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# Preliminary tight-fit Neogene paleoreconstruction of Baja California Peninsula, Mexico

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**RESUMEN**

Una reconstrucción de las posiciones relativas de la península y la parte continental de México, obtenida por un método computacional puramente geométrico, es empleada para investigar las posibles modificaciones y la segmentación de la península. La reconstrucción considera la apertura del Golfo y la extensión asociada al proto-Golfo, lo que resulta en un arreglo apretado de la península y el noreste de México. No se observaron modificaciones mayores asociadas por ejemplo al movimiento de segmentos del margen o fallamiento trans-peninsular (mayores a las zonas de hueco y traslape en la reconstrucción). Las zonas mayores de hueco en la reconstrucción corresponden a las cuencas Wagner, Delfin y Sal si Puedes en el norte y a la Bahía de La Paz en el sur. El hueco en el norte corresponde a las regiones de la cuenca Pliocena del Bajo Colorado y las islas de Tiburón y Angel de la Guarda y el hueco en el sur corresponde a la Bahía de La Paz y las islas Espíritu Santo y Cerralvo. Rotaciones de bloques y desplazamientos laterales dentro de la zona de extensión pueden acomodar parte de las discrepancias en las zonas de huecos en la reconstrucción. La zona mayor de traslape corresponde a la región de Los Mochis sobre la región de Loreto en Baja California Sur. La reconstrucción es empleada para estimar los parámetros de rotación para los últimos 16 Ma. El polo de rotación se localiza en 32.0°N, 107.5°W y el desplazamiento angular es de 2.64 por Ma; esto corresponde aproximadamente a un cociente de apertura en la boca del Golfo de 3 cm/año. El polo de rotación y el desplazamiento angular integran la fase inicial de extensión y la apertura del Golfo asociada al esparcimiento del fondo oceánico en el sistema de dorsales y cuencas.

**PALABRAS CLAVE:** Península de Baja California, Golfo de California, paleoreconstrucción, márgenes desplazadas, proto-Golfo de California, extensión cortical.

**ABSTRACT**

A preliminary paleoreconstruction of the relative position of Baja California peninsula with respect to mainland Mexico prior to the opening of the Gulf of California is obtained by a geometric-based computational method. The reconstruction restores the Gulf rifting and the proto-Gulf extension, thus resulting in a tight fit of the peninsula against northwestern Mexico. No major modifications of the margins have occurred since proto-Gulf crustal extension and attenuation, break-up and Gulf opening, particularly not in the form of coast-parallel transport of margin slivers or trans-peninsular faulting. Major gap areas correspond to the Wagner, Delfin and Sal Si Puedes basins in the northern section, and La Paz Bay in the southern section. Block rotations and strike-slip motion within the extensional zone can accommodate part of the gap areas. The major overlap area corresponds to Los Mochis region of Sinaloa over the Loreto region in the peninsula. The long-term rotation parameters for the past 16 Ma of the Baja California peninsula and the North American plate are found for a best-fitting rotation pole at 32.0°N, 107.5°W and a computed angular rate of 2.64° per Ma, which corresponds to an average half-spreading rate of about 3 cm/yr at the East Pacific rise at the mouth of the Gulf. These values integrate the early crustal extension phase of the proto-Gulf and the subsequent seafloor spreading process, with the recent plate reorganization phases.

**KEY WORDS:** Baja California peninsula and Gulf, paleoreconstruction, rifted margins, proto-Gulf of California, crustal extension.

## INTRODUCTION

Since the work of Bullard *et al.* (1965), the past relative positions of continental blocks have been obtained by several computational fitting procedures. These methods of paleoreconstruction are purely geometric and in essence they depend on the absence of significant deformation at the rifted margins of the continental blocks. A 'perfect' paleoreconstruction with no overlaps and gaps implies that the blocks behaved as rigid bodies during the break-up and drift-apart process. Crustal extension, if significant, occurred in a homogeneous manner and was distributed evenly along the rifted margins. Geometry-based computational methods also test for any significant modifications of the margins, in the form of accreted terranes and lateral displacements of margin slivers.

This note is concerned with the paleoreconstruction of the Baja California peninsula and northwestern Mexico (Figure 1). Our reconstruction accounts for rifting and lateral displacements and for the early proto-Gulf extension during the Neogene. Our main interest is to investigate whether any significant modifications of the Gulf of California margins have taken place since break-up and drift of the peninsula, particularly in the form of segmentation and independent movement of parts of the peninsula. Deformation in areas adjacent to the Gulf (e.g., block rotations and strike-slip motion in the northeastern sector; Stock and

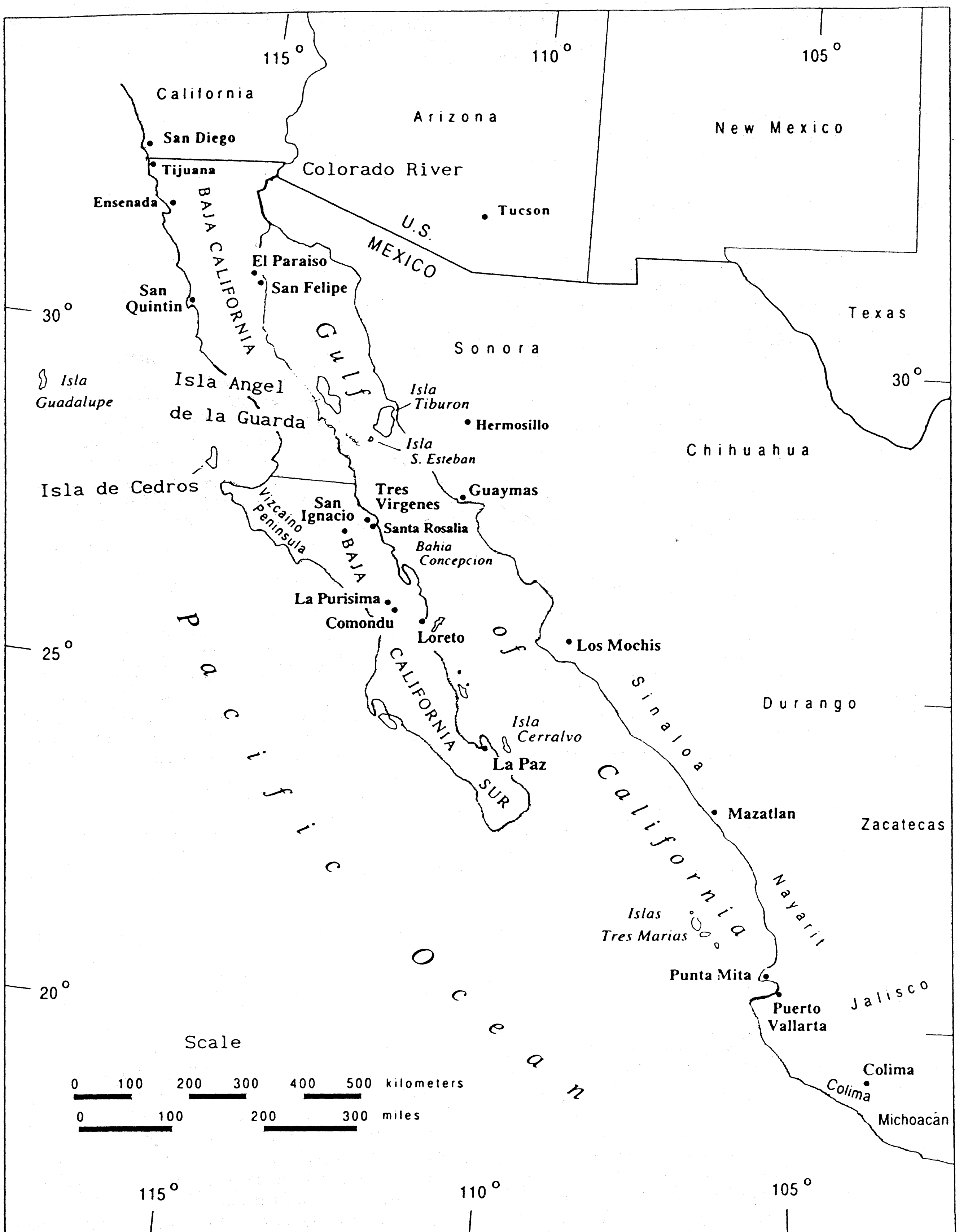


Fig. 1. Schematic map of the Baja California area showing location and names of some features and localities (adapted from Sawlan, 1991).

Hodges, 1989, 1990; Lewis, 1994) has been documented by structural and paleomagnetic studies. Our reconstruction examines any type of modifications of the margins, including sedimentary and coastal processes, internal margin deformation and crustal extension.

The paleoposition of Baja California peninsula is among the earliest problems of plate tectonics (McKenzie and Parker, 1967; Morgan, 1968). Different models have been advanced to explain the origin and evolution of Baja California (Menard, 1960; Hamilton, 1961; Kovach *et al.*, 1962; Harrison and Mathur, 1964; Karig and Jensky, 1972; Curray and Moore, 1984; Spencer and Normark, 1989; Stock and Hodges, 1989). These models support the separation of Baja California from the mainland during the Neogene. The same break-up and drift processes are also supported by other geophysical and geological studies (e.g., Lomnitz *et al.*, 1970; Thatcher and Brune, 1971; Bishoff and Henyey, 1971; Elders *et al.*, 1972; Henyey and Bishoff, 1973; Reichle, 1975; Sharman, 1976; Moore and Curray, 1982; Lonsdale, 1989; Spencer and Normark, 1989).

Magnetic anomaly fanning recorded at the mouth of the Gulf of California suggests that plate separation and crustal growth have occurred at an average rate of about 3 cm per year on each flank, with the initial separation at about 4 Ma ago (Larson *et al.*, 1968; Moore and Buffington, 1968; Larson, 1972). Several arguments against a segmented movement of the peninsula were given by Gastil *et al.* (1968). There is no confirmed trans-peninsular faulting of Neogene and younger age, and the La Paz fault cuts Pliocene or younger sediments only in the southern part of the peninsula (Normark and Curray, 1968). The Agua Blanca, San Miguel and Valle San Felipe faults are active in the northern part of the peninsula (Allen *et al.*, 1960; Stock and Hodges, 1990). Major tectonic features in the Gulf of California are illustrated in Figure 2. They correspond to a series of transform faults that separate several tectonic basins and small segments of sea floor spreading ridges.

## PRE-PROTO-GULF PALEOPOSITION OF BAJA CALIFORNIA PENINSULA

If the peninsula was detached from mainland Mexico as a unit which moved essentially without significant trans-peninsular faulting, and if Gulf crustal growth has been symmetrical, then a paleoreconstruction of the pre-rifted configuration can be obtained by using only geometric constraints.

In this paleoreconstruction the arrangement of Baja California and northwest continental Mexico prior to the formation of the Gulf was determined by means of a computer FORTRAN IV program (for further details see Urrutia-Fucugauchi, 1977). The input consisted of equally-spaced digitized data of the Baja California peninsula and Sonora-Sinaloa coastlines (95 and 135 data points, respectively). The coastline contours were digitized from the geologic map for Mexico, scale 1: 2,000 000 (López-Ramos, 1976). The program tranforms the digitized coastlines into two data sets in the wavenumber-frequency domain. The method makes use of Euler's Theorem, which states that any point or set of points on the surface of a sphere may be relocated to any other position by a single rotation about an axis passing through the center of the sphere. The intersections of the axis with the spherical (Earth) surface represent the poles of rotation. Thus, any movement on the Earth's surface can be represented in terms of a rotation pole and an angular displacement. If the time involved by the movement is known, then the displacement may be replaced by

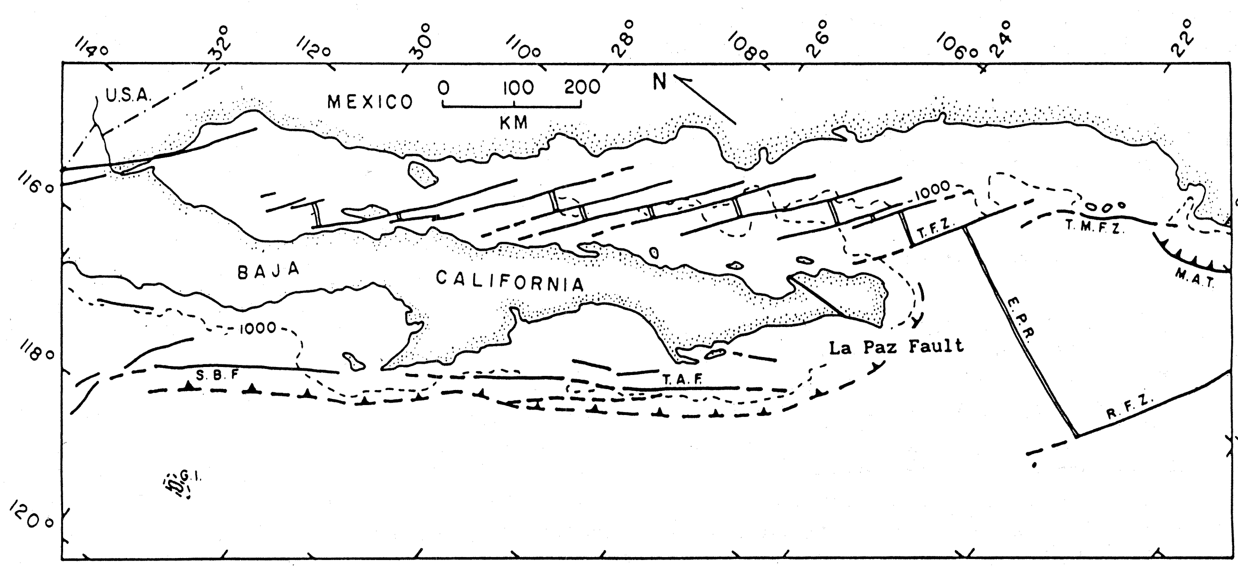


Fig. 2. Schematic simplified tectonic map of the Baja California area, showing the spreading ridge-transform fault system of the Gulf and major features off Baja and mainland Mexico (adapted from Spencer and Normark, 1989). Symbols are: T.F.Z., Tamayo fault zone; R.F.Z., Rivera fault zone; E.P.R., East Pacific rise; T.M.F.Z., Tres Marías fracture zone; M.A.T., Middle American trench; T.A.F., Tosco-Abreojos fault zone; S.B.F., San Benito fault.

an angular velocity. The rotation may represent the resultant of several rotations about successive rotation poles. The method of calculation of rotation poles is given in the Appendix. In this method, the angular displacement is undefined and should be obtained in an iterative form. For the paleoreconstruction of Baja California, the angular displacement was given in successive increments of 2.5 degrees from 0° to 15°. In addition, a cross correlation between the two series of data was carried out at each step, by using a FORTRAN IV subroutine modified from Rudman and Blakeley (1976). The cross correlation function, $\Phi_{xy}$ (f) is given by:

$$\Phi_{xf}(f) = \sum_{i,j=1}^{L,N} X_i^*(f)\, Y_j(f) \tag{1}$$

where $X_i(f)$ and $Y_j(f)$ are the Fourier coefficients of the digitized coastline functions $X(t)$ and $Y(t)$, and $X^*i(f)$ is the corresponding conjugate complex function.

The best fit minimizes the overlaps and gaps between the two contours (Figure 3). The pole of rotation is at 32.0°N, 107.5°W, with an angular velocity of about 2.64°/Ma The angle of rotation is about 10° and the displacement at the mouth of the Gulf is over 211 km. Assuming a half-spreading rate of 3 cm per year, the time of initial separation found to be is 3.6 Ma B.P. This is in agreement with the age of the oldest magnetic anomalies which can be recognized at the mouth of the Gulf between the Rivera and Tamayo fracture zones (Moore and Buffington, 1968; Larson, 1972; Moore, 1973; Urrutia-Fucugauchi, 1985; Atwater, 1989).

A reconstruction with a slightly northward position of Baja California relative to mainland Mexico results in a tighter fit, and consequently in a larger amount of overlap areas (Figure 4). The reconstructions proposed by Spencer and Normak (1989) for the peninsula at 5.5 Ma ago and for the proto- Gulf at 13.5 Ma ago are shown in Figure 5. The proto-Gulf reconstruction also results in a larger area of overlap, particularly in the La Paz block and the Loreto-Los Mochis region, as compared with our preferred reconstruction of Figure 3.

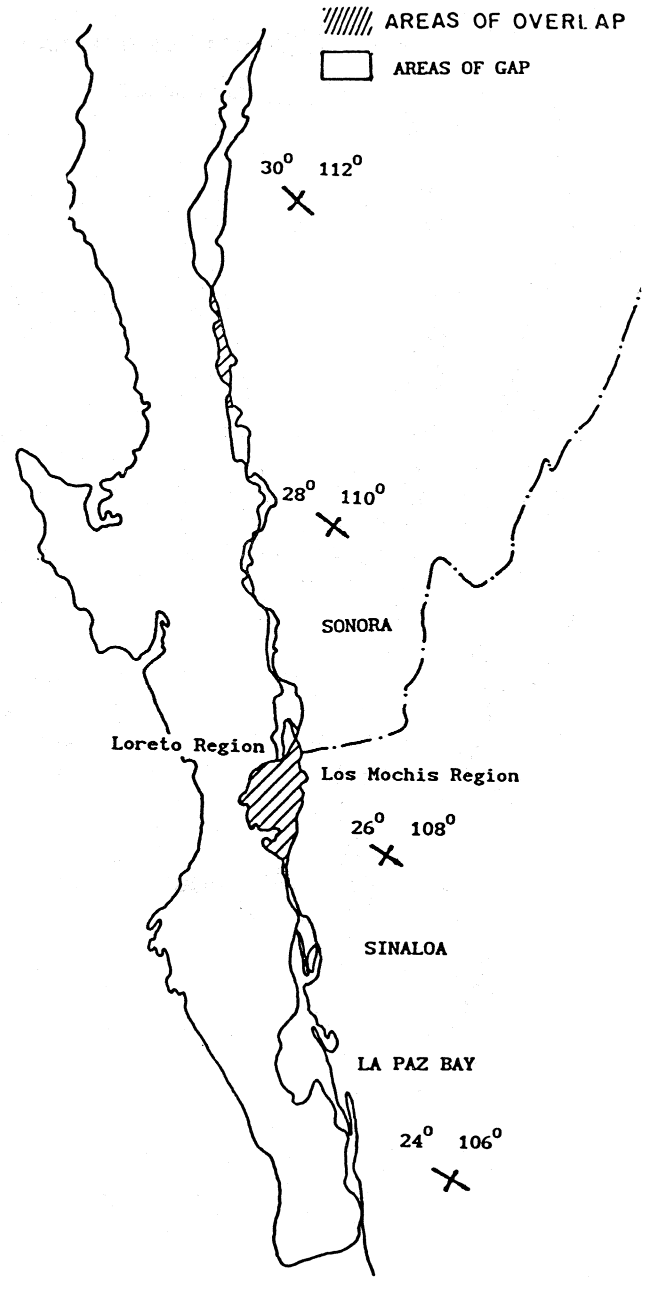


Fig. 3. Schematic representation of the assembly obtained for Baja California and mainland Mexico which is obtained on a geometric-based computational method. The paleoreconstruction restores the crustal extension and attenuation of the proto-Gulf and the subsequent rifting of the Gulf producing a tight-fit assembly.

## DISCUSSION

The present tight-fit paleoreconstruction (Figure 3) shows that it is possible to obtain a purely geometry-based assembly with relatively small gap and overlap areas which does not require either excessive lateral displacements or trans-peninsular offsets. The Baja California peninsula and mainland Mexico are treated as rigid bodies. This suggests that no significant modifications of the Gulf margins have occurred since break-up and rifting. Major gap areas lie in the Wagner, Delfin and Sal Si Puedes basins in the northern section and in La Paz Bay in the southern sector (Figure 3). The major overlap area is in the Los Mochis region of Sinaloa, over the Loreto region in the Baja California peninsula. The southern section of the northern gap corresponds to the large Tiburon and Angel de la Guarda islands, and its northern section corresponds to the Pliocene marine embayment in the lower Colorado basin (Smith, 1970; Moore, 1973). Clockwise block rotations associated with left lateral faults antithetic to the major transpressive dextral system have been documented in the northeastern sector of Baja California peninsula (Johnson *et al.*, 1983; Lewis, 1994). These block rotations accomodate part of the movement between the peninsula and the continent. The Agua Blanca and San Miguel faults account

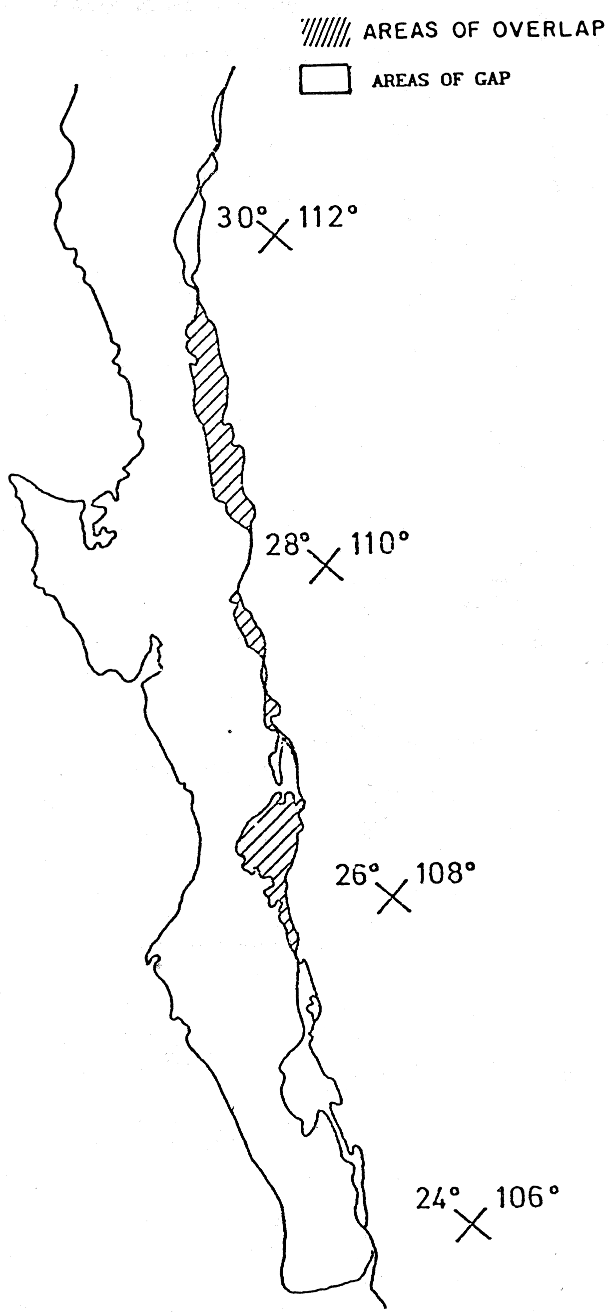


Fig. 4. Example of a paleoreconstruction that results in a tight fit with larger areas of overlap as compared with the preferred reconstruction of Figure 3 (compare also with the reconstruction of Figure 5b).

for part of the movement. Early motion along those faults may have accomodated part of the deformation (Allen *et al.*, 1960) and may partly explain the gap in the northern sector of the Gulf. The southern gap corresponds to the Espíritu Santo and Cerralvo islands. These represent regions in which modifications of the coastline and continental slope have taken place. Early episodes of crustal extension followed by plate motion reorganization may also account for the misfits, including along the Gulf (Moore and Curray, 1982; Curray and Moore, 1984) and in the Tres Marías islands (Moore, 1973; Mammerickx, 1980).

The opening of the Gulf by sea-floor spreading and dextral transform motion has resulted in some 5° clockwise rotations and about 3° northward latitudinal translations of the peninsula with respect to northern Mexico (Stock and Hodges, 1989). In the northern part of the Gulf, dextral transform displacements are in the order of 300 km. Stock and Hodges (1990) have proposed that the Baja California peninsula was a continental sliver being deformed between the San Benito-Tosco-Abreojos fault zone and the Gulf extensional province. Transfer of Baja California from the North American to the Pacific plate was then a gradual process during the past 12 Ma. The shear deformation estimated by Lewis (1994) from paleomagnetic studies (clockwise block rotations) in the northeastern part of the peninsula is in the order of 34±6 km (about 11 % of the 300 km dextral displacements). The amount of deformation is consistent with the limits estimated from the geometric reconstruction in terms of the gap/overlap areas, which are in the order of < 40-50 km (some 13-16 % of the dextral displacements in the northern sector of the Gulf). Lewis and Stock (in Lewis, 1994) estimate an average Pliocene to Recent dextral shear rate for northeastern Baja California of about 5±1 km/Ma, which is consistent with fault slip rates (Agua Blanca fault).

Simple restoration for rifting during the past 5.5-3.5 Ma is well known to leave a wide elongated gap with depths in excess of 1000 m (Figure 5a). This deep gap has been called the proto-Gulf of California (Karig and Jensky, 1972), caused presumably by crustal extension during the Neogene. The characteristics of the extension are poorly constrained and were probably like those in the Basin and Range province, in an east-west direction as suggested by old normal faults (Dokka and Merriam, 1982; Curray and Moore, 1984). The misfit in the southern sector due to the extension is in the order of 150 km (Figure 5a). Spencer and Normark (1989) have proposed a reconstruction that accounts for the crustal extension (Figure 5b) and incorporates additional constraints from an assumed initial configuration of faults (i.e., continuity of the Tosco-Abrojos fault and Tres Marías escarpment and of the old subduction zone along the entire margin). Their reconstruction (Figure 5b) results in significant overlap, with segments of the peninsula onto mainland Mexico (southern tip of Baja) and viceversa (Los Mochis region of Sinaloa onto the peninsula). This problem, and the lack of evidence for strike-slip faulting north of Tres Marías, led Spencer and Normark (1989) to conclude that there was no continuity of the Neogene transform plate boundary. The reconstruction obtained in this paper minimizes the areas of overlap and gap (Figure 3), and predicts a northern position of the peninsula relative to mainland Mexico. Thus it brings the San Benito fault, Tosco-Abrojos fault and Tres Marías scarpment into alignment and also allows for continuity of the old trench system.

The mouth of the Gulf is one of the most intensively studied areas worldwide. However, it still presents important problems, particularly during its early stages of development. Ness *et al.* (1981) studied the marine magnetic

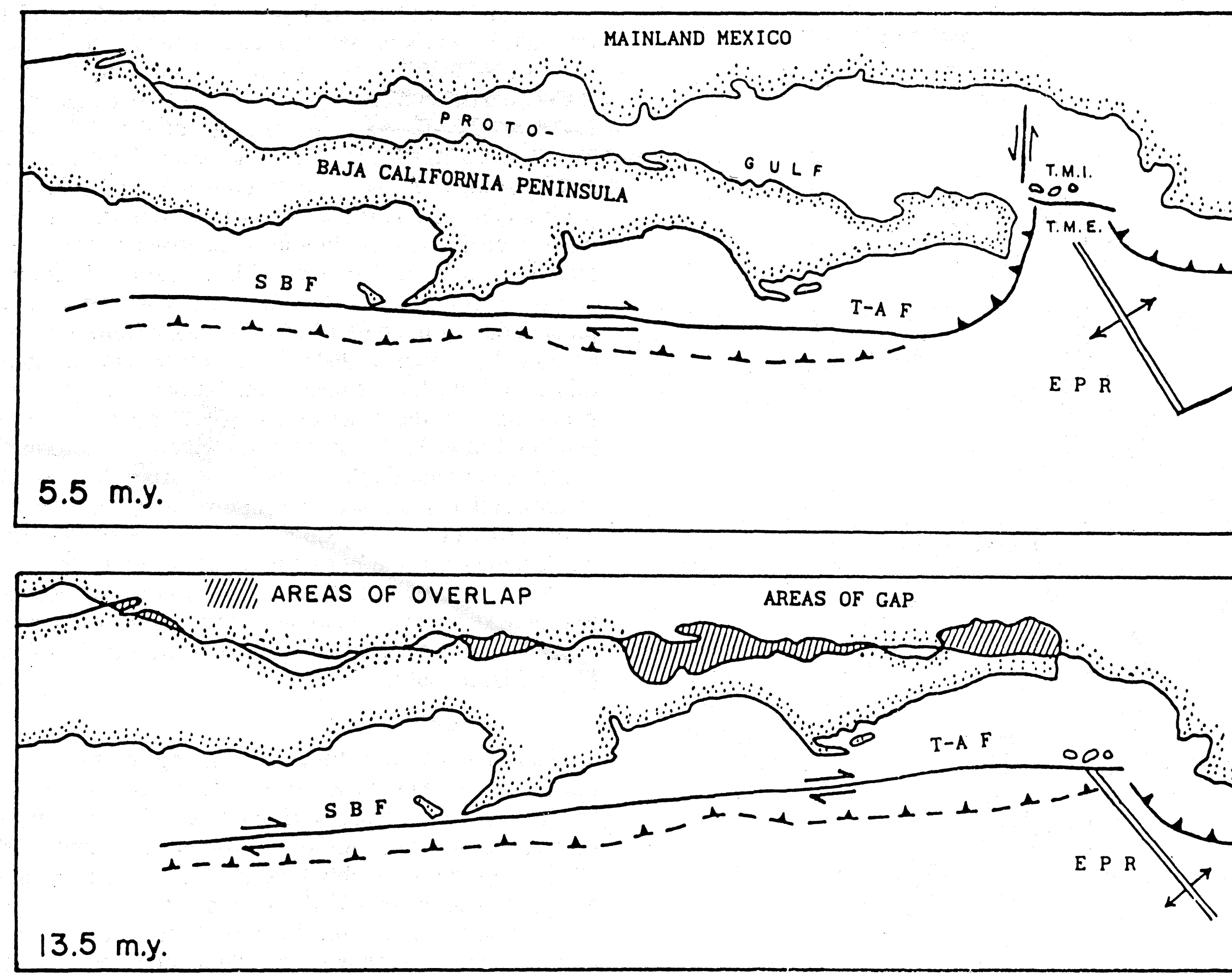


Fig. 5. (a) Paleoreconstruction of the Baja California peninsula at 5.5 Ma ago, showing the elongated gap region interpreted as the proto-Gulf of California. The approximate location of the San Benito fault (S B F), Tosco-Abrojos fault (T-A F), Tres Marías escarpment (T M E) and the trend of the trench system (dashed and continuous thrust curve) are shown for reference. (b) Paleoreconstruction for 13.5 Ma ago, closing the proto-Gulf of California. Note the large overlap areas and the linear trend of the San Benito, Tosco-Abrojos and Tres Marías fault system (Figure adapted from Spencer and Normark, 1989). Compare with the reconstruction of Figure 3.

anomaly patterns and identified crust as old as 7.3 Ma, which contrasts with the ages of 4 to 3.6 Ma estimated for the old crust at the tip of Baja California. They suggested that northwestward subduction occurred beneath the tip of the peninsula. Spencer and Normark (1989) examined the possible presence of a continental block located to the south of Tres Marías Islands which was subjected to attenuation and foundering. This resulted in the anomalously shallow María Magdalena rise. Mammerickx (1980) analyzed the possible occurrence of an early episode of seafloor spreading, between about 6 Ma and 3.5 Ma ago. This early spreading process rifted crust at the foot of Tres Marías Islands from Baja California.

Some questions related to the contour similarity between the Baja California and northwestern Mexico coastlines remain. The coastlines are used to obtain a tight-fit paleo-reconstruction that effectively restores the Neogene proto-Gulf extension and which could permit evaluation of any modification of the rifted margins. Over periods of the order of a few thousand to a million years coastlines are often unstable and their shape and position change. Detailed studies of the marine terraces of Baja California, Sonora and Sinaloa indicate tectonic uplift and sea level variations which have shaped the present coastlines around the Gulf (Ortlieb, 1980). The continental coastline during early Pliocene was probably displaced some 10-30 km. During glacial times the sea level was significantly lower than at present, and coastal areas emerged. These modifications may explain part of the misfit observed in the computer solution. If so, we may impose constraints on maximum changes during the Pleistocene and Holocene. Bullard *et al.* (1965) suggested that the edge of a continent lies somewhere on the continental slope, where the sea bottom falls rather abruptly. This theoretical edge is about 2 kilometers below sea level. Le Pichon *et al.* (1977) argued that there is no accurate selection procedure to obtain an assembly of continental blocks: "it becomes clear that the only rationale for choosing a given isobath as the location of the original continental edge is the absence of other clear-cut criteria". If the continental slopes are similar to the coastlines, in a first-order approximation this reconstruction should estimate well the relative positions.

The edges of continental blocks are reconstructed, e.g. in Bullard *et al.*, (1965), on the strength of the bimodal distribution of global topography for land and oceans and on estimations of subsidence rates at passive continental margins. Subsidence rates beneath sedimentary prisms at passive margins have exponential time constants of some 50 Ma, similar to the time constants for the oceanic lithosphere (Sleep, 1971). Margin subsidence is thus thermally controlled and isobaths representing the continent-ocean transition are time dependent. In general, the continental edge of a young rifted margin is shallower than for an old margin (where the sedimentary prism may be thicker). In the case of the Red Sea, a rifted basin less than 50 Ma old, McKenzie *et al.* (1970) showed that the Arabian and African coastlines are the best isobaths to represent the continental edges in the paleoreconstruction. The Gulf of California is still younger and subsidence effects can be assumed to be less significant. Hence Gulf coastlines may provide good first-order estimates of the pre-rifted margins.

Paleoreconstructions that incorporate additional constraints from tectonic, structural and marine geophysical studies should be preferred over those based solely on geometric constraints. The main purpose of our paleoreconstruction (Figure 3) is in the evaluation of significant alterations of the rifted margins since proto-Gulf extension and Gulf opening. It is considered a good first-order approximation in terms of the relative positions of the peninsula and of northern Mexico. Its accuracy can be tested by incorporating constraints from structural features, radiometric dates, matching of geologic provinces or tectonic lineaments, etc.

The distribution of radiometric dates of Cretaceous intrusives in the northern sector (Krummenacher *et al.*, 1975; Anderson, 1977; Anderson and Silver, 1977) is shown in Figures 6, 7 and 8. Ages of magmatic activity were estimated by U-Pb dating in zircons and covered the interval from about 120 Ma to 60 Ma. The arrangement of the U-Pb dates along two profiles seems to agree well with the paleoreconstruction of Figure 3. Tie points provided by matching some units (e.g., conglomerates) on the base of lithology, age and deformation have been mentioned by Abbott and Smith (1989) and Gastil (1993). They provide constraints for the northward displacement of the peninsula.

This reconstruction provides a simple basis on which structural lineaments and geophysical and geological features can be compared. Additional constraints resulting from these comparisons may improve our knowledge of the past assembly and the framework of the Gulf of California opening. For instance, the geographical distribution of ore deposits in northern Mexico can be interpreted in terms of recent plate tectonics (e.g., Sawkins, 1972;

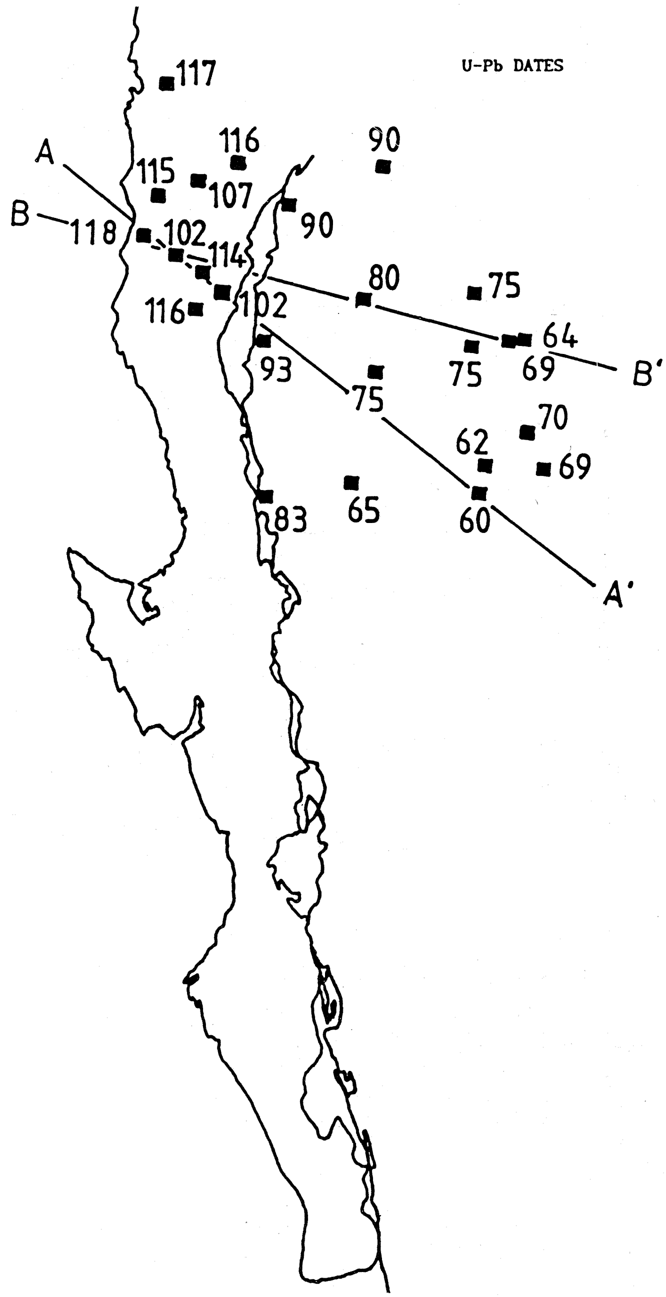


Fig. 6. Distribution of radiometric dates of igneous rocks plotted in the paleoreconstruction of Figure 3. Dates are taken from Anderson (1977) and Anderson and Silver (1977) and correspond to U-Pb determinations on zircons from monzonites, granodiorites, diorites and monzodiorites. Location of the profiles shown in Figures 7 and 8 are indicated.

Mitchell, 1973; Rona, 1973; Tarling, 1973). Independently of tectonic history and local crustal structures, the emplacement, characteristics and locations of ore deposits appear to be compatible with a mineralization at an old convergent plate boundary with polarity to the east (Urrutia-Fucugauchi and Delgado-Argote, 1976; Urrutia-Fucugauchi, 1979). There is a broad alignment, from west to east, of iron, gold, copper, base metals and gold deposits (Figure 9). Applications of paleoreconstructions may thus

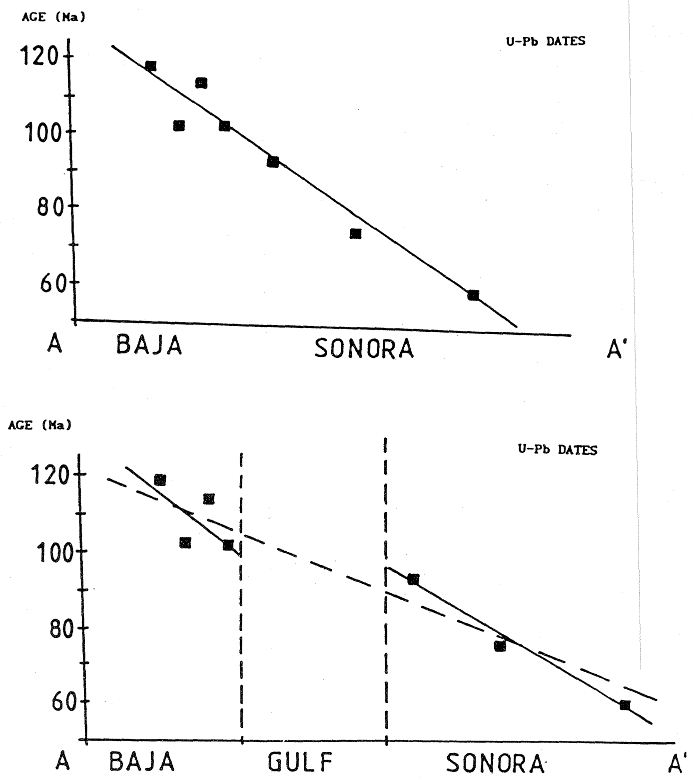


Fig. 7. Distribution of radiometric dates along profile A-A' (Figure 6), plotted with the Gulf closed (above) and the Gulf open (below).

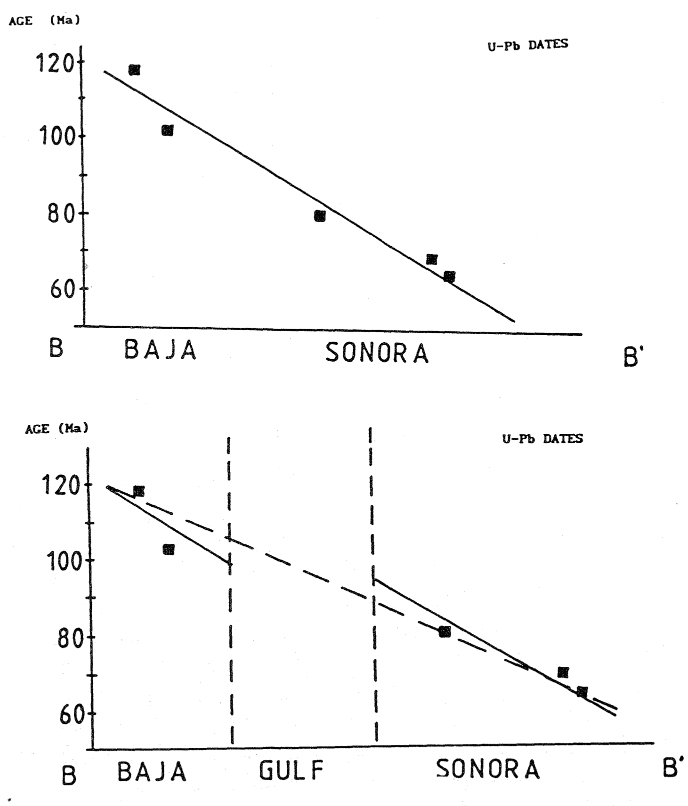


Fig. 8. Distribution of radiometric dates of igneous rocks along profile B-B' (Figure 6), plotted with the Gulf closed (above) and the Gulf open (below).

allow estimation of potential ore reserves. For instance, the present reconstruction may point to possible locations of Pliocene copper ores in Mexico to match those of El Boleo in southern Baja California (Wilson, 1988), or of gold deposits in Mexico to match those of La Escondida, Las Chollas and San Juan in northern Baja California and of Santiago in southern Baja California.

Our estimates of the rotation pole and mean angular displacement are only intended to provide quantitative data for the paleoreconstruction (Figure 3) and not to represent instantaneous plate motion parameters, since they actually integrate motions over a fairly long time interval since the Miocene. They include major changes in plate motion related to the early proto-Gulf crustal extension process and the subsequent break-up and rifting process of the Gulf. Determination of the true pole of relative motion in the Gulf of California region remains a difficult problem (e.g., Larson, 1972; Le Pichon *et al.*, 1973; Sharman *et al.*, 1976; Atwater, 1989; DeMets and Stein, 1990). The Pacific-North America plate motion parameters have been discussed in several studies and their applicability to the Gulf region is also a matter of debate. This is partly due to the influence of small microplates and the frequent plate reorganization. Some of the rotation poles are plotted in Figure 10. Three poles are based on directional data for the plate boundary (McKenzie and Parker, 1967; Le Pichon, 1968; Morgan, 1968). Another three solutions are based on global models for major plates: an 8-plate model (Chase, 1972), an 11-plate model (Minster *et al.*, 1974) and a more recent plate model (DeMets *et al.*, 1990). The early estimates have been discussed by Larson (1972) and Sharman *et al.* (1976), in terms of the implications for plate motion and structural features in the Gulf of California. When the rotation poles are far away from the Gulf of California region (Le Pichon, 1968; Morgan, 1968), they cannot produce a close up of the Gulf; instead they predict a parallel-to-margin displacements. Sharman *et al.* (1976) found a large scatter in directional data for the Gulf, with angular discrepancies of some 5 up to 28 degrees between physiographic features and seismic slip data. They concluded that no single rotation pole can account for all the characteristics in the Gulf region. They suggested that the angular discrepancies may be due to the detail with which the region has been studied, or to the Gulf of California being a young, rapidly evolving, plate boundary.

The occurrence of small microplates in the region, especially the Rivera plate, may explain part of the apparent discrepancies between the various pole estimates. In particular, this helps explain the poles located closer to the Gulf region, since motion between Rivera and North America will result in close relative rotation poles. (e.g., DeMets and Stein, 1990; Bandy, 1992). A detailed discussion lies beyond the scope of the present study. These plate motion parameters are related to the more recent past, after the development of the Rivera plate and the reorganizations in the mouth of the Gulf region. They have profound implications for the tectonics of the Mexican mainland, particularly the adjacent Jalisco area. Our pole of relative motion

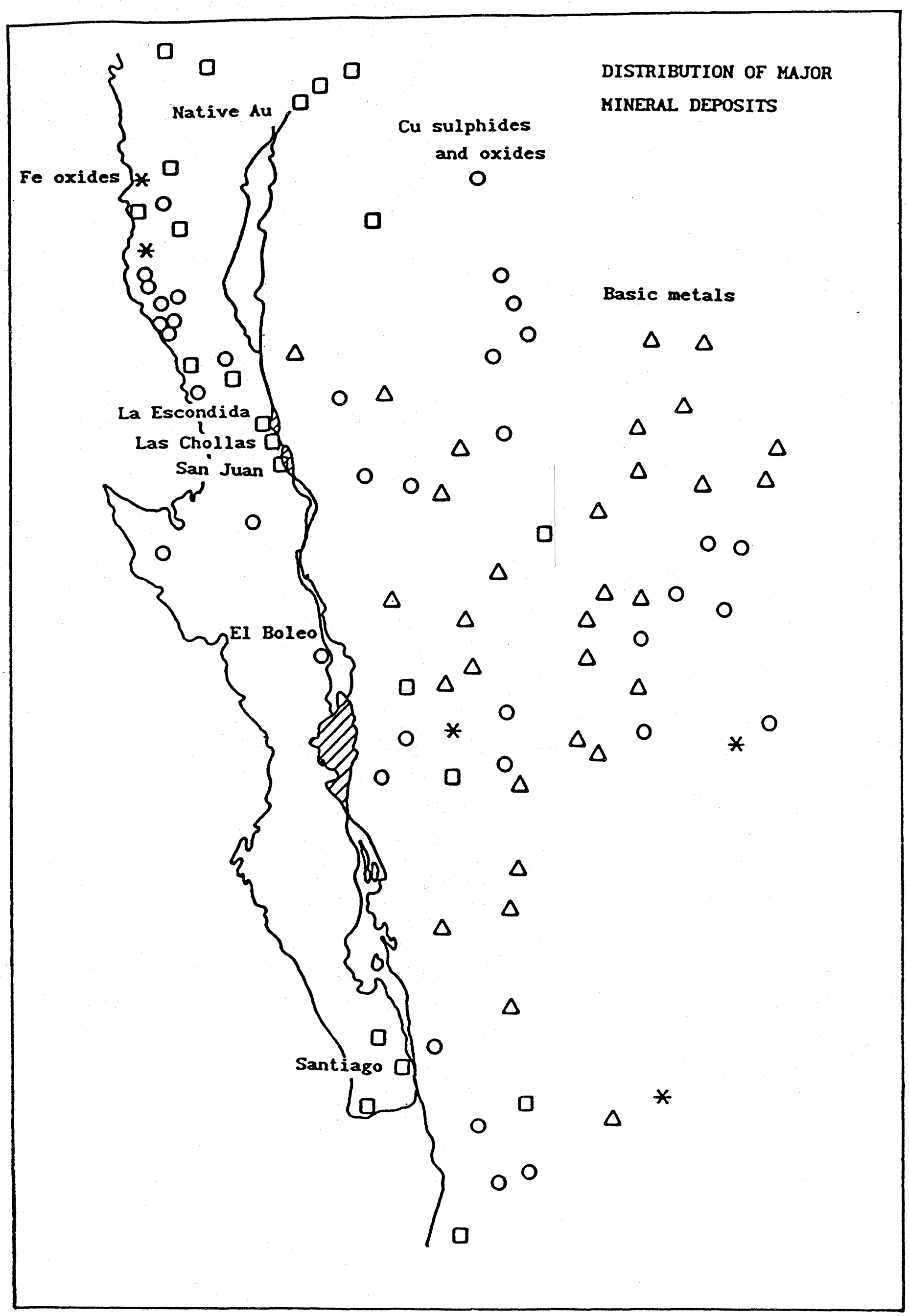


Fig. 9. Approximate location of mineral deposits in Baja California and northern Mexico plotted in the paleoreconstruction of Figure 3. Symbols are: * Fe-oxides; □ native gold; ○ copper sulphides and oxides; and △ base metals (sulphides).

represents an intermediate estimate between Pacific-North America poles and Rivera-North America poles, due to the integration of relative motions over a long interval since early Miocene time (past 16 Ma). It effectively averages out plate motion reorganizations involved during the early crustal extension episode of the proto-Gulf formation and the subsequent break-up and seafloor spreading process of the Gulf.

Rifting in the Gulf occurred along the elongated magmatic arc and was partly related to the trenchward migration of activity, southward Pacific-Farallon-North America triple junction migration and cessation of subduction. Magmatic arc products cover an extensive area in western North America; the distribution has been interpreted in terms of across and along arc migration of activity (Coney and Reynolds, 1977; Urrutia-Fucugauchi, 1978, 1980, 1986). Analysis of spatial patterns of radiometric dates indicate that activity migrated landward between about 140 and 60 Ma, and reached locations far from the margin at about 60 to 35-30 Ma. Then, at about 35-30 Ma and corresponding with a change in tectonic pattern to mainly ex–

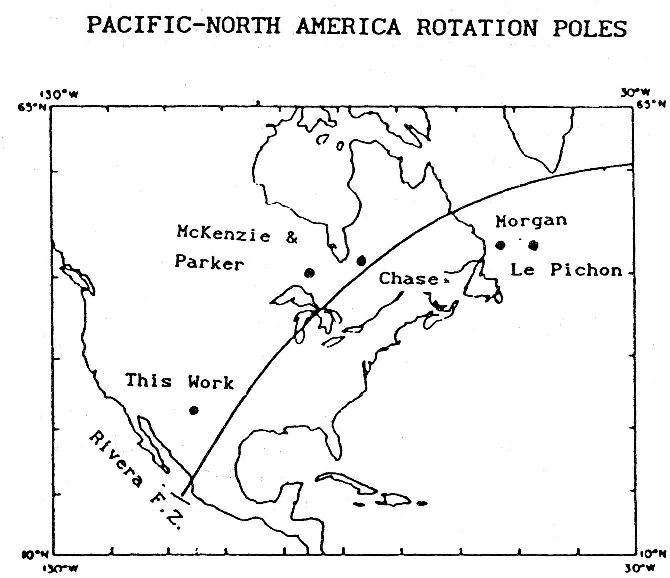


Fig. 10. Comparison of some early estimates of poles of relative motion for the Pacific-North American plate boundary. The great circle shown is orthogonal to the Rivera fracture zone (Larson, 1972).

tensional (mid-Tertiary orogeny, 35-15 Ma), magmatic activity was rapidly displaced trenchward (Urrutia-Fucugauchi, 1986). Rifting may have approximately followed the trend of the magmatic arc, in the back-arc region. This has left elongated sub-parallel belts of orogenic calcalkaline volcanic rocks of rhyolitic ignimbrites in the Sierra Madre province (about 34 to 27 Ma) and the andesitic province along the eastern Baja California peninsula (about 24 to 11 Ma) (Sawlan, 1991).

## ACKNOWLEDGMENTS

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## APPENDIX

### Calculation of pole of rotation by spherical trigonometry

The data should fulfill the following conditions:

rotation pole $\bar{p}(\lambda_p, \varphi_p)$ $\quad 0 \le \lambda_p \le \pi/2, \quad -2n\pi \le \varphi_p \le 2n\pi, \quad n = 0,1,2,...$

unrotated point $\bar{u}(\lambda_u, \varphi_u)$ $\quad 0 \le \lambda_u \le \pi/2, \quad -2n\pi \le \varphi_u \le 2n\pi, \quad n = 0,1,2,...$

rotated point $\bar{r}(\lambda_r, \varphi_r)$ $\quad -\pi/2 \le \lambda_r \le \pi/2, \quad -2n\pi \le \varphi_r \le 2n\pi, \quad n = 0,1,2,...$

where the data are expressed in terms of latitudes ($\lambda$) and longitudes ($\varphi$). Latitude is measured positive (negative) to the north (south) of equator, and longitude is measured positive (negative) to the east (west) of the zero reference meridian.

The angle of rotation $\theta$ may have any values, except $2n\pi$, $n=0,1,2,...$

The proposed sequence of calculation of a rotation pole ($\bar{p}$) is as follows:

$$\delta = \varphi_r - \varphi_u \qquad (1)$$

$$\Delta = \pi - \delta/2 \qquad (2)$$

$$\varphi_p = \varphi_u - \Delta \qquad \text{(longitude)} \qquad (3)$$

then,

$$\text{Sin}\,\lambda_r - \cos\lambda_u \sin\delta\cos\lambda_r = \begin{cases} \ge 0 & b = \cos^{-1}(\sin\lambda_r \sin\lambda_u + \cos\lambda_r \cos\lambda_u \cos\delta) \\ < 0 & b = \sin^{-1}\left[\dfrac{(\sin\lambda_r - \cos\lambda_u \sin\delta\cos\lambda_r}{\sin\lambda_u}\right] \end{cases} \qquad (4)$$

$$e = \cos^{-1}\left[\frac{(\sin\lambda_r - \sin\lambda_u \cos b}{\cos\lambda_u \sin b}\right] \qquad (5)$$

$$a = \sin^{-1}\left(\frac{1-\cos b}{1-\cos\theta}\right)^{1/2} \qquad (6)$$

$$c = \sin^{-1}(\sin a \sin\theta / \sin b) \qquad (7)$$

$$d = e + c \qquad (8)$$

$$\lambda_p = \sin^{-1}(\sin\lambda_u \cos a + \cos\lambda_u \sin a \cos d) \qquad \text{(latitude)} \qquad (9)$$

The procedure needs to be applied in the form of successive approximations by giving different values of the angle of rotation.

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