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GEODETIC AND TECTONIC ANALYSES ALONG AN ACTIVE PLATE BOUNDARY: THE CENTRAL GULF OF CALIFORNIA

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Abstract. The Gulf of California is traversed by the shear plate boundary between Pacific and North American plates and, because of several islands in its central part, offers the possibility of direct geodetic measurements of plate motion. A geodetic network of 150 km aperture, and comprising 11 stations, was measured in 1982 and 1986 by laser trilateration methods. The deformations deduced from the comparison of the two epochs indicate right-lateral shear strain covering the entire gulf rather than localized movements. In the eastern part of the network, between the axial islands and the Sonoran coast, significant right-lateral shear deformation occurs with a relative displacement of about 23 ± 12 cm over 4 years. In the northwestern region (Canal de Ballenas) a right-lateral displacement of about 17 ± 4 cm is observed, whereas in the southwestern part of the network (Canal Sal-si-Puedes), the deformation remains very weak. This suggests that south of the Canal de Ballenas the plate boundary is locked. A tectonic analysis of Neogene and Quaternary faults in Baja California, Sonora, and the central islands of the gulf, permitted the reconstruction of the stress pattern evolution of this area. These data also indicate the predominance of right-lateral motion on a NW-SE trending zone within a regional framework characterized by an approximately N-S compression and an E-W extension. The geodetic results are discussed in comparison with the neotectonic analysis and the seismic data available in the area. The data suggest a broad strain accumulation zone covering the totality of the central Gulf of California. A NW-SE relative velocity of about 8 ± 3 cm/yr is found between the two sides of the gulf during the 1982-1986 interval.

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INTRODUCTION

The Gulf of California

Since the early times of plate tectonics, the Gulf of California has been considered to be an active plate boundary between the North American continent and the Baja California peninsula attached to the Pacific plate (Figure 1). Most of the kinematic reconstructions indicate a right-lateral transform displacement with limited extensional motion between both sides of the Gulf of California [Wilson, 1965; Morgan, 1968; Atwater, 1970; Minster and Jordan, 1978, 1987; Moore and Curray, 1982].

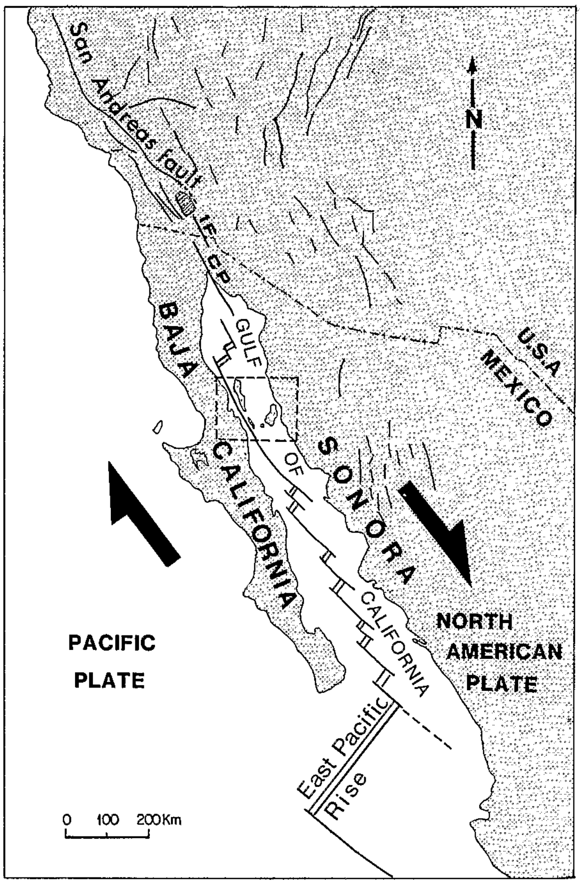

Fig. 1. Location map of the Gulf of California and related geodynamic surroundings. Dashed quadrangle: location of the geodetic network.

The analysis of the magnetic anomalies pattern in the oceanic crust located immediately south of the tip of the peninsula revealed that Baja California has been moving northwestward during the last 4 m.y. at a mean velocity of about 60 mm/yr with respect to mainland Mexico [Larson et al., 1968]. From more recent magnetic results, values varying between 66 ± 1.5 mm/yr and 49 ± 2 mm/yr have been computed for the relative motion at the mouth of the gulf [Ness et al., 1985, 1987].

Seismic moment determinations, based on 1918-1974 earthquake data, led to estimates of motion rates ranging from 48 to 81 mm/yr, with an average velocity of 65 mm/yr [Reichle, 1975; Reichle et al., 1976]. Preliminary results from satellite geodetic data supported determinations of similar rates of about 64 mm/yr [Ness et al., 1985].

Thus in spite of the differences in methods of evaluation and in time intervals (1 to 10^5), there is a striking similarity between the estimates of motion rates across the Gulf of California plate boundary. An attempt to estimate the present day motion between the Baja California peninsula and the second major island of the gulf (Angel de la Guarda Island), based on an optical parallax device, suggested that there was no measurable motion during a 2-year interval (March 1970-March 1972 [see Vacquier and Whiteman, 1973]). This result was surprising because the Canal de Ballenas, which runs between the peninsula and Angel de la Guarda Island, is the locus of one of the best defined fault lines of the gulf system [Moore, 1973; Bischoff and Henyey, 1974].

Geodetic Surveys Across Plate Boundaries

Repetition of geodetic surveys in plate boundary areas provides a powerful tool, used to define the pattern of present day relative plate motions in terms of direction as well as amount of displacements.

Accurate geodetic measurements have been carried out in California [e.g., Savage and Burford, 1973; Thatcher, 1979; Savage, 1981), in Iceland [Wendt et al., 1985], and in the Asal-Ghoubbet rift near Djibouti [Ruegg et al., 1979, 1984]. These surveys were generally performed with trilateration methods, using electronic distance measurements (EDM), and provided a description and interpretation of the distribution and the evolution of active deformation across different kinds of plate boundaries.

New geodetic technologies, such as very long baseline interferometry (VLBI) and the satellite laser ranging (SLR), are playing an increasing role in the analysis of plate motions. Such methods, which potentially are very accurate (of the order of a few centimeters, for distances up to 10,000 km), involve heavy equipment and cannot be used everywhere. They are principally applied to large intercontinental distance measurements rather than to narrow plate boundaries areas. The development of differential measurements of baselines, based on the global positioning system (GPS) enables geodetic surveys to be made on intermediate scales. Some promising results [Beutler et al., 1987] suggest that an accuracy within the range 0.1-1 ppm is possible, but application of the GPS methods to deformation studies is still in an early phase.

In spite of a width of about 150 km, the central Gulf of California was considered an appropriate area to carry out EDM measurements: several islands are adequately distributed in the central area of the gulf, and atmospheric conditions are exceptionally favorable during the winter (with clear visibility and windy weather).

The Gulf of California Geodetic Survey

The geodetic network (Figure 2) was set up in 1982 [Kasser et al., 1984] and resurveyed for the first time in 1986.

The geodetic data and results have been already published [Kasser et al., 1987, Lesage et al., 1988], so details of data acquisition and processing will not be presented here. We are more concerned with the comparison of the present day plate motion (as inferred

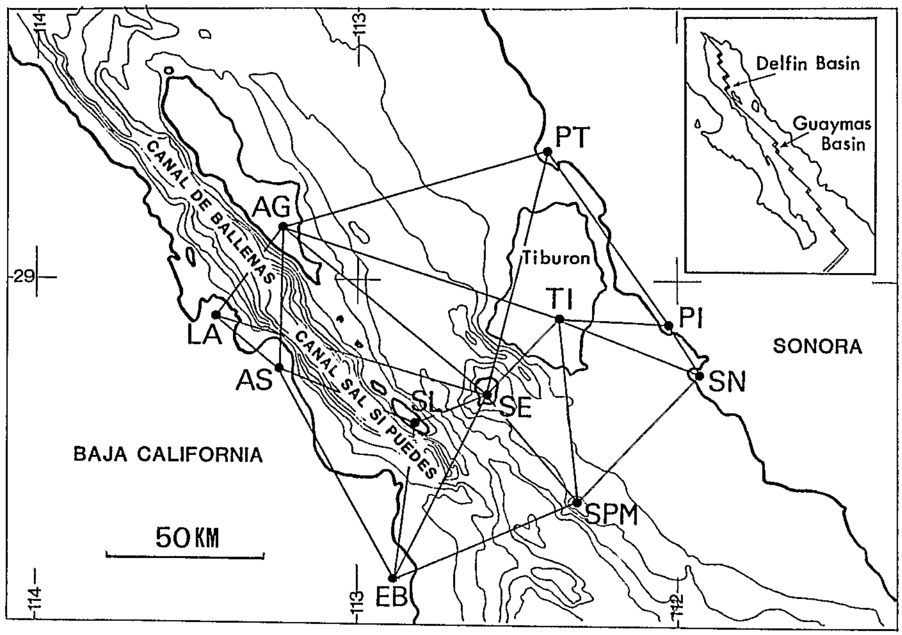

Fig. 2. The geodetic network in the central Gulf of California. Stations are: AG, Angel de la Guarda; LA, Bahia de Los Angeles; AS, Agua de Soda; EB, El Barril; SL, San Lorenzo; SE, San Esteban; SPM, San Pedro Martir; TI, Tiburon. PT, Punta Tepoca; PI, Punta Ignacio; SN, San Nicolas. The bathymetric contours (every 100 fathoms (183m)) are from Rusnak et al. [1964].

from geodetic data) with the total late Cenozoic deformation (revealed by neotectonic observations) and also with the seismic data available since the beginning of the century. Such a study implies that we examine the following points : (1) the global motion of the plates across the central gulf area at a time scale of 4 years, (2) the distribution of present deformation and location of the main active fracture zones and (3) the relative importance of strike-slip motion along the transform fault system and of E-W extension related to normal faulting.

THE GEODETIC DATA

The Network

The network set up in the central Gulf of California has a total aperture of approximately 150 km [Figure 2]. The 11 stations are located on topographic summits; they were connected by 24 distance measurements in 1982 (25 in the 1986 survey). Three stations are located on the Baja California coast (LA, AS and EB), three others on the Sonora coast (PT, PI and SN), and the remaining five stations were positioned in the five largest islands of the central part of the gulf (AG, TI, SE, SL and SPM). Explanation of station labels is given in Figure 2. The distance measurements were carried out by means of laser geodimeters (AGA model 8) used with specific operating conditions. Details on field campaigns, methodology, and processing methods have been given elsewhere [Kasser et al., 1987; Lesage et al., 1988]. The total redundancy is rather weak (only 5 control measurements), but it provides enough control between the 11 stations [Kasser et al., 1987] to give a rough estimation of the precision. It is estimated by computing the mean of residuals divided by the corresponding distances. This gives a rms of 0.75 ppm for the 1982 survey and 0.43 ppm for the 1986 one. The precision corresponding to the comparison of the two epochs is then estimated to be 1 ppm. Although this estimate is rough because of the low number of degrees of freedom for the network, we think it is realistic because of the operating conditions of the measurements (i.e., measurement at night, monitoring of the modulation frequency of the instruments,etc.).

The Main Results

Two modes of representation for the deformation pattern for the interval 1982-1986 will be considered herein: the displacement vectors resulting from a method adapted to the detection of strike-slip motion [Prescott, 1981] and a mean strain tensor analysis for subareas of the network.

In the displacement vector solution (Figure 3) the displacement perpendicular to the N135°E azimuth (i.e., the direction of the gulf axis) is minimized, according to the Prescott method. The representation of errors is shown by a distribution of points which are the extremities of the displacement vectors calculated with a Monte-Carlo method from a gaussian distribution of measurement errors (J. Pagarete et al., Evaluation et representation des erreurs sur les déformations d'un réseau géodésique; utilisation de la méthode de Monte-Carlo, submitted to *Bull. Géodésique,* 1989).

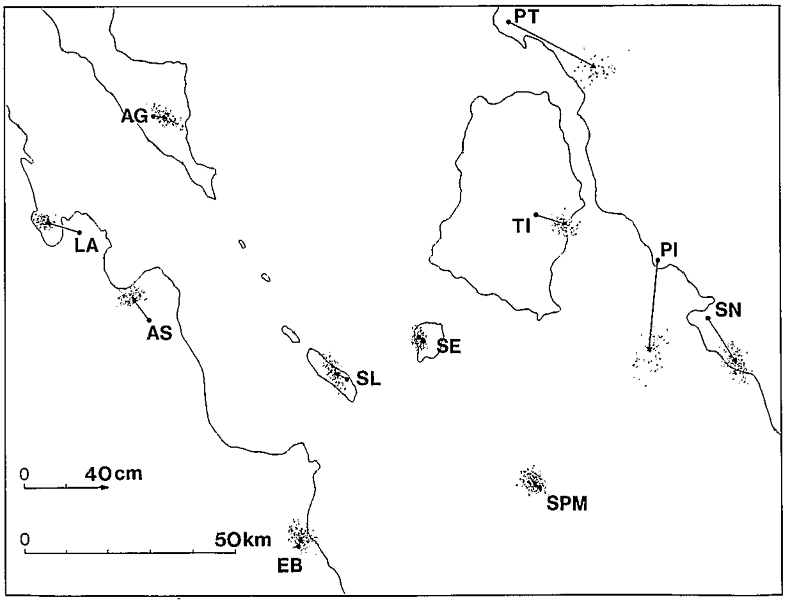

Fig. 3. Displacement vectors for the interval 1982-1986, from geodetic data. The displacement vector solution is obtained by minimization of the displacement perpendicular to the direction of the gulf (N135°E) according to the Prescott [1981] method. The representation of errors results from a Monte-Carlo analysis considering a gaussian distribution of measurement errors (J. Pagarete et al., 1989).

In the principal strain representation (Figure 4), the mean strain tensor for every triangle or subarea of the network is calculated for the interval 1982-1986. The errors are also shown by the Monte-Carlo method.

From the network geometry and the results of Figures 3 and 4 we distinguished four regions:

1. In the Canal de Ballenas area a dextral strike-slip movement of about 17 ± 4 cm is evident in the N135° E direction, between Angel de la Guarda Island and the Baja California peninsula.
2. In the Canal Sal-si-Puedes and in the area west of San Esteban and San Pedro Martir islands, very small deformations occurred and, in any case, remain within the range of the estimated errors.
3. In the southeastern part of the network a dextral shear deformation is identified with a N133° E direction between the central gulf islands and the Sonoran coast. A relative displacement of about 23 ± 12 cm is measured.
4. In the northeastern area of the network a deformation pattern similar to the southeastern and northwestern parts is obtained but with larger incertitude due to weak geometrical constraints.

According to these raw geodetic interpretations, the deformation cannot be attributed to a simple strike-slip movement along a single fault line. Either there is a dextral shear occurring along several discontinuities (or fracture zones), or the deformation is distributed across a broad active zone. In any case, the lack of deformation within the southwestern part of the network should be opposed to the activity registered in the northwestern part.

An estimation of the relative motion between the Sonoran coast and the Baja California peninsula is obtained from the mean of the relative displacements in the direction of the gulf, between stations PI, PT and SN, on one hand, and stations EB, AS and LA, on the other hand. The mean displacement is estimated to be about 32 ± 12 cm during the observational interval, e.g., about 8 ± 3 cm/yr.

THE NEOTECTONIC FRAMEWORK

Geodynamic Evolution

Kinematic reconstructions mainly based on the analysis of magnetic anomalies in the Pacific plate led to a widely accepted model of geodynamic evolution of northwestern Mexico [Atwater, 1970; Karig and Jensky, 1972; Moore, 1973; Colletta et al., 1981; Mammerickx and Klitgord, 1982; Moore and Curray, 1982]. This model may be summarized as follows :

In Oligocene and early Miocene times the East Pacific Rise was located west of the future Baja California peninsula. The subduction of the Farallon plate under the North American plate produced an intense volcanism (the "Comondu Formation" in southern Baja California and the Sierra Madre Occidental volcanics).

During the Miocene, as the East Pacific Rise approached the subduction zone, a large NE-SW extension developed in the Basin and Range province and produced numerous NW-SE elongated troughs. The westernmost grabens were partly invaded by seawater and formed the "protogulf" of California.

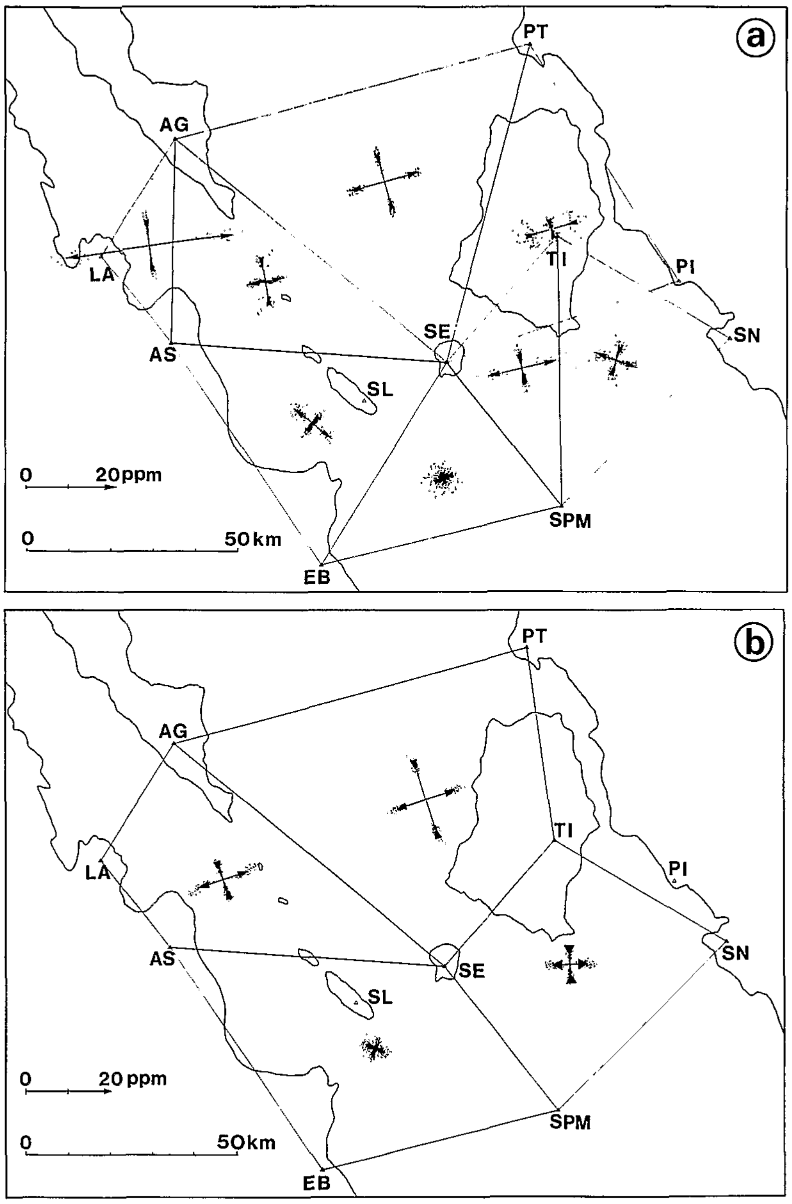

Fig. 4. Principal components of strain tensors estimated from geodetic data. (a) for individual triangles of the geodetic net, and (b) for selected polygons. As in Figure 3, the representation of errors is obtained by a Monte-Carlo method.

In mid-Pliocene times, when the East Pacific Rise merged with the subduction zone (approximately 3.5 m.y. ago), the Pacific/North American plate boundary jumped from the western margin of Baja California to the protogulf area. The NW-SE trending transform plate boundary located west of the peninsula (Tosco-Abreojos fault zone) became almost inactive. The new plate boundary was approximately parallel to the dominating NW-SE trending structural fault pattern of the "protogulf" of California; as a result, numerous preexisting faults were reactivated.

During the Quaternary the peninsula of Baja California has been moving toward the northwest relative to the North America mainland, with a mean velocity of about 6 cm/y.

Tectonic Events and Paleostress Orientations

An analysis of late Cenozoic tectonics allows us to constrain the distribution of fault movements and mechanisms. Fault analyses have been carried out on both sides of the Gulf of California and in some islands of the gulf. These studies led to a reconstruction of the late Cenozoic stress regime in the central gulf

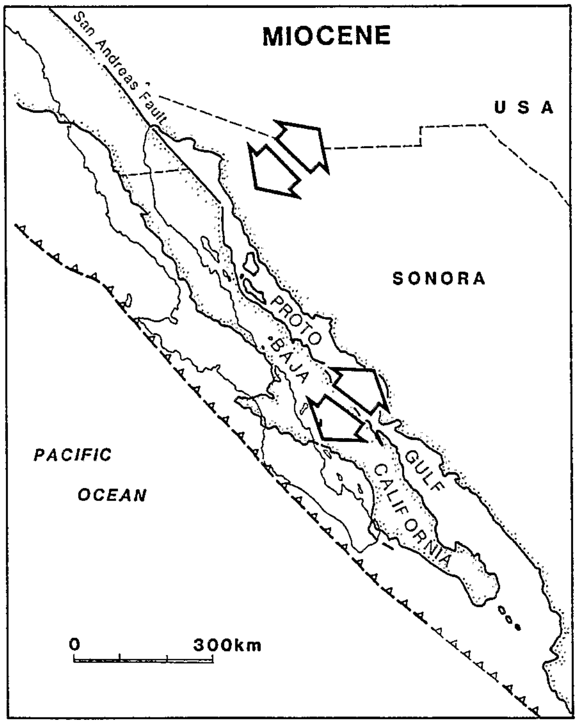

Fig. 5. Neotectonic data for the late Miocene; extension as observed in NW Sonora and east central Baja California, the former plate boundary and reconstruction of the protogulf of California.

surroundings [Angelier et al., 1981; Colletta, 1981; Colletta et al., 1981; Colletta and Angelier, 1983]. The methods used to reconstruct paleostress trajectories through fault slip analysis have been described elsewhere [Angelier, 1984]. Other methods used to determine the deformation (instead of stress) related to past tectonic events, are difficult to apply in most areas because they require the precise value of each fault offset in addition to orientation data [Gauthier and Angelier, 1985].

Most of the fault slip data have been collected in various Cenozoic rocks: the "Comondu volcanics", the Pliocene sediments of several small basins along the Baja California coast, and Quaternary continental or marine deposits. Two contrasting tectonic regimes have been clearly identified :

First, a major extension of Upper Miocene age was characterized by a least principal stress σ_3 oriented WSW-ENE (Figure 5) and by a large amount of extension which produced tilted blocks bounded by NW-SE trending dip-slip normal faults. In some areas (northwestern Sonora, Nevada, and Arizona) this amount of extension reached locally up to 100%. In such places the block tilting has been larger than 45^0 and was often associated with low-angle detachment faults. This first major event was probably related to a thinning of the lithosphere. Close to the Miocene-Pliocene boundary, the "protogulf" area was already subsiding.

The second tectonic regime (Figure 6) is characterized by the association of strike-slip and oblique to dip-slip normal faults. The first occurrence of large strike-slip movements is probably Pliocene in age; it appeared along the western coast of the gulf where the development of marine basins (Santa Rosalia, Loreto) has been controlled by NNW-SSW trending faults with strike-slip as well as dip-slip components of motion. This regime is not limited to the Gulf of California area but has also been recognized far inland in the Sierra Madre Occidental [Chaulot-Talmon, 1984] and in the Basin and Range province [Zoback et al., 1980]. The two contrasting mechanisms (strike slip and pure extension) display the same E-W direction of least principal stress σ_3 (Figures 5 and 6).

These two major stress patterns have been distinguished in Figure 6. However, during Pliocene and Quaternary times, a given fault may have been reactivated several times, according to various alternating dip-slip and strike-slip motions. This complex succession of contrasting events corresponds to a state of stress close to an axial extension ($\sigma_1 = \sigma_2$), with a stable σ_3 axis oriented E-W and permutations of σ_1 and σ_2 stress axes. The importance of strike-slip movements relative to dip-slip normal faulting has been increasing with time [Angelier et al., 1981].

Major Fault Lines

As evidenced by bathymetry and seismic profiling [Moore, 1973; Bischoff and Henyey, 1974], the structural pattern in the Gulf of California is controlled by a series of straight parallel features, generally oriented N140^0 E. These fault lines belong to the transform fault system which connects the San Andreas Fault (to the north) to the end of the East Pacific Rise (to the south). These transform faults bound several rhombic basins, which are often considered as pull-apart spreading centers (Figure 1).

Focusing on the central part of the Gulf of California where the geodetic network has been set up (Figure 7), the major identified fault zones are located along the Baja California coast between the peninsula and Angel de la Guarda and San Lorenzo islands (Canal de Ballenas and Canal Sal-si-Puedes). This major fault line, which runs N125^0 -140^0 E, is marked by a 700-to 1500 -m-deep narrow valley bounded by steep scarps. A small rhombic-shaped basin, about 1100 m deep, located east of Bahia de los Angeles separates the Canal de Ballenas from the Canal Sal-si-Puedes; this feature is interpreted as a small pull-apart basin which interrupts the fault zone. East of San Lorenzo Island a deep basin is bounded by two fault scarps which can be followed from the San Pedro Martir basin to the southern tip of the Angel de la Guarda Island (Figure 7). The westernmost fault probably cuts through the narrow high between San Lorenzo and Angel de la Guarda

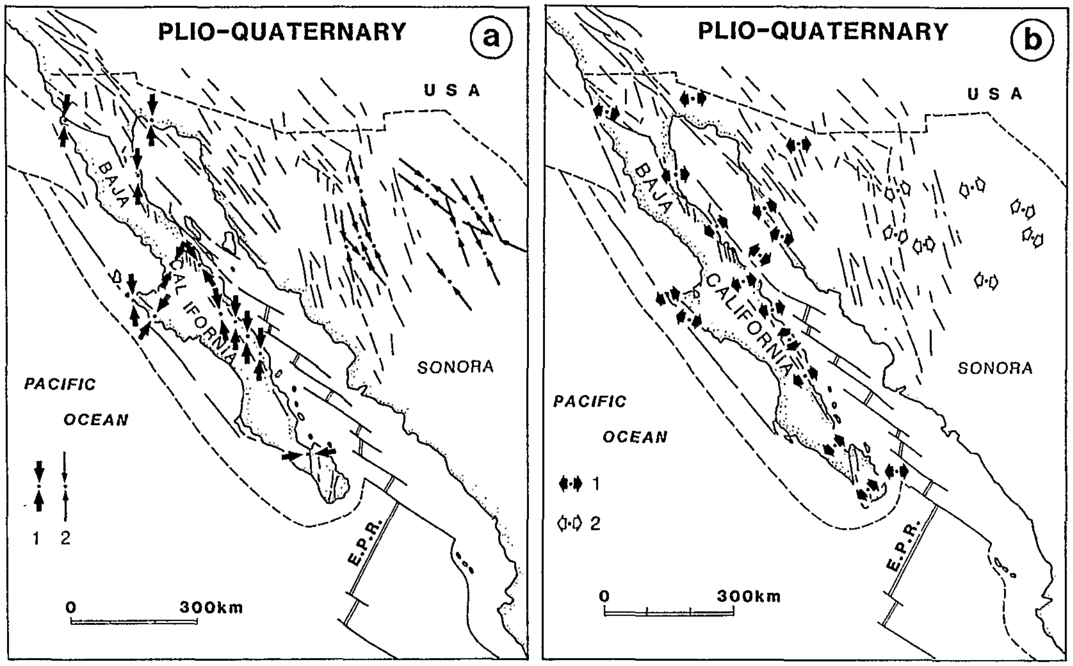

Fig. 6. Neotectonic data for the Plio-Quaternary; extension observed in many sites in NW Mexico. (a) predominantly normal faulting (arrows indicate σ_3 azimuth), data from Colletta et al. [1981]. (b) predominantly strike-slip faulting (arrows indicate σ_3 azimuth), data from Chaulot-Talmon [1984].

islands, while the eastern one seems to die out on the eastern margin of the Angel de la Guarda Island.

In the eastern part of the central Gulf of California, to the southwest of Tiburon and San Esteban islands, two other prominent fault zones, also striking NW-SE, have been described [Bischoff and Henyey, 1974; Sanchez et al., 1985]. Along the Sonoran margin, active faults are not well expressed (Figure 7), and sediments which drape the gently west dipping slope look generally undisturbed.

On land, recent tectonic activity produced fault scarps in Quaternary deposits. Fault activity is often associated with sag ponds or "playas" like Playa San Bartolo east of Punta Tepoca (PT) on the Sonoran side of the gulf. On the Sonoran coast the pattern of recently active faults is much more regular; it involves a predominant NW-SE direction and both oblique slip and dip-slip mechanisms.

In the Bahia de los Angeles area on the Baja California peninsula, N-S trending faults which bound the westerly tilted blocks of Punta Roja and Punta Animas had a recent dip-slip activity, as evidenced by fault scarps cutting Quaternary alluvium [Colletta and Angelier, 1983]. To the south these two normal faults merge with a NW-SE fault which has also been active during the Quaternary times. This fault arrangement indicates recent dextral strike-slip motion along the NW-SE fault, with pure E-W extension between Las Animas (LA) and Bahia de los Angeles.

In the islands of the central gulf the fault pattern is more complex since several fault sets have been active during the last 5 My. On Tiburon Island, three sets may be distinguished : N-S, NW-SE, and NNE-SSW trending faults. All sets display pure dip-slip or oblique slip motions, in agreement with the regional stress pattern (that is, σ_1 is N-S or vertical and σ_3 is E-W). But on San Esteban Island, most of the faults have a NE-SW azimuth and indicate a NW-SE extension; this particular orientation probably reflects a pull-apart type mechanism rather than the regional extension [Colletta and Angelier, 1983].

Thus in the central Gulf of California area, as more generally in northwestern mainland Mexico, the general neotectonic fault pattern is principally controlled by NW-SE and N-S trending faults. However, the fault distribution widely varies from place to place; this suggests that the gulf system is not a simple pattern of strike-slip faults offset by pull-apart basins but rather an assemblage of independent blocks limited by inherited, or recently formed, boundaries.

SEISMIC ACTIVITY

Most of the earthquakes registered in the Gulf of California area (Figure 8) are related to the strike-slip motions along right-lateral transform faults [Sykes, 1968; Molnar, 1973; Reichle et al., 1976]. The magnitude M_s of the larger seismic events is in the range 5 to 6.5. In the pull-apart basins the seismic activity is generally characterized by swarms of lower magnitude

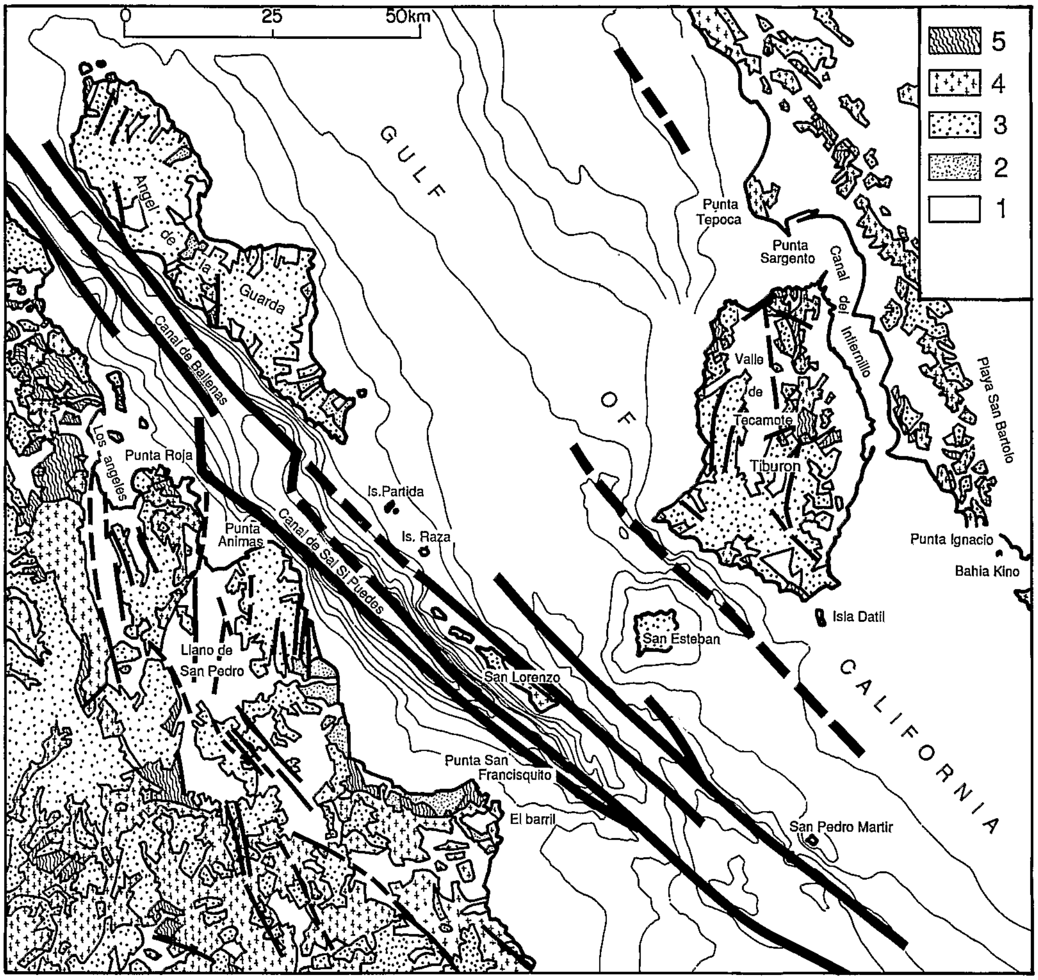

Fig. 7. Schematic structural geology of the central Gulf of California area, modified from Gastil and Krummenacher [1974] and Gastil et al. [1975]. (1) Quaternary, (2) Pliocene, (3) Tertiary volcanics, (4) Batholitic rocks and (5) Pre-batholitic rocks.

and corresponds mainly to normal fault mechanisms [Reichle, 1975; Reichle and Reid, 1977].

The instrumental seismicity of the Gulf of California is known either from the catalogue of the International Seismological Center (ISC), from local networks located outside the northern part of the gulf, or from some temporary stations. This variety of seismic networks results in a relative inhomogeneity of data and in possible bias in locating the epicenters. For example, the Canal de Ballenas earthquake ($M_s = 6.5$) of July 8, 1975, was relocated by Munguia et al. [1977] 30 km southward with respect to the previous ISC determination.

In the axis of the gulf the shallow depth of the foci (<10 km) suggests that the brittle layer of the upper lithosphere is relatively thin. Gravimetric and seismic refraction data also show that under the gulf the crust is thinner than below the surrounding areas of Baja California and Sonora [Phillips, 1964; Harrison and Mathur, 1964; Calderon Riveroll, 1978].

A source mechanism analysis from long-period body waveform inversion was recently carried out by Goff et al. [1987] for 19 large earthquakes in the Gulf of California. The principal results of this study indicate a predominantly right-lateral strike-slip mechanism for 15 of the events located close to the inferred plate boundary between Pacific and North American plates in the gulf. Three other events within the gulf show extensional mechanisms. The epicentral position of these events include a correction to account for the systematic mislocation by ISC. The focal mechanisms described by Goff et al. [1987] are consistent with the Plio-Quaternary paleostress pattern previously discussed (Figures 6 and 8).

In the region covered by the geodetic network, the 1982-86 seismicity has been moderate (Figure 8 inset), and does not differ from that observed in earlier equivalent time intervals. It may be noted that no significant earthquake has been registered in the Canal de Ballenas. Reichle et al. [1976] noticed that the seismic

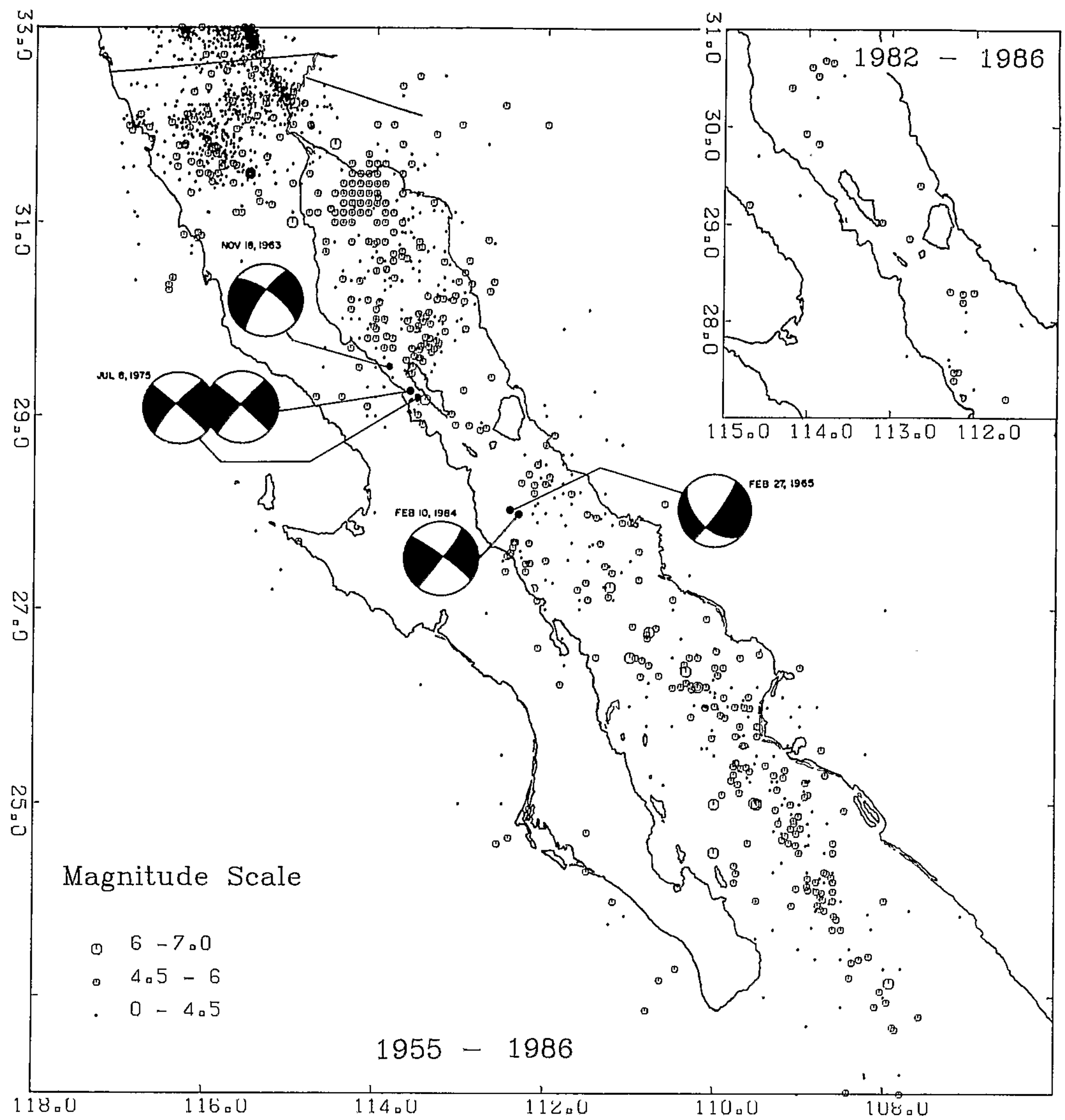

Fig. 8. Seismicity of the Gulf of California between 1955 and 1986 from the International Seismolocical Center catalogue. Focal mechanisms and relocated epicenters (solid circles) are from Goff et al. [1987]. Inset: 1982-1986 seismicity in the central part of the gulf.

activity of the transform fault located between Guaymas and Delfin basins was particularly weak since 1955. The only important earthquake occurred in the Canal de Ballenas on July 8, 1975, and corresponds to a reactivation of a 50-km-long transform fault segment [Munguia et al., 1977]; there has been no evidence of motion along the remaining 240 km of the same transform fault. In the eastern part of the central gulf (east of the Angel de la Guarda-San Pedro Martir axis), the 1982-86 seismic activity remained moderate ($M_s < 5.6$) and should not have produced coseismic movements large enough to be identified by geodetic surveys.

DISCUSSION

In a comparison of deformations interpreted on geodetic and neotectonic bases, differences in space and time scales must be kept in mind. Neotectonic data are obtained from numerous local fault slip measurements which provide access to reconstructions of paleostress patterns during periods of hundred thousands, or millions, of years. On the contrary, geodetic data result from an estimation of the mean strain field between several points of a network, during a period of few years.

Strike-Slip Motion Versus Extension

The geodetic results (Figures 3 and 4) suggest that most of the deformation corresponds to a dominating strike-slip mode within a general NW-SE dextral shear strain pattern and that actual extension (related to crustal thinning) plays a moderate role in the area under investigation.

In terms of reconstructed paleostress directions using fault slip data analyses, the recent Plio-Quaternary period has been dominated by regional E-W extension and N-S compression (Figure 6). This pattern is consistent with the present directions of maximum lengthening (N80°E) and of maximum shortening (N170°E), indicated by the geodetic analysis (Figure 4), and with the analysis of earthquake mechanisms [Goff et al., 1987].

In order to define more accurately the role of strike-slip and extensional deformation within the pattern of present day motions shown in Figures 3 and 4, one may examine separately the components of displacement, respectively, parallel (N135°E) and perpendicular (N45°E) to the major transform fault zones. This is done by using the displacement vectors of Figure 3. First, five stations (SE, SL, EB, SPM, and AG) in the gulf, plus EB on the Baja California coast, do not display large amounts of relative displacement in this reference system. Second, the two stations of Baja California peninsula along the Canal de Ballenas (LA and AS) display similar components of northwestern displacement (about 12 cm, relative to San Esteban). Third, although the displacement vectors of the three stations along the Sonora coast (PT, PI, and SN) display large differences in amplitude and orientations, these stations are shifted to the southeast by 22 cm on average (relative to SE). Finally, the single station on Tiburon Island (TI) displays an intermediate southeastern component of displacement in this reference frame. In spite of discrepancies (especially on the Sonoran side), one may consider that most of the 1982-1986 dextral strike-slip motion is concentrated between three major areas: the Baja California peninsula to the west (LA-AS), the central gulf islands (SE, SL, SPM, and AG) plus a portion of the peninsula (EB), and Sonora to the east (PT, PI, and SN). The displacement vector TI suggests that the actual displacement pattern is complex, but the limited accuracy and the poor density of the network cannot provide further information on the actual distribution of present deformation.

The remaining components of displacement vectors (i.e., perpendicular to the major transform trends), show small average magnitudes. The E-W displacement between stations LA and AS is in agreement with the presence of Quaternary normal faulting with E-W extension across N-S trending faults near Bahia de los Angeles [Colletta and Angelier, 1983]. However, the geometrical constraints on the displacement of LA are weak and need to be reassessed in a future geodetic survey.

The principal conclusion of this part of the discussion is that the dextral strike-slip motion is predominant through a large area of the Gulf of California, while E-W extensional strains remain of weak magnitude.

Motion at Plate Boundary and Strain Accumulation

The model hypothesized by Reid [1910] after the San Francisco earthquake in 1906 remains the basis of seismotectonic studies and has been verified (at least at the first order), particularly on the San Andreas fault system, which is the northern continuation of the Gulf of California. The relative movement of plates gradually accumulates elastic strains in a rather large region on both sides of the boundary; the energy is episodically released by strong earthquakes breaking the upper brittle lithosphere. At depth, below 15 km, it is generally admitted that the motion occurs aseismically and continuously in the ductile zone [Prescott et al., 1979].

From geodetic observations that were carried out in the San Andreas fault area for several decades [e.g. Savage et al., 1979] or from modeling [Turcotte and Spence, 1974; Nur, 1981; Prescott and Nur, 1981], the width of the elastic strain accumulation zone is about 20 km in central California and broadens to about 60 km, at least in southern California [Scholz and Fitch, 1969]. In this area the plate motion is probably taking up over several individual faults as well as a diffuse deformation zone. The same situation occurs in the northern Gulf of California, where several active faults are invoked [Goff et al., 1987; Ortlieb, 1987] to accommodate the plate motion (Agua Blanca, San Miguel, and Cerro Prieto faults).

In the central Gulf of California the gravimetric and seismic profiling data [Phillips, 1964; Calderon Riveroll, 1978], as well as the neotectonic data, indicate the existence of a thinned crust in comparison with the continental borders of Baja California and Sonora coasts. This hypothesis is supported by the estimation of thickness of the brittle seismogenetic layer, estimated from the seismic data [Goff et al., 1987] to be in the range of 5-6 km. Consequently, we may assume a width of at least 100 km for the zone of weakened lithosphere available for strain accumulation during the seismic cycle induced by the plate motion. It is then possible to interpret that at least an important part of the geodetically observed motion is the result of a spatially distributed elastic strain accumulation across the entire gulf. This interpretation is strengthened by the lack of a major earthquake within the geodetic network area during the observational time interval.

It is generally recognized that large earthquakes are responsible for at least a notable part of the release of the strains accumulated by the relative plate motion across the plate boundaries. Numerous detailed studies have been carried out in order to investigate the seismic potential along the plate boundaries in an earthquake prediction perspective (Kelleher et al. [1973] and Ohtake et al.[1977], among others). These studies show that localized segments along the tectonic plate boundaries are successively ruptured during the seismotectonic process, remaining unbroken areas, are good candidates for the next strong earthquakes. During the interseismic interval the principal fault of these areas generally remains locked or small earthquakes occur that cannot release the total of the strain accumulation [Carlson et al., 1979; Harris and Segall, 1987]. Such a mechanism is required to explain the lack of motion on the Canal Sal-si-Puedes segment of the plate boundary.

On the other hand, different release mechanisms of the accummulated strains may coexist along the same shear plate boundary, as is well known along adjacent segments of the San Andreas fault in northern California. For example, the Parkfield segment is limited on the northwest by a creeping zone where aseismic slip occurs and on the southeast by a nonslipping segment which has been locked since the 1857 M = 8 earthquake [Thatcher, 1983; Harris and Segall, 1987]. A similar process may explain the 17 ± 4 cm of dextral motion that occurred in the Canal de Ballenas during the interval between geodetic measurements, when the contiguous southern segment remained undeformed.

The relative velocity between the two sides of the Gulf of California obtained from the geodetic results during the 1982-1986 interval, is found to be about 8 ± 3 cm/yr. This result is consistent with previous estimations of the relative rate of movement in this region between the North American and Pacific plates [Larson et al., 1965 ; Reichle et al., 1976 ; Ness et al., 1985 ; Demets et al., 1986], but the significance, at larger time scale, of this comparison remains limited, principally because of the small time interval (4 years) between geodetics surveys.

The difference between the results obtained from independent neotectonic analyses and geodetic analyses in the central Gulf of California is almost entirely accounted for by the difference between the time scales involved. The migration of active zones related to strain accumulation and seismic cycles within the broad plate boundary zone remains undetectable in the analysis of Plio-Quaternary tectonics, whereas it strongly influences the location of the present deformation, identified by geodetic means.

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