Translation of terranes: Lessons from central Baja California, Mexico

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ABSTRACT

Baja California is one of the best modern examples of a continental block, or terrane, that is translating hundreds of kilometers along a highly obliquely divergent plate. The central domain of Baja California is particularly appropriate as a modern analogue for terrane translation because it has a relatively simple late Neogene history and is a buoyant continental block that is likely to be preserved in any future accretion to the North American continent. In contrast, the deep, dense oceanic crust of the Gulf of California, where the main transform faults of the plate boundary lie, has little preservation potential. It is surprising that there is little strike-slip faulting in the central domain of Baja California, even though the plate boundary has a rift angle (angle between rift trend and azimuth of plate motion), α, of only 20°. Recent field data confirm modeling studies of oblique rifting and show that there is a predictable change in fault type, fault orientation, and extension direction with changing rift angle. That is, from secondary structures alone, one can predict the approximate obliquity of rifting and the orientation of the plate motion. With rift angles of 0°–20°, strike-slip faults at low angles to the rift trend will dominate the secondary structures; with rift angles from ~20° to ~35°, there are strike-slip faults subparallel to the rift trend and normal faults 20°–40° clockwise from the rift trend in dextral shear; above ~35°, normal faults are dominant, and there are few or no strike-slip faults as secondary structures.

INTRODUCTION

Tectonostratigraphic terranes make up major parts of many ancient orogenic belts (e.g., Coney et al., 1980), and the accretion of terranes to continental margins is a major process of continental growth. The question of how far terranes have been translated along the margin of a continent after accretion has led to much controversy. We submit that this controversy is partly due to the lack of understanding of how translation works. Three major debates concerning the Late Cretaceous to early Tertiary history of western North America involve the translation of terranes. (1) Was Baja British Columbia translated northward ~3000 km (Irving et al., 1985; Wynne et al., 1995) or a few hundred kilometres (Monger and Price, 1996)? (2) Did the Salinia block originate immediately south of the Sierra Nevada before translation on the San Andreas fault system (Ross, 1985; Butler et al., 1991) or much farther south (Champion et al., 1984)? (3) In the Early Cretaceous, was Baja California ~300 km south of where it is today due to rifting in the Gulf of California (Gastil, 1991), or did it originate along southern Mexico ~1000 km south of its present position (Beck, 1991)?

Translation modes of ancient terranes include nearly pure transform motion (San Andreas fault of central California), oblique convergence along a major strike-slip fault within the volcanic arc (Sumatra; Fitch, 1972), oblique divergence along en echelon transform faults (Gulf of California; Larson et al., 1968), and lateral motion of smaller fore-arc slivers (Beck, 1986). In all these cases, strike-slip faults are the dominant structure responsible for translation. Despite the dominance of strike-slip faults, their preservation potential in the cases of oblique convergence and oblique divergence is low. In the Sumatra case, the magmatic arc is likely to obliterate most faults. In the Gulf of California, transform faults and short spreading ridges have created small ocean basins, 2–3 km deep (Fig. 1), that are underlain by oceanic crust. If Baja California moves northward along North America and eventually is reaccreted to the continent, then these relatively deep, dense basins and transform faults are much less likely to be preserved than Baja California, which consists of more buoyant continental crust and is largely above sea level. Secondary structures, rather than the main strike-slip faults, therefore provide key data for structural recognition of the translation history of many terranes.

In this paper, we examine tectonic patterns in the central domain of Baja California, a modern analogue for terranes that have translated long distances (e.g., Stone and Packer, 1977; Kelts, 1982; Umhoefer, 1987). Despite central Baja California sitting astride a highly obliquely divergent plate boundary, there are no large-offset strike-slip faults in central Baja California. Recent field data from faults in the central domain and modeling of oblique rifting suggest that we should expect only small-scale, local strike-slip faults along this plate margin. These studies show that the nature of secondary faults allows reconstruction of the general obliquity of a plate margin in an ancient terrane that was translated by oblique divergence. For the arguments here to be relevant, it is critical to establish that structures in ancient terranes formed during early oblique rifting.

MAJOR TECTONIC DOMAINS OF BAJA CALIFORNIA

The plate boundary in the Gulf of California is a highly oblique rift with a rift angle (angle between the azimuth of plate motion and azimuth of the rift), α, of ~20°. The Gulf of California and Baja California can be divided into three major domains on the basis of the active transform faults in the gulf as defined by bathymetry (Larson et al., 1968; Lonsdale, 1989), seismicity (Molnar, 1973; Goff et al., 1987), and active faults that cross the peninsula (Fig. 1). In the northern domain, from Puertecitos to the Salton trough, many strike-slip faults diverge to the west from the transform faults and cut across Baja California and southern California (e.g., Suarez-Vidal et al., 1991). Thus, the active plate boundary is at least 200–300 km wide and characterized by numerous major strike-slip and normal faults. In the central domain, from lat ~30°N to ~25°N, most seismicity occurs along the major transform faults in the Gulf of California (Goff et al., 1987), and there are no faults cutting across Baja California (Fig. 1). Geomorphic and seismic data suggest that an important, but probably minor, component of active faulting is occurring along the eastern margin of central Baja California (L. Mayer, 1996, personal commun.; E. Nava-Sanchez, 1996, personal commun.). In the southern domain, from lat ~25°N to the mouth of the Gulf of California, seismically active normal and oblique faults, especially the La Paz fault (Normark and Curray, 1968), cut through Baja California. The relation of these faults to the transform fault system is unknown. The wide zones of strike-slip and normal faults in

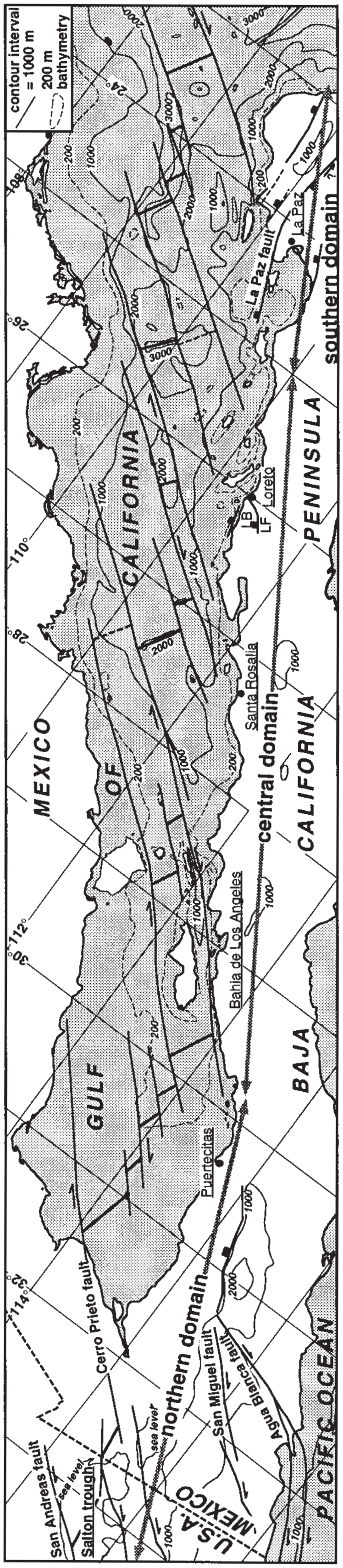

Figure 1. Major faults of plate boundary in Gulf of California and Baja California, simplified bathymetry and topography, and localities and three major domains discussed in text. LB and LF are Loreto basin and Loreto fault.

the northern and southern domains can be explained as inherited from the complex evolution of the plate boundary, which jumped from west to east over the past ~15 m.y. (e.g., Lonsdale, 1989; Suarez-Vidal et al., 1991). Thus, the central domain is the simpler region that may represent a more typical example of a highly obliquely divergent plate margin.

In the central domain, Baja California can be divided into two parts from west to east. The western part of the central domain is a largely unfaulted region of flat to gently inclined strata of the Miocene fore arc and older units. The eastern ~5 to ~25 km of the peninsula and the narrow shelf in the Gulf of California are part of the gulf extensional province, which contains virtually all of the structures related to rifting (Gastil et al., 1975). A nearly continuous, east-facing rift escarpment forms the western boundary of the Gulf of California extensional province.

LACK OF MAJOR STRIKE-SLIP FAULTS IN THE CENTRAL DOMAIN

Space photographs and topographic maps of the major physiographic features of Baja California (Hamilton, 1971) and the continuity of magmatic belts (Gastil et al., 1975; Sawlan, 1991) strongly suggest that no major strike-slip faults cut across the central domain (cf. Rusnak et al., 1964). The most compelling evidence for lack of crosscutting faults is the nearly continuous exposure of rocks of the Miocene volcanic arc for more than 400 km from near La Paz at lat 24°N to 28°N (Sawlan, 1991). Similar Miocene volcanic rocks are exposed discontinuously to at least lat 31°N (Gastil et al., 1975). Reconnaissance study of the transition between the Miocene volcanic rocks and the sedimentary fore-arc rocks that interfinger with them to the west indicates that there are no major strike-slip faults cutting across the peninsula in the central domain (Sawlan, 1991). North of lat 30°N, widespread exposure of rocks of the Cretaceous magmatic arc and fore arc (e.g., Gastil et al., 1975) confirm that no large strike-slip faults cut across the central domain.

SYNOBLIQUE-RIFTING FAULTS AND BASINS IN THE CENTRAL DOMAIN

In the central domain, detailed studies of Pliocene-Pleistocene faulting that was coeval with oblique rifting near Santa Rosalia (Angelier et al., 1981) and Loreto (Fig. 2) (Zanchi, 1994; Umhoefer and Stone, 1996) consistently show that fault populations include mainly north-striking normal faults, secondary populations of northwest- to north-northwest–striking dextral and dextral-normal faults, and minor northeast-striking sinistral-normal faults. Kinematic analyses of these fault populations indicate nearly east-west extension.

The southern part of the Loreto basin was subsiding in Pliocene time during oblique rifting. The Loreto fault bounds Pliocene strata of the basin and was active during basin formation (Fig. 2D) (Umhoefer et al., 1994). The fault may have had a pre-Pliocene history, but striae from clay gouge along the southern segment of the fault, where it is juxtaposed with basinal strata, indicate that late Pliocene motion was dominantly dextral slip, and movement of the basin hanging wall was toward the east (94°). The fault array in the southeastern part of the Loreto basin is well constrained by local angular unconformities and well-dated strata to have been active in latest Pliocene time, and limited faulting continued into the Quaternary (Umhoefer and Stone, 1996). This fault array is an anastomosing set of faults with offsets of meters to tens of meters, and includes a western domain of north-northwest–striking dextral-normal faults, a majority of north-striking normal faults, and a few north-northeast–striking sinistral-normal faults. The fault array has consistent kinematic features that indicate bulk extension oriented 278°–98° (Fig. 2, E and F), close to the average azimuth of striae (94°) on the southern Loreto fault. The orientation and style of small faults of the fault array and the extension direction are compatible with dextral shear in the Gulf of California, as shown by experimental modeling of oblique rifting (Fig. 2) (Withjack and Jamison, 1986; Umhoefer and Stone, 1996). Most important is that the strikes of the dominant normal faults are consistently oriented ~30°–40° clockwise from the rift trend.

There are few Pliocene to Quaternary basins in the central domain, perhaps in part because basins are more common in the unstudied offshore region, closer to the main plate boundary. Known basins near Bahia de Los Angeles and Loreto are half grabens or modified half grabens (Umhoefer et al., 1994; Dorsey et al., 1995), consistent with the dominance of north-striking normal faults.

DISCUSSION

Recent analytical models of oblique convergence and divergence have yielded predictions of the relation between the orientation of instantaneous strain axes and the direction of relative plate motion (Withjack and Jamison, 1986; Fossen and Tikoff, 1993). These results and the experiments of Withjack and Jamison (1986) are confirmed by field data from populations of small faults from the central domain of Baja California that probably formed in response to the orientation of infinitesimal strain (Angelier et al., 1981; Umhoefer and Stone, 1996).

As the rift angle increases in obliquely divergent margins, there are two basic thresholds, at rift angles of 20° and ~35°, that result in three styles of deformation. (1) Below a rift angle of 20°, the instantaneous strain axes are in an orientation that favors formation of strike-slip faults (Withjack and Jamison, 1986; Fossen and Tikoff, 1993). Few or no normal faults will form during this type of deformation, as verified by experiments (Fig. 2A) (Withjack and Jamison, 1986). (2) At rift angles between 20° and ~35°, experiments (Withjack and Jamison, 1986) and field data reveal mixed strike-slip and normal faults in a predictable orientation and with a predictable extension direction (Fig. 2, B and E). (3) Experiments at a rift angle of 45° produce only en echelon normal faults (Withjack and Jamison, 1986; McClay and White, 1995). Thus, there is a less well defined, but important threshold at a rift angle of ~35°, above which no strike-slip faults form. The existence of the latter threshold means that a terrane moving at a rift angle of ~45° will have no secondary strike-slip faults, even though half of the relative plate motion is translational. The extension direction is the bisector between the azimuth of plate motion and the perpendicular to the rift trend (Withjack and Jamison, 1986; Fossen and Tikoff, 1993) and thus changes smoothly across these two thresholds in the style of faulting.

These three styles of faulting are relevant only for populations of small faults that record infinitesimal strain. As faulting continues, complications are expected to arise and later faults in response to finite strain will have a different orientation than initial faults (Teyssier et al., 1995). An additional complexity is the role of regional strain partitioning of the strike-slip and dip-slip components of strain. The greater the percentage of strike-slip deformation that occurs on major faults, the greater the extensional deformation in the areas between large strike-slip faults (Teyssier et al., 1995). Likewise, the angle between the maximum infinitesimal extension direction and the rift trend increases steadily as the amount of strike-slip partitioning increases (Teyssier et al., 1995). Therefore, if a plate boundary has a constant rift angle, but there is increasing strike-slip partitioning over time, then normal faulting will become more important.

CONCLUSIONS

An important conclusion from the central domain of Baja California is that the margins of obliquely divergent plates need not have significant strike-slip faulting. Thus, the direct structural record of long-distance lateral transport in terranes similar to Baja California is likely to be missing, so that secondary structures formed during the early stages of oblique rifting may be key to identifying the nature of the plate boundary (Fig. 3). We consider the following secondary indicators to be of potential importance. (1) Small strike-slip faults with the same sense of offset as the plate boundary will be nearly parallel to the rift trend. (2) Small strike-slip faults will dominate at rift angles below 20°. (3) Mixed strike-slip and normal faults will occur at rift angles from 20° to ~35° (Fig. 3). (4) No strike-slip faults will form above a rift angle of ~35°. (5) Normal faults will be oriented about 20°–40°

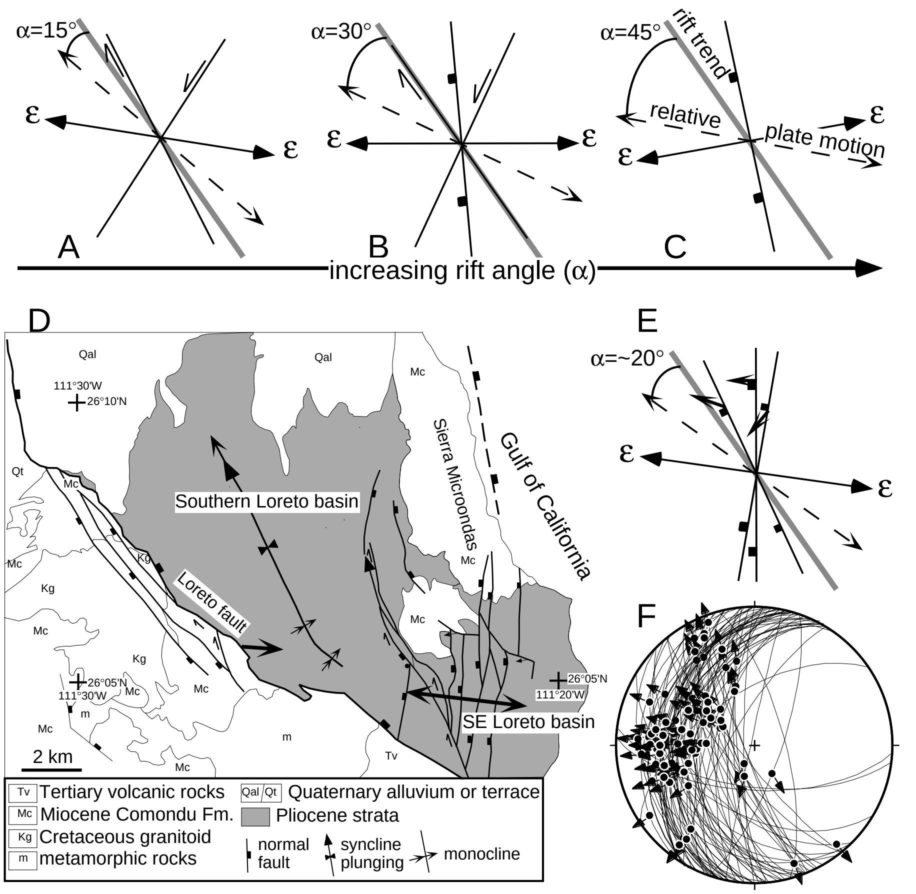

Figure 2. A–C: Dominant faults, their orientations, and bulk extension direction (ε) as rift angle (α = angle between rift trend [gray] and relative plate motion [dashed line with arrows]) increases (modified after Withjack and Jamison, 1986). All diagrams are oriented such that rift trend in each is parallel to that in Gulf of California. D: Simplified geologic map of southern Loreto basin and related faults, including Southeast fault array. Large arrows show bulk extension direction on Loreto fault and Southeast fault array in Pliocene. E: Dominant faults, their orientations, and bulk extension direction (ε) of Southeast fault array, after Umhoefer and Stone (1996). F: Stereonet of faults and striae (arrows) from Southeast fault array. Note that Southeast fault array, with rift angle of ~20°, closely matches experimental results when we interpolate between A and B.

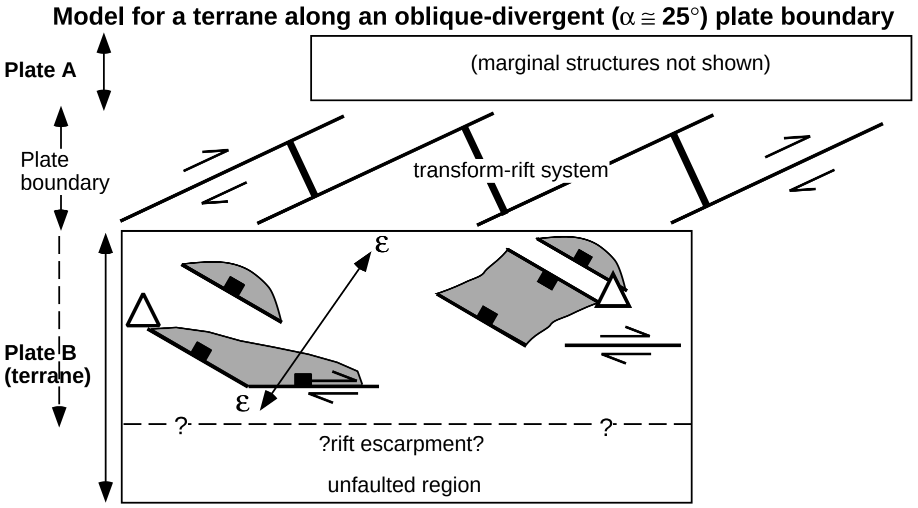

Figure 3. Simplified model of terrane (plate B) formed along highly obliquely divergent plate boundary. Model is based on geology of central domain of Baja California. Gray indicates basins; triangles indicate volcanoes.

clockwise from the rift trend in transtensional plate boundaries undergoing dextral shear. (6) The extension direction changes smoothly with increasing rift angle. (7) Consistent with the pattern of faulting, basins are oriented at moderate angles to the rift trend.

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