape measure to measure distance along the slope. These measurements were then used to construct topographic profiles of the scarps. We identified the upper and lower fan slope profiles manually and projected them to the fault trace to determine the vertical offset. We did not determine the uncertainty in the profile measurements, but 1°–2° clinometer error propagated over 5–10 slope segments averaging 10 m yields 0.5–1 m error accumulated along the entire profile, and is thus probably a maximum error in the vertical offset estimate. Because there is error in our vertical scarp height data as well as variability in scarp heights along the fault zone, we estimated the average vertical offset rate by dividing the average scarp height by the underlying deposit age. The underlying deposit age was estimated with OSL dating techniques and correlated with mapped units (Busch et al., 2011). We do not have direct measurements of the fault dips, but these normal faults appear to be steep because of the nearly linear fault traces crossing fans and valleys. The vertical offset rate therefore approximates the dip-slip rate. If the gross fault dips were as low as 60°, the dip-slip rate is 13% greater than the vertical offset rate.

Marine High-Resolution Seismic Reflection Profiling

High-resolution marine geophysics methods were employed to explore the offshore extent and character of faulting. In 2008, CHIRP sub-bottom data and complimentary side-scan data were acquired in the Gulf of California, just north of the San Juan de los Planes and Saltito fault zones (Fig. 2). The CHIRP system can resolve sedimentary layers as thin as 10–20 cm with a penetration depth to 100 m beneath the seafloor (Schock et al., 1989; Quinn et al., 1998), but more typically to 30–50 m depth. These data reveal detailed images of faulted late Quaternary sediment, providing insight into the position and scale of offshore faulting and leading to a more complete construction of the fault architecture in the Saltito–San Juan de los Planes region.
RESULTS

We present the results of our detailed onshore fault zone investigations separately for the San Juan de los Planes and Saltito fault zones. We begin by describing the map units (bedrock and geomorphic surfaces) and the dominant structures along the San Juan de los Planes fault zone. A delineation of the characteristics of each geometric section of the San Juan de los Planes fault zone follows. The rock units and geomorphic surfaces as well as geometric segmentation of the Saltito fault zone are then described. We follow the onshore results with a description of the offshore fault study based on the CHIRP survey.

San Juan de los Planes Fault Zone

Granite makes up most of the footwall along the San Juan de los Planes fault zone; however, the southern end of the fault zone is composed primarily of quartz diorite that has undergone deformation and low-grade metamorphism. More rock unit descriptions were presented in Busch (2011) and Coyan (2011). Quaternary alluvial deposits overlie the bedrock in the hanging wall and form a thin cover over the footwall.

Quaternary Geomorphic Surfaces

Quaternary geomorphic surfaces along the San Juan de los Planes fault zone were identified and differentiated from aerial photographs based on color, texture, and shape as well as in the field using criteria such as surface height, vegetation cover, and soil development. Four hanging-wall surfaces were identified (Qya; see Fig. 3A). Sands and silt collected from the layers associated with each surface revealed that the four surfaces range in age from Holocene to late Pleistocene (OSL analyses presented in Busch et al., 2011) (Fig. 3). The OSL ages indicate that Qya is the oldest hanging-wall surface and that lower surfaces are younger. The San Juan de los Planes fault offsets only the Qya surface (Fig. 3B). Brief descriptions of the geomorphic surfaces follow; for further detail, see Busch (2011).

Qya (footwall) and Qya (hanging wall) surfaces are the prominent high surfaces that represent the culmination of aggradation or planation (hanging wall and footwall, respectively). They are differentiated on our map to accommodate our uncertainty in their relative ages, although based on similarities in vegetation cover and soil profiles as well as our interpretation of the fault evolution, it is likely that they are the same age. Qya is a footwall pediment surface. Qya is the highest and most expansive hanging-wall fan surface. Because the San Juan de los Planes fault offsets only the Qya surfaces, and not the younger surfaces, our vertical displacement measurements are calculated from the vertical separation of the Qya and Qya surfaces. If these two surfaces are not age equivalent, then our measured vertical offsets represent minimum values. In areas where there is no fault scarp, the Qya surface joins with the extensive Qya footwall surface, which is preserved along much of the active fault. Qya and Qya surfaces are moderately to heavily vegetated; these surfaces are 16.2 ± 1.8 ka based on a combination of single OSL ages with 2σ errors (Busch et al., 2011).

Hanging-wall surfaces result from alluvial fan incision and aggradation. Qya surfaces are younger and lower in elevation than Qya surfaces. These surfaces are generally found inset into Qya surfaces. Based on OSL dating, Qya surfaces are 4 ± 3 ka (Busch et al., 2011). Qya surfaces are younger and lower than Qya surfaces. Based on OSL dating, Qya surfaces are 2.5 ± 2.5 ka (2σ; Busch et al., 2011). Qya and Qya surfaces are moderately to heavily vegetated. Qya surfaces are active channels, and therefore are the youngest surfaces.

Structural Character of the Fault Zone

The young, active fault juxtaposes bedrock in the footwall against Pliocene–Pleistocene conglomerate in the hanging wall. The active fault zone is ~10–50 m wide in cross-sectional exposures observed in drainages and is expressed as highly fractured bedrock infused with carbonate; it is generally accompanied by a meters-wide zone of carbonate-rich granite fault gouge. It offsets Qya surfaces and forms scarps ~2–8 m high. Fault planes exposed primarily in drainages within the active fault zone tend to strike north-northwest–south-southeast, and
have an average strike of N4°W and an average dip of 62°E; however, outcrop dips range from 34°E to 88°E.

In addition to the active, scarp-forming faults, numerous older faults as well as centimeter-scale ductile and brittle-ductile shear zones cut the Cretaceous bedrock. The oldest preserved bedrock structures record ductile deformation. These ductilely deformed mylonites were later overprinted by discrete, thin shear zones formed near the brittle-ductile transition. Both the ductile and brittle-ductile shear zones tend to strike north-south. Brittle structures, including faults, fractures, and brecciated zones, overprint both the ductile and brittle-ductile structures. All of these structures exhibit a down-dip sense of shear, indicating extensional deformation (Coyan, 2011). The older, inactive fault zones have various orientations, but the majority strike northeast-southwest (N13°E on average) and, similar to the modern faults, dip 62° on average.

Extensive hydrothermal mineralization, including microscopic gold emplacement, is present within the steeply dipping brittle structures that trend north to northeast and crosscut all other features (except the active faults). The active, scarp-forming fault is not mineralized. Overall, alteration associated with gold mineralization is observable in faults and fractures that formed in shallow hydrothermal conditions, relatively late in the structural evolution of this region, probably during Cenozoic extension (Coyan, 2011).

Slickenlines are present along some of the older and modern fault surfaces. The rake of slickenlines varied from 0°–5° to 85°–90°; however, intermediate values were most common, providing evidence that these faults accommodated primarily oblique slip. Due to the protracted, complex slip history of the fault zone, some of the young, active fault surfaces contained slickenlines indicative of dip-slip, strike-slip, and oblique-slip motion; however, we did not observe any geomorphic evidence of obliquity from the most recent phase of faulting, such as offset channels or terrace edges. It is therefore likely that the young fault surfaces contain slickenlines from older faulting events.

**Geometric Segmentation**

Four geometric sections are defined along the San Juan de los Planes fault zone. The section boundaries are defined by geometric discontinuities such as stepovers, gaps in faulting, and changes in fault strike. From north to south, the El Sargento, Los Planes, Fandango, and San Antonio sections compose the San Juan de los Planes fault zone. We describe the character of each section in the following, beginning at the northern end of the fault zone. Together these sections define a fault zone that is concave toward the east (Fig. 4).

The El Sargento section, named after the small coastal community of El Sargento, is the northernmost stretch of the San Juan de los Planes fault zone, extending southward from the Gulf of California (Fig. 5). This section has an average trend of ~200° and is ~13 km long. It is marked by discontinuous scarps 1–2 km long. Vertical offsets of the QyaIV surface, estimated from scarp profiles, range from 2 to 3 m. The scarps are separated by an embayed, sinuous range front, implying a low Quaternary slip rate.

The southern end of the El Sargento section is marked by a right step (an uncommon feature in the overall left-stepping system), ~2 km wide with no overlap, to become the Los Planes section. It trends ~160° and is nearly 16 km long. The vertical offset ranges from ~3 to 8 m and generally increases toward the south (Fig. 6). The southern end of the Los Planes section exhibits stepping and splaying fault-strand geometries suggestive of segment linking. Splaying from slight jogs in the modern fault are fault traces that lack scarps. This lack of modern scarp expression might indicate that deformation is diffuse, scarps have been eroded, or that...
these fault strands have not been active within the past ~16 k.y. If they have not been active as recently as fault strands marked by scarps, it is likely that this long Los Planes section has grown by smaller segments stepping and linking together. As these steps formed, sections of the original faults may have become inactive (Fig. 6).

The footwall ranges along the northern and southern ends of the San Juan de los Planes fault zone have been reduced along this Los Planes section to a gently sloping erosion surface. The footwall is expressed as a low-relief granite pediment overlain by a thin veneer of Quaternary sediments through which inselbergs protrude. Older fault zones identifiable as zones of pulverized bedrock have been buried by the thin sediment cover, but are exposed in drainages. Recent faulting has offset the pediment surface (Fig. 7). Field observations, aerial photographs, and digital elevation models indicate that the pediment forms a swath ~8 km wide of the fault zone. Not only does the footwall host a thin sediment cover, but drainage incision on the hanging wall adjacent to the fault zone also reveals thin Quaternary cover over the granite bedrock, ranging in thickness from a few meters to ~100 m. As in the footwall, the thin sediment cover on the hanging wall buries a series of older fault zones.

From the southern tip of the Los Planes section, the fault steps prominently left 2 km with no overlap to the Fandango section (Fig. 8). This section was named for Fandango Wash, the large drainage with a conspicuous ~90° bend that extends through the section. The fault trends ~145° and vertical offset ranges from 3 to 6 m (Fig. 8). Vertical offset decreases toward the southern end of the section, reflecting a gradient in fault displacement.

The bedrock in this area is not granite like that of the sections to the north, but rather quartz diorite that has undergone low-grade metamorphism and into which the Las Cruces granite has intruded. This quartz diorite hosts lenses of schist and gneiss as well as intrusions of granite, gabbro, and diorite. Hydrothermal mineralization, including microscopic gold, is pervasive within this section of the fault zone (Coyan, 2011).

Like the Los Planes section, the footwall along the Fandango section is a low-relief pediment surface with a thin Quaternary cover. The pediment is highly incised with remnants of a thin veneer of Quaternary sediments forming patches that cap the ridges of the incised drainages in the northern portion of the Fandango section. This landscape is present in an ~2-km-wide swath from the range front on the west to the fault scarp on the east. The young fault has offset this pediment surface.

The southern tip of the active scarp of the Fandango section diminishes until it is no longer observed, marking the beginning of the ~8.5-km-long, ~200° trending San Antonio section (Fig. 9). This section, named after the town of San Antonio, which is situated near the midpoint of the section and 2.5–3 km west of the active fault zone, is the southernmost part of the San Juan de los Planes fault zone. The fault bounds the San Antonio range. It is marked by 2–4-m-high discontinuous scarps and embayed bedrock, reflecting relatively lower rates of slip in this location. An axial drainage runs from south to north, parallel to the fault for nearly the entire extent of this section. Consequently, it is difficult at some locations to distinguish between fluvial erosion and the active scarp.

Overall, the inferred vertical scarp offset within each geometric section of the San Juan de los Planes fault does not appear to display the typical normal fault displacement geometry.
Figure 6. (A) Geologic and geomorphic map of the Los Planes section of the San Juan de los Planes fault zone. The footwall along this section is expressed as a low-relief granite pediment overlain by a thin veneer of Quaternary sediments through which inselbergs protrude. The pediment forms a swath ~8 km wide west of the fault zone. The southern end of the Los Planes section exhibits stepping and spaying fault-strand geometries suggestive of segment linking. Spaying from slight jogs in the modern fault are inactive fault traces indicating that this long Los Planes section has grown by smaller segments stepping and linking together. (B) Fault scarp profiles indicate that offset ranges from ~3 to 8 m, and there is a general increase toward the south. The estimated error for each vertical offset value is ±0.5–1 m. Letters along the active fault trace correspond to scarp profile locations.
in which the greatest offset occurs in the middle of the section and diminishes toward the tips (Cowie and Scholz, 1992). With a denser distribution of scarp profiles it is possible that the expected trend might emerge, although this is unlikely given the observed patterns in our data set. For example, the scarp profiles we measured along the southern tip of the Los Planes section show greater displacement than along the central portion of the section. In addition, the profile locations were selected during our mapping as representative for those fault reaches. We would have noticed significant deviation from this pattern and been able to document it. Vertical offset magnitudes along the San Juan de los Planes fault zone as a whole (independent of segmentation), however, do reflect the predicted elliptical pattern, thus the fault displacement profile shows evidence for kinematic linking between these fault sections (Fig. 10). These measured offsets are younger than the fault as a whole and so only record the most recent phase of slip.

Saltito Fault Zone

The Saltito fault zone is northwest of the San Juan de los Planes fault zone and northeast of the city of La Paz. It is a significantly smaller onshore structure than the San Juan de los Planes fault zone; however, it continues offshore to the north, where it probably links with the Espiritu Santo fault zone (Fig. 2). The footwall of the Saltito fault zone is composed primarily of granite; however, tonalite becomes the dominant rock toward the southeastern end of the fault. Tonalitic and gabbroic hills protrude through hanging-wall sediments (Fig. 11A) (for more detailed rock unit descriptions, see Busch, 2011).

Quaternary Geomorphic Surfaces

Three surfaces were identified along the Saltito fault zone. The highest hanging-wall unit (Qya4) represents the culmination of aggradation and is the oldest surface, whereas the lowest hanging-wall unit (Qya1) is the active channel (Figs. 11 and 12). We cannot say whether the Qya1 surface of the Saltito fault correlates with the Qya1 surface of the San Juan de los Planes fault, but merely refer to the highest surface along this fault (for detailed descriptions of these surfaces, see Busch, 2011).

Geometric Segmentation

The Saltito fault is a northwest-striking, northeast-dipping normal fault made up of three sections (Fig. 11A). The northwesternmost section trends ~160° and has an onshore fault trace that is ~2.5 km long. Its southeastern tip steps left ~250 m with an ~100 m overlap. The central section of the Saltito fault trends ~130° and is almost 4 km long. It steps ~2.4 km to the left with no overlap. The third, and most eastern section, trends ~130° and is ~1 km long, and marks the southern termination of the Saltito fault.

Fault-scarp profiles were constructed along all three sections perpendicular to the fault zone (Fig. 11B). Scarp heights along the two westernmost sections range from ~7 to 14 m; however, height does not vary systematically. The fault scarp of the easternmost section is lower than that of the other two sections with a maximum scarp height of ~3 m. The two westernmost fault sections are marked by more well-developed, higher fault scarps than the shorter, eastern section, probably indicating that the easternmost section slips at a lower rate and/or became active later than the other two sections. Toward the northwestern end of the fault, the scarps do not diminish in height as would be expected if the fault were to terminate onshore (Fig. 13).

Offshore Faulting

High-resolution, offshore CHIRP profiles reveal offset strata and a bathymetric scarp in the Gulf of California along strike of the northernmost section of the Saltito fault. The offshore scarp is observed on at least three CHIRP profiles. Figure 14, which presents the profile with the most unambiguous signature for determining offset, shows two main offsets totaling ~9.5 m, consistent with the lower end of onshore scarp heights of the two western sections. These data provide evidence that the Saltito fault continues at least 8 km offshore, although it is possible that it extends considerably farther north, linking with the more significant offshore...
Espíritu Santo fault. A splay off the main fault is ~6 km offshore (Fig. 15), and may suggest that the Saltito fault ends within a few kilometers of the CHIRP survey.

In addition to providing evidence of an offshore component to the Saltito fault, CHIRP data also allow for slip-rate estimates along the offshore Saltito fault. The top of the 9.5-m-high offshore scarp is at a water depth of ~66 m (Fig. 14). Late Quaternary sea-level reconstructions suggest that rising sea level would have passed the 66 m elevation of this scarp 12,000–10,000 yr ago (Chappell et al., 1996). Assuming that rising sea level would have eroded and leveled (or smoothed) any irregular seafloor topography, including a fault scarp, and planed off any existing unconsolidated scarp-related sediments, it is unlikely that the sediment offsets...
Figure 9. (A) Geologic and geomorphic map of the San Antonio section of the San Juan de los Planes fault zone. This southernmost fault section is a range-bounding structure. Discontinuous fault scarps are separated by embayed bedrock, reflecting diminished fault activity. An axial drainage extends from south to north parallel to the fault for nearly the extent of this section. Consequently, it is difficult at some locations to distinguish between fluvial erosion and the active scarp; a conservative mapping approach was taken and a symbol denoting a queried fault was added at such locations. (B) Fault scarp profiles indicate that offset ranges from ~2 to 4 m. The estimated error for each vertical offset value is ±0.5–1 m. Letters along the active fault trace correspond to scarp profile location.
observed in the profile formed prior to 12,000–10,000 yr ago, or they would not have been preserved. We also observe homogeneous marine sediment growth packages thickening toward the offset reflectors, suggesting that there has been no change in depositional environment since deposition of the package began (post–sea-level rise). The offset on this offshore scarp has therefore probably occurred within the past 12,000–10,000 yr, reflecting a maximum late Quaternary slip rate of 0.8–0.95 mm/yr along the offshore Saltito fault.

There is no evidence to indicate that the San Juan de los Planes fault extends offshore toward the north. However, the CHIRP profiles reveal offshore structural and stratigraphic data east of the San Juan de los Planes fault zone indicating that the west-dipping La Gata fault, which bounds the eastern side of the San Juan de los Planes basin, extends offshore through fault steps toward the west Cerralvo fault (Fig. 15). These data reveal eastward-dipping strata between an east-dipping antithetic fault (Fig. 16) and the west-dipping Cerralvo fault. The east-dipping stratigraphic geometries are predominantly parallel (concordant) and probably result from eastward tilt of the hanging wall of the west Cerralvo–La Gata system (Fig. 16). There is evidence of west-dipping stratigraphy near the eastern extent of the CHIRP profiles. A submarine canyon, which is probably controlled by the southern end of the west Cerralvo fault, delimits this change in dip (Fig. 15). In addition, side-scan sonar imagery from our CHIRP cruise shows the easternmost splay of the La Gata fault offshore as it dies out to the north.

DISCUSSION

In the following, we review slip rates for the gulf margin system and the implication of these slip rates to rifting in the Gulf of California region. We discuss scarp morphology and slip-rate distribution along the San Juan de los Planes fault zone. Modern faulting along the San Juan de los Planes fault zone has reactivated older structures, leading to a comparison of the different styles of faulting manifest among the major onshore gulf margin faults. In an attempt to assess seismic hazard in the region, we derive simple estimates of paleoearthquake magnitude and earthquake recurrence intervals along the San Juan de los Planes fault zone. We then compare the geometry and offset along the San Juan de los Planes fault to some other late Quaternary normal faults in western North America.

Slip Rates and Slip-Rate Distribution

The San Juan de los Planes, La Gata, and Saltito fault zones and their offshore projections accommodate relatively low slip rates. OSL ages of offset Quaternary surfaces (Busch et al., 2011) coupled with vertical offsets of scarps provide Quaternary slip-rate estimates of 0.25–1.0 mm/yr along the San Juan de los Planes fault; the lower of these estimates are comparable to estimated Quaternary slip rates of 0.1–0.4 mm/yr along the El Carrizal fault (Maloney, 2009). Quaternary slip-rate estimates along the offshore extension of the Saltito fault zone are 0.8–0.95 mm/yr. These late Quaternary slip-rate estimates are consistently low along three of the faults within the gulf margin system and suggest that all gulf margin faults may also have equally low slip rates. Consequently, this active gulf margin system accommodates only a few percent of the 46.8 ± 0.4 mm/yr (Plattner et al., 2007) horizontal motion between North America and the Baja California microplate.

Along the San Juan de los Planes fault zone, low slip rates are accompanied by low fault-scarp relief. Along the entire fault zone, vertical offset, as reflected by scarps, has not exceeded 8 m since ca. 16 ka. Vertical offset magnitudes along the fault zone as a whole display the expected elliptical profile (Cowie and Scholz, 1992) (Fig. 10). If this fault did grow by linking of smaller, individual faults, it now apparently behaves as a single, kinematically linked structure.

Reactivation of Older Structures

Despite the low magnitude of offset along the San Juan de los Planes fault zone, the rocks within a zone tens of meters wide surrounding the active fault are generally highly fractured and shattered. This wide zone of shattered rock suggests that the active, scarp-forming fault has reactivated an older fault zone. In addition, ductile and brittle-ductile shear zones have orientations similar to that of the active fault plane. These shear zones formed at depths consistent with temperatures Þ300 °C (Sibson, 1986). Assuming a geothermal gradient of 25 °C/km, these shear zones formed 10–15 km beneath the surface and were exhumed.
Figure 11. (A) Geologic and geomorphic map of the northwest-striking, northeast-dipping Saltito fault. Three sections compose the onshore sections of this fault zone. The northwestern end of the fault extends offshore. (B) Fault scarp profiles indicate that scarp heights along the two northwestern sections range from 7 to 14 m (the estimated error for each vertical offset value is ±0.5–1 m). Height, however, does not vary systematically. The scarp (h) along the short eastern section is smaller than that of the other two sections, and has a maximum height of nearly 3 m. Letters along the active fault trace correspond to scarp profile locations.
Figure 12. Photograph looking out over the Saltito fault zone showing three levels of Quaternary hanging-wall surfaces. White dashed lines delineate the extent of the surfaces in the foreground. The highest hanging-wall unit (Qya3) represents the culmination of aggradation and is the oldest surface, whereas the lowest hanging-wall unit (Qya1) is the active channel. Photograph was taken looking toward the northwest.

Figure 13. Vertical offset of fault scarps plotted as a function of distance along the Saltito fault zone. Scarp heights along the two westernmost sections range from 7 to 14 m. The fault scarp of the easternmost section is lower than that of the other two sections, and has a maximum scarp height of ~3 m. Toward the northwestern end of the fault, the scarps do not diminish in height, as would be expected if the fault were to terminate onshore, indicating that faulting extends offshore toward the north.

Figure 14. High-resolution CHIRP (compressed high-intensity radar pulse) profile of an offshore scarp of the Saltito fault showing two main offsets totaling ~9.5 m (offset indicators are shown with black dots). The offset layer is the transgressive surface, which separates subaerial deposits below from submarine deposits above. These data provide evidence that the Saltito fault continues at least 8 km offshore, although it is possible that it extends considerably farther north, linking with the more significant offshore Espiritu Santo fault. The profile location is shown in Figure 15. VE—vertical exaggeration.

Figure 15. High-resolution CHIRP profile showing the transition from subaerial to submarine environments along the fault. The profile location is shown in Figure 14. VE—vertical exaggeration.
Figure 15. Onshore and offshore active fault traces of the Saltito and San Juan de los Planes fault zones. White lines show active fault traces. Balls are on downthrown block. Black dashed line in gulf illustrates path of offshore data collection. SC—location of the submarine canyon, which projects to the north of the labeled location and is likely controlled by the southern end of the west Cerralvo fault. The offshore Saltito fault traces are inferred from CHIRP (compressed high-intensity radar pulse) data. The offshore La Gata fault traces are inferred from side-scan sonar and CHIRP data. The onshore La Gata fault trace is inferred from topography (Espíritu Santo fault trace is from Fletcher and Munguía, 2000). Base map is from GeoMapApp (www.geomapapp.org/).
The low fault-scarp height, however, along with relatively shallow basin depth estimates (~1.5 km) from gravity surveys (Busch et al., 2011), suggest that the offset from recent faulting has not been sufficient to exhume rocks 10–15 km. Exhumation must have been accommodated by an older structure or broad areal uplift of the crystalline rocks of the southern Baja California peninsula. This exhumation may be related to offshore margin reorganization from a subduction-style to transtension-style margin (e.g., Brothers et al., 2012). The older, inactive fault surfaces along this fault zone are in a favorable orientation to provide an opportune location of weakness to accommodate modern faulting.

Along the Los Planes and Fandango sections of the San Juan de los Planes fault zone, a low-relief pediment is overlain by a thin veneer of Quaternary sediments. The bedrock making up this pediment is faulted. However, any topography resulting from past faulting has been eroded to the modern low relief (Fig. 7). From the post-faulting leveling of the bedrock, it is evident that this fault zone had a long period of inactivity and erosion of the footwall (and probably hanging wall) prior to the late Quaternary offsets on which we focus.

The style of faulting along the San Juan de los Planes fault zone is characterized by separate phases of active faulting along a single zone of weakness, separated by quiescent periods dominated by fluvial erosion; this style differs from that of the other major onshore faults (Fig. 2). The San José del Cabo fault zone is characterized by relatively higher slip, as evidenced by the high footwall topography (~1000 m relief). This interpretation is also supported by footwall exhumation rates (Fletcher et al., 2000) and basin depth (Busch et al., 2011), which indicate that this fault zone likely has been active longer than the onshore El Carrizal fault zone and the modern San Juan de los Planes fault zone. The El Carrizal fault zone exhibits a style of faulting unlike that of the San Juan de los Planes and San José del Cabo faults in that it underwent neither episodic slip along a single weak zone nor sustained continuous deformation, but rather evolved by activating different fault strands. The earliest activity along the Carrizal fault likely occurred offshore along the northern stretch of this fault (Maloney, 2009). Faulting then progressed to the south and stepped eastward to the onshore Centenario fault. The offshore portion of the Carrizal fault continued to lengthen southward and eventually became active onshore. Once onshore activity along the Centenario and Carrizal faults overlapped, activity became localized along the onshore Carrizal fault, while the Centenario fault became inactive (Maloney, 2009).

The Saltito fault zone geomorphology and fault zone structure do not indicate reactivation following planation. Given its minimum length (onshore and offshore) of ~13–14 km, it may be the southern extension of an ~80-km-long fault if it links to the Espiritu Santo fault to the north.

Seismic Hazard Analysis

The 4 sections of the San Juan de los Planes fault zone together form a zone that is ~42 km long, which corresponds to an ~M 7.0 earthquake if they ruptured together (Wells and Coppersmith, 1994). All fault steps along the San Juan de los Planes fault are <3–4 km, a threshold distance that Wesnousky (2006) found to limit rupture propagation in strike-slip faults. If this pattern can be applied to normal faults, then the geometric continuity of the sections of the San Juan de los Planes fault implies that these sections could rupture together (Wesnousky, 2006). The Saltito fault zone has an onshore rupture length of ~14 km (but continues farther offshore), which corresponds to an M 6.5 earthquake.

The magnitude of paleoearthquakes can be used to estimate the average displacement per event. Earthquakes of M 7.0, such as those expected along the San Juan de los Planes fault zone, correspond to an average displacement of ~2 m (Wells and Coppersmith, 1994). The fault scarps along the San Juan de los Planes fault zone range in height from 2 to 8 m (Fig. 10), and therefore may record 1–4 different events. If the offsets along the fault zone were produced by a single earthquake, it would be >M 7.5, and the offset to length scaling suggests that the San Juan de los Planes faults would likely have linked with other faults to increase the total rupture length. Ages of the youngest offset Quaternary geomorphic surface (ca. 16 ka, Qya3) and the oldest unfaulted Quaternary geomorphic surface (ca. 4 ka, Qya3) indicate that these 1–4 events occurred within ~12 k.y., which suggests an average recurrence of 3–12 k.y. Earthquake recurrence can also be estimated using late Quaternary slip-rate estimates (0.25–1.0 mm/yr) coupled with the average displacement per event (2 m). This method provides an earthquake recurrence estimate of 2–8 k.y. Although both methods of estimating recurrence are crude, they suggest a multimillennial scale of earthquake recurrence. The San Juan de los Planes fault therefore poses a low seismic hazard. When all gulf margin faults are considered together, however, the average rate of earthquake recurrence and the cumulative hazard in the region increase.

Fault interactions, even among faults tens of kilometers apart, influence displacement magnitudes and slip rates along the individual faults in a system (e.g., Wallace, 1987; Nicol et al.,...
The San Juan de los Planes fault zone probably serves to transfer strain between the more significant El Carrizal or Espíritu Santo and San José del Cabo fault zones. Consequently, the episodic slip history along the San Juan de los Planes fault zone is likely influenced by activity along the El Carrizal, Espíritu Santo, and San José del Cabo faults. Slip along these larger systems affects the regional stress field, modulating loading along the San Juan de los Planes fault zone and possibly influencing the timing and magnitudes of earthquakes along this relatively smaller fault system.

**Comparison to Other Normal Fault Systems**

Overall, the San Juan de los Planes fault zone exhibits a typical slip behavior and map pattern compared with normal faults of the western United States that are approximately the same length and age. A search of the U.S. Geological Survey (2006) Quaternary fault and fold database for the United States filtered by fault length (35–55 km), age of most recent event (ca. 15 ka or younger), and sense of movement (normal) yielded 12 fault zones comparable to the San Juan de los Planes fault zone (Table 1). Recent work from the Lake Tahoe basin has also been added to Table 1. Of these 13 fault zones, 7 have slip rates that are <0.2 mm/yr, 5 have slip rates of 0.2–1.0 mm/yr, and 1 has a slip rate of 1.0–5.0 mm/yr (U.S. Geological Survey, 2006; Dingler et al., 2009; Brothers et al., 2009). The San Juan de los Planes fault zone supports a low-relief erosion surface that has been offset by the active fault. Low fault-scarp heights (~2–8 m high) coupled with OSL age estimates of the offset geomorphic surfaces imply that this fault slips <1 mm/yr. Field evidence (~10–50-m-wide zone of highly fractured bedrock and ducile shear zones within the fault zone) suggests that this young active fault has reactivated an older fault zone, following sufficient time to completely bevel the granitic footwall to a pediment.

**Table 1. Length and Slip Rates of Late Quaternary Faults of the Western United States**

| Name                                  | Length (km) | Slip Rate (mm/yr) |
|---------------------------------------|-------------|-------------------|
| Cricket Mountains (west side) fault   | 41          | <0.2              |
| East Franklin Mountains fault         | 45          | 0.2–1.0           |
| Eastern Carson Sink fault zone        | 41          | <0.2              |
| Gunnison fault                        | 42          | <0.2              |
| Snake Valley faults                   | 46          | <0.2              |
| Cherraw fault                         | 45          | <0.2              |
| Greys River fault                     | 50          | 0.2–1.0           |
| Pine Valley graben fault system       | 38          | <0.2              |
| Rock Creek fault                      | 41          | 0.2–1.0           |
| Round Valley fault zone               | 36          | 1.0–5.0           |
| Squaw Creek fault                     | 47          | <0.2              |
| Williams Fork Mountains fault         | 38          | 0.2–1.0           |
| West Tahoe–Dollar Point fault*        | 56          | 0.44–0.81         |

*Note: Faults are younger than 15 ka. All data are from U.S. Geological Survey (2006), except where noted. *Dingler et al. (2009); Brothers et al. (2009)

**Conclusions**

The San Juan de los Planes and Saltillo fault zones are active normal faults within the gulf margin fault system. Both have concave fault trace geometries. Offset geometric features indicate that both faults accommodate dip-slip motion. The San Juan de los Planes fault zone is an entirely onshore structure, whereas the Saltillo fault is mainly offshore.

Three geometric sections compose the onshore Saltillo fault zone and are differentiated by changes in the orientation of the scarp and stepovers in the fault zone. The short, easternmost section accommodates the least amount of offset, indicating that activity along the Saltillo fault diminishes toward the east. The westernmost section extends at least 8 km offshore. Four geometric sections are defined along the San Juan de los Planes fault zone, also differentiated by changes in the fault orientation and geometric discontinuities. Fault surfaces within the active fault zone tend to strike north-northwest–south-southeast. Older faults along the fault zone are present as well and have various orientations; however, the majority strike north-northeast–southwest.

The footwall of the San Juan de los Planes fault zone supports a low-relief erosion surface that has been offset by the active fault. Low fault-scarp heights (~2–8 m high) coupled with OSL age estimates of the offset geomorphic surfaces indicate that this fault slips <1 mm/yr. Field evidence (~10–50-m-wide zone of highly fractured bedrock and ductile shear zones within the fault zone) suggests that this young active fault has reactivated an older fault zone, following sufficient time to completely bevel the granitic footwall to a pediment.

During the late Quaternary, the San Juan de los Planes fault zone has probably ruptured with ~2 m of vertical displacement per event, likely producing ~M 7.0 earthquakes with recurrence between 2 and 12 k.y. Over greater time scales, the San Juan de los Planes fault zone has had a two-stage slip history in which modern faulting exploited older bedrock structures that accommodated an earlier phase of exhumation that reduced the relief of the footwall piedmont. Currently, this fault zone probably serves to transfer strain between El Carrizal or Espíritu Santo and San José del Cabo fault zones. Whereas these gulf margin faults only accommodate a few percent or less of the total horizontal motion between North America and the Baja California microplate, their persistent activity provides an important window into the early processes involved in oblique-divergent rifting and valuable constraints on regional seismic hazard for southern Baja California.

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