TECTONICS

A Selection of Papers Presented at the 26th IGC, Paris, July 1980

Journal of Structural Geology, Vol. 3, No. 4 1981

Special Editors: J. F. Dewey, P. L. Hancock, M. Mattauer, A. Nicolas

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Preface: Tectonics at the 26th IGC, Paris

This issue of the *Journal of Structural Geology* contains fourteen articles which were originally presented as papers to the Tectonics Section of the International Geological Congress held in Paris during July 1980. The fourteen articles represent a very small sample of the approximately 200 talks given to the Tectonics Section; our selection is taken from contributions reported to the thematic meetings, some symposia papers being reserved for other periodicals. Judging from the relatively large audiences and lively discussions at the thematic meetings it was clear that the appeal of structural geology and tectonics extends beyond that of its practitioners to include many earth scientists who are not specialists in those fields.

The papers in this issue are not organised into the same thematic groupings as were used at the IGC in Paris. The first five articles are all concerned with the analysis of neotectonic structures, the following seven papers are linked by the theme of deformational processes and tectonics within the Alpine–Himalayan zone, and the two final papers discuss aspects of Hercynian or Caledonian tectonics in Europe.

I am most grateful to J. F. Dewey, M. Mattauer and A. Nicolas who were the conveners of the Tectonics Section of the 1980 IGC for allowing this Journal to publish some of the excellent talks which their planning of the programme had stimulated; their assistance as special editors was much appreciated.

P. L. Hancock

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Fault tectonics of the Baja California Peninsula and the opening of the Sea of Cortez, Mexico

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Abstract—A detailed field analysis of Neogene and Quaternary faults in Baja California has enabled us to reconstruct the stress pattern and the tectonic evolution of the central and southern parts of the peninsula. The deformation, which is related to the opening of the gulf, affects the whole peninsula, but decreases from east to west. Most observed faults, normal and or dextral, strike NNW–SSE to WNW–ESE; their mechanisms include both strike-slip and dip-slip, as well as intermediate motions. Compressional events have occurred since Late Neogene times, but were probably of minor quantitative importance because reverse faults are rare and small.

The principal fault pattern includes dextral NNW–SSE Riedel shears and N–S tension faults induced by dextral strike-slip along two main NW–SE fault zones bordering the peninsula: the Gulf of California to the east, which is the most important, and the Tosco–Abreojos fault to the west. The resulting pattern of deformation shows that the eastern part has been a complex transform-extensional zone since Late Miocene–Early Pliocene times.

INTRODUCTION

NUMEROUS papers on the recent geodynamic evolution of the Sea of Cortez (Gulf of California) have been published since Shepard (1950) and Carey (1958) first illustrated the rhomboidal morphology of its basins. The continuity between the gulf and both the East Pacific Rise to the south (Menard 1960) and the San Andreas Fault System to the north (Kovach *et al.* 1962, Wilson 1965, Crowell 1974), as well as the characteristics of the gulf itself (Hamilton 1961, Rusnak *et al.* 1964, Moore 1973, Bischoff & Henyey 1974, Lonsdale & Lawver 1980) have been analysed. Along the gulf, in the adjacent Baja California Peninsula, the role of dextral strike-slip faulting has been emphasized (e.g. McFall 1968, Hamilton 1971). These results led to the present interpretation of the Sea of Cortez as an intercontinental NW–SE rift zone with oblique separation of the Baja California Peninsula to the west (Pacific plate) and Sonora to the east (North American plate). The structural pattern of the gulf is thus explained by an alternation of short spreading axes and longer dextral transform faults (Larson *et al.* 1968, 1972, Moore & Buffington 1968, Sharman 1976), as shown in Fig. 1. According to Karig & Jensky (1972) and Moore (1973), the Plio-Quaternary Gulf of California was created at the site of an older protogulf of Middle and Late Miocene age. More generally, the evolution of Western North America has been discussed by Atwater (1970) in terms of plate tectonics. Obviously, the actual pattern of motion along the Baja California region is complex in detail: for example, Spencer & Normark (1979) have pointed out the existence of recent tectonic activity along the western margin of the peninsula, the former boundary of the Pacific and North American plates.

The geology of various parts of the Baja California Peninsula has been studied for different purposes by, for example, Wilson (1948), Mina (1957), McFall (1968), Lopez-Ramos (1973), Gastil *et al.* (1975, 1979), Ortlieb (1978) and Rangin (1978). It is surprising, however, that while the geodynamic evolution of the Sea of Cortez has raised so much interest, no detailed analysis of Late Neogene and Quaternary fault mechanisms has been performed in the adjacent peninsula. Here we summarize some results of field analyses of Late Miocene and Plio-Quaternary faults. The fieldwork was carried out in 1977, 1979 and 1980 using existing geological maps (Wilson 1948, McFall 1968, Rangin 1978) and neotectonic observations (Ortlieb 1978). The probable ages of observed structures were mostly inferred from earlier stratigraphic studies (e.g. Wilson 1948), scattered analyses of nannofossils (determinations by C. Müller), comparisons of relative tectonic chronologies and criteria for tectonic consistencies (i.e. geometrical and mechanical analogies between fault patterns observed in formations of different ages). The determinations of directions of principal stresses from measurements on populations of fault planes with slickensides were made using methods described in detail elsewhere (Angelier 1979). Other structures, such as tension gashes, were also taken into account. Because multiphase populations of faults were commonly found, the relative chronology of faulting events was established by qualitative observations (e.g. superimposed slickenside lineations, which indicate successive directions and senses of motions on fault planes), and in some cases by using the mathematical method of Angelier & Manoussis (1980). We also used techniques of photo-interpretation and teledetection, the details of which will be published separately.

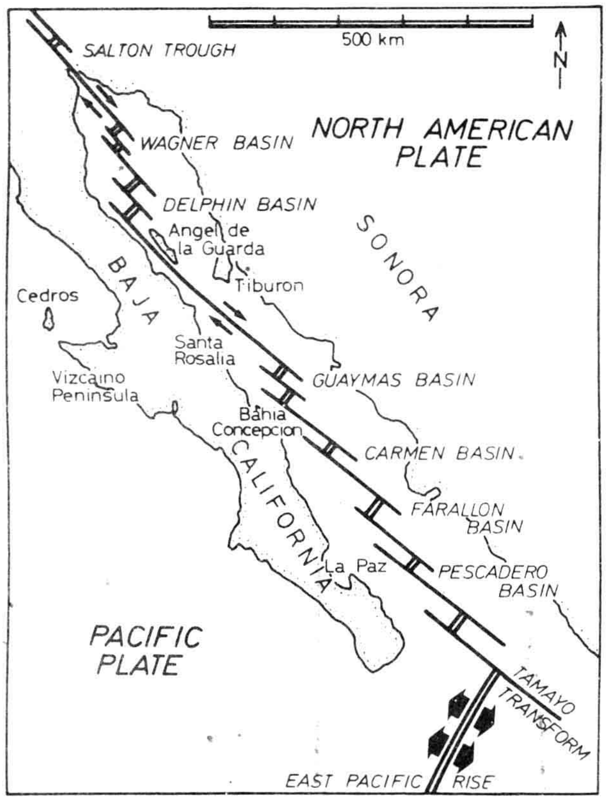

Fig. 1. General distribution of spreading basins and transform faults in the Gulf of California, after various authors (e.g. Lonsdale & Lawver 1980).

The studied areas are shown in Fig. 2. Our observations are numerous at some places (e.g. Santa Rosalia Basin, Bahia Concepcion, Vizcaino Peninsula), while in other areas they are rare and scattered as a consequence of the localization of Neogene and Quaternary outcrops, the localization of the faults themselves and problems of access. A more extensive analysis, now in progress by B. Colletta, will increase the density of the network.

GEOMETRY OF THE FAULTS

The example of the Santa Rosalia Basin illustrates the geometry of Late Neogene and Plio-Quaternary fault movements in the eastern central part of the Baja California Peninsula. This deformed sedimentary basin was mapped by Wilson (1948), who described three main formations: the Boleo, Gloria and Infierno Formations, from oldest to youngest. At least the Gloria and Infierno Formations are of Pliocene age (Wilson 1948). Seven of our samples contained nannofossils of Early Pliocene age (probable NN12 zone, determination by C. Müller); they were found in different layers of the Gloria Formation and near the boundary between the Gloria Formation and the underlying Boleo Formation. These deposits unconformably overlie the thick Comondu group of Formations, of probable Late Miocene age (Gastil *et al.* 1979) (older Oligo–Miocene ages were reported by McFall [(1968), in the Bahia Concepcion area], and they are locally cut and overlain by the thin Santa Rosalia Formation and by marine terraces of Pleistocene age (Wilson 1948, Ortlieb 1978).

More than 800 measurements were made within an area of about 15 × 5 km around the city of Santa Rosalia. A detailed picture of the Late Neogene and Plio-Quaternary fault pattern was obtained for the area by using simple statistics as applied to observed directions and dips of various structures (e.g. faults and tension gashes), and observed directions and senses of relative motions indicated by slickensides, as well as computed ratios of strike-slip and dip-slip components of fault movements. Figure 3 (a) shows that among the 418 fault planes which we were able to measure in the field, most strike N–S to NW–SE while 204 tension gashes mostly strike N–S to NNE–SSW. In detail, the azimuths of the main groups are 160°, 175° and 115–145° for the faults, and 10°, 30–40° and 175° for the tension gashes. Figure 3(b) indicates that the fault planes dipping towards the WSW are more numerous than those dipping towards the ENE. All but a few of the dips exceed 45°, as shown in Fig. 3 (c), and it is clear that most faults have dips of either 65

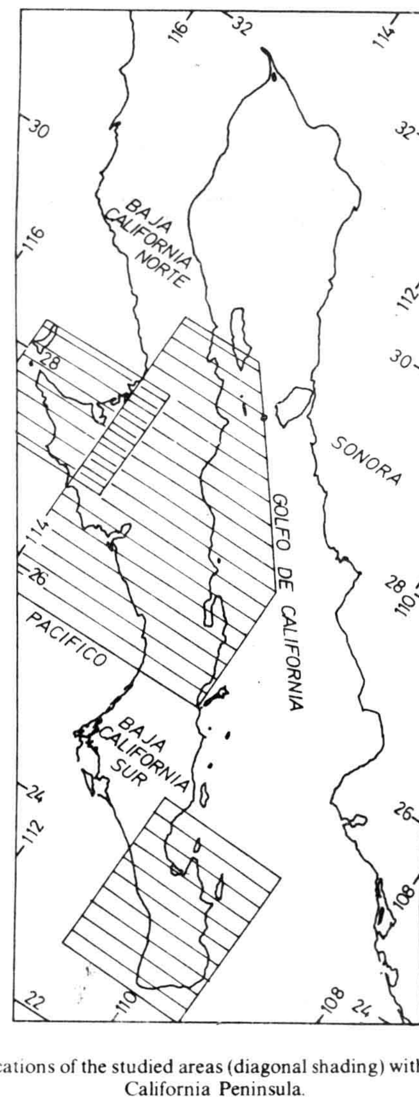

Fig. 2. Locations of the studied areas (diagonal shading) within the Baja California Peninsula.

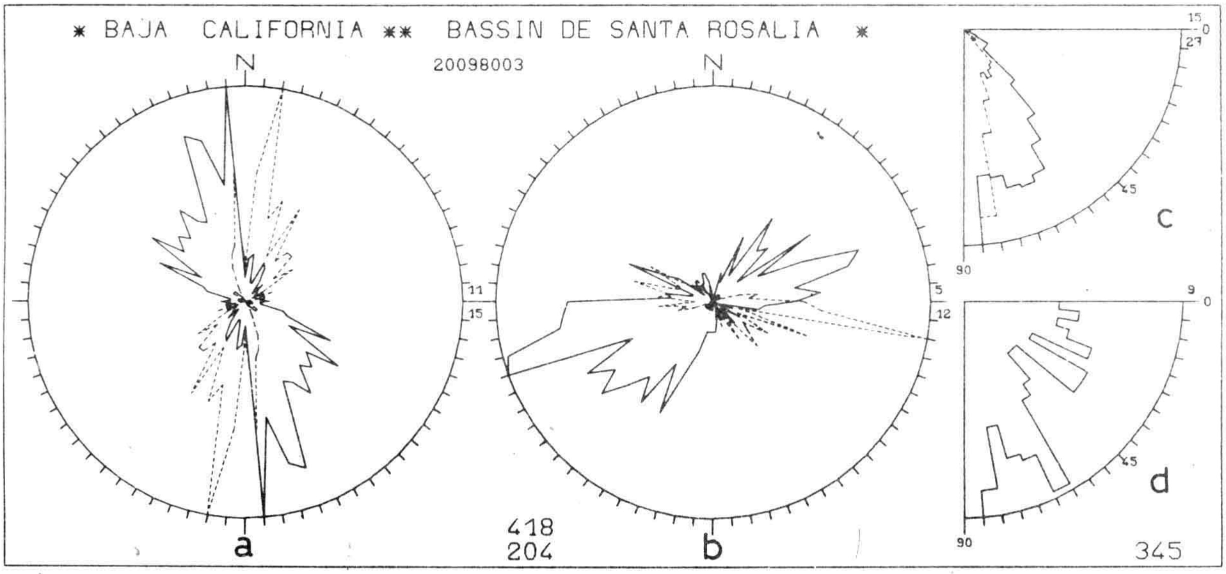

Fig. 3. Main geometrical features of structures measured in the Santa Rosalia Basin. Numbers of measurements: 418 faults (including 345 faults with observed slickenside lineations), and 204 tension gashes. (a) Strikes of faults (continuous lines) and tension gashes (dashed lines). (b) Directions of dip of faults (continuous lines). (c) Dips of faults (continuous lines) and tension gashes (dashed lines). (d) Pitches of slickenside lineations within fault planes. For each diagram, maximum frequencies are given as percentages on the right.

or 90°, while most tension gashes are vertical (90°). It is noteworthy that dips of about 65° are observed in various countries for normal faults near the surface of the earth, while strike–slip faults are more commonly observed to be vertical. However, Fig. 3 (d) demonstrates that although pure strike–slip and pure dip–slip are present, most faults in the Santa Rosalia Basin show evidence for oblique-slip. The angle between the slickenside lineations and the horizontal direction in the fault plane (i.e. the pitch) may reach values as small as 0–5° (indicating strike–slip) or as large as 85–90° (indicating dip–slip), but intermediate values were also commonly observed.

As Fig. 4 shows, there is no strict correlation between the dip of a fault plane and the pitch of the contained slickenside lineation in the Santa Rosalia Basin: the obliquity of slickenside lineations is highly variable, regardless of the inclination of fault planes. In detail, however, dips of about 60° are much more frequent for high values of pitch (60–90°), while pitches from 40 to 50° are rare, whatever the dip (Fig. 4).

Although relative amounts of strike–slip and dip–slip components of motion on faults may be inferred from Figs. 3 and 4, a more rigorous analysis is given in Fig. 5. Moreover, this figure takes into account the sense of relative motion, so that normal/reverse and dextral/sinistral faults are distinguished. Both direction and sense of motion were determined in the field for 329 faults in the Santa Rosalia Basin. The ratios of transverse and lateral horizontal motions relative to net motions are then easy to compute and give quantitative information about the type of regional deformation (cf. Angelier 1979). Let us recall that the transverse horizontal motion is the extensional or compressional component of the horizontal slip (i.e. perpendicular to the strike of the fault), whereas the lateral horizontal motion is the strike–slip component (i.e. parallel to the strike of the fault). Figure 5 shows that reverse fault mechanisms are rare. In addition, some of the reverse mechanisms shown in Fig. 5 relate to fault motions which were originally normal: these normal faults have been subsequently rotated by block tilting due to more recent normal faulting. Principally, Fig. 5 demonstrates that most oblique–slip faults are normal and dextral (upper-right quadrant): the tectonic regime of the Santa

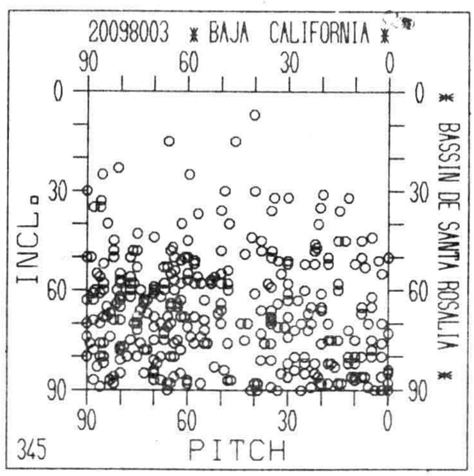

Fig. 4. Relation between dip of faults and obliquity of motion from field measurements in the Santa Rosalia Basin (345 faults). Values in degrees. Abscissa shows pitch of slickenside lineations (pure normal or reverse motion is 90°, pure strike–slip is 0°). Ordinate shows dips of fault planes. Compare with Figs. 3 (c) & (d).

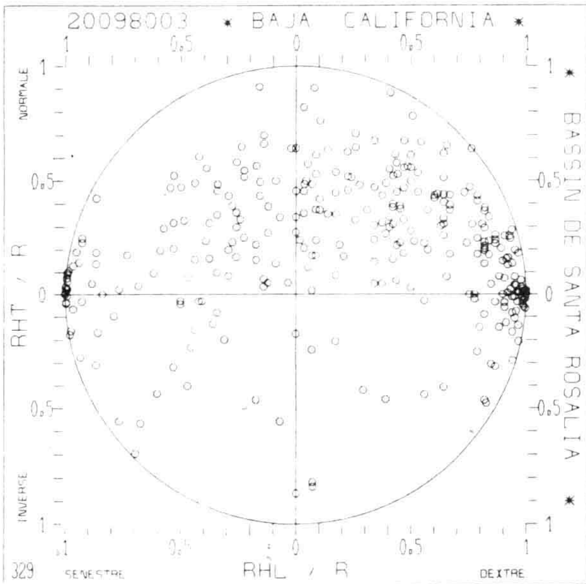

Fig. 5. Strike–slip and dip–slip components of motion on faults with observed slickenside lineations, from measurements in the Santa Rosalia Basin (329 faults). Abscissa shows ratio RHL/R, where RHL is the horizontal-lateral component of net slip *R* (left half-circle for sinistral motions, right half-circle for dextral motions). Ordinate shows RHT/*R* where RHT is the horizontal-transverse component of net slip *R* (upper half-circle for normal motions, lower half-circle for reverse motions).

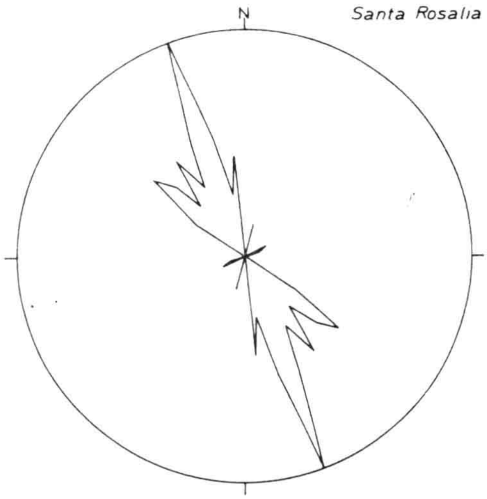

Fig. 6. Directions of large faults inferred from geological mapping of the Santa Rosalia Basin (principally after Wilson 1948). Compare with Fig. 3(a).

Rosalia Basin was clearly dominated by normal-dextral oblique–slip faulting. Note that pure strike–slip is present, as shown by the concentration of points near the left and right sides of the diagram: both sinistral and dextral strike–slip faults having been observed, the latter are more frequent. Dip–slip normal faults are also present, but are not especially abundant, as there is no concentration of points along the vertical axis of the diagram.

Most of the measurements shown in Figs. 3–5 were recorded from numerous scattered but relatively small outcrops (i.e. 100–10,000 m^2). We believe however that the geometrical analysis of these measurements leads to results which are significant at the scale of the fracture pattern of the whole of the Santa Rosalia Basin. For example, we argue that the distribution of azimuths of faults, as determined from our local measurements, closely resembles that inferred from Wilson's (1948) geological mapping. The distribution of fault directions on a larger scale is shown in Fig. 6, the azimuths of the main families being 160°, 130–145° and 175° (cf. Fig. 3 (a), although the relative frequencies are slightly different). Comparisons with structural analyses made from aerial photographs and satellite imagery led us to similar conclusions (paper in preparation).

In summary, during the Late Miocene and especially during the Plio-Quaternary, the pattern of faulting was dominated by normal dextral motion on fault planes the azimuths and dips of which vary from 130 to 175° and from 60 to 90°, respectively. This geometry is consistent with the average azimuth of vertical tension gashes, that is 10°, because NW–SE dextral faults and N–S tension gashes are obviously mechanically compatible. Both sets of observations suggest that extension occurred principally along an E–W to ESE–WNW direction (average azimuth 100°, i.e. perpendicular to most tension gashes).

Other examples have been analysed, as for the Bahia Concepcion area 100 km south-southeast of Santa Rosalia; but the results are similar to those shown in Figs. 3–5. In point of fact, the fault pattern of the Santa Rosalia Basin is representative of that along the whole of the west coast of the central Gulf of California.

EXAMPLES OF FAULT MECHANISMS AND TECTONIC CHRONOLOGY

Figure 7 illustrates a type of fault population that we frequently found in the Pliocene outcrops of Baja California. Thirty-one faults were measured in a narrow area of the Arroyo Soledad, 5 km west-northwest of Santa Rosalia. The faulted sediments, which belong to the Boleo and Gloria Formations, are subhorizontal. Almost all the faults are normal, with dip–slip motions predominating, but strike–slip and oblique–slip playing an important role (Figs. 7a & b). Although the poor quality of the fit suggests that the population may be heterogeneous, both the method of the right dihedra of Angelier & Mechler (1977) used for Fig. 7 (c), and the mathematical inversion of the data of Angelier (1979) used for Fig. 7 (d), show that motion on these faults was induced by extension along a mean ENE–WSW direction. This result seems quite logical if it is recalled that numerous NW–SE to N–S normal faults dipping, either to the ENE or WSW, are probably conjugate (Figs. 7a & b).

Similar mechanisms were also computed from measurements in older rocks: for example, Fig. 8 illus-

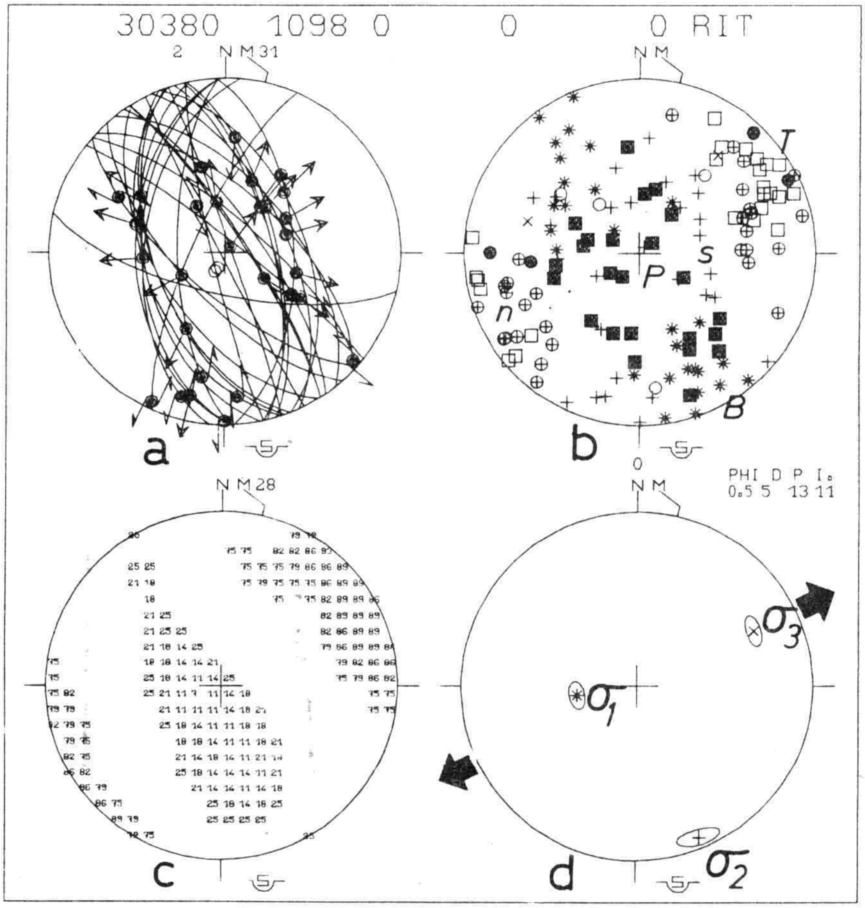

Fig. 7. Example of a detailed analysis of a population of faults. Gloria and Infierno Formations, Arroyo Soledad, Santa Rosalia Basin. Schmidt's projection, lower hemisphere. (a) Fault planes and slickenside lineations and poles to stratification. (b) Axes related to individual fault mechanisms (n, poles to fault planes, s, slickenside lineations, B. P, and T, axes of earthquake focal mechanisms solutions). (c) Diagram of the method of right dihedra which define mechanical compatibilities between all faults (Angelier & Mechler 1977). Small numbers are frequencies (percentages) for maximum compressive stress (σ_1), large numbers are frequencies for minimum stress (σ_3), (d) Result of the inversion of data. The axes of the computed stress tensor are plotted ($\sigma_1, \sigma_2, \sigma_3$). Large arrows show the direction of extension. Methods are described in detail in Angelier (1979). The mathematical inversion of data was also done using a new method (Tarantola *et al.* in preparation).

trates normal faults in the Comondu Formation, south of the Tres Virgenes volcano, 15–20 km northwest of Santa Rosalia. Faults and slickenside lineations are compatible with an ENE–WSW direction of extension (Fig. 8d). This is the same ENE–WSW extension that we computed after measurements of faults within younger sediments (see Fig. 7d). In addition, the tension gashes have a geometry consistent with this stress pattern, despite their dispersion about a mean NNW–SSE strike (Fig. 8c).

In many cases, the direction of extension is not perpendicular to the average strike of the faults, owing to a systematic strike–slip component of motion on normal faults. The measurements shown in Fig. 9 were recorded in the Gloria and Infierno Formations of Arroyo del Montado, 2–3 km south of Santa Rosalia. All faults are normal, dipping either to the SW or NE. Both groups exhibit oblique–slip with normal–dextral motion, so that the direction of extension averages E–W.

Pure strike–slip faults are also present; most of them are dextral, but some are sinistral. For example, south of Mulege (50 km southeast of Santa Rosalia), N–S sinistral faults were observed in outcrops (Fig. 10) while larger NW–SE dextral faults were detected on aerial photographs.

In detail, tectonic analysis enabled us to detect some variations in the extensional stress pattern during Plio-Quaternary time. Both the geometry of intersections between successive faults and the superposition of slickenside lineations on fault planes allow the establishment of a relative chronology of faulting events. Thus the tectonic analysis for several places in central eastern Baja California shows that NE–SW to ENE–WSW extension was followed by E–W to ESE–WNW extension. Both movements reactivated the same NNW–SSE fault planes: along the faults, the second motion generally has a greater strike–slip component than the first one. This time variation in the direction of extension is also illustrated by the presence, in several localities, of two main groups of subvertical tension gashes; the first group strikes NW–SE

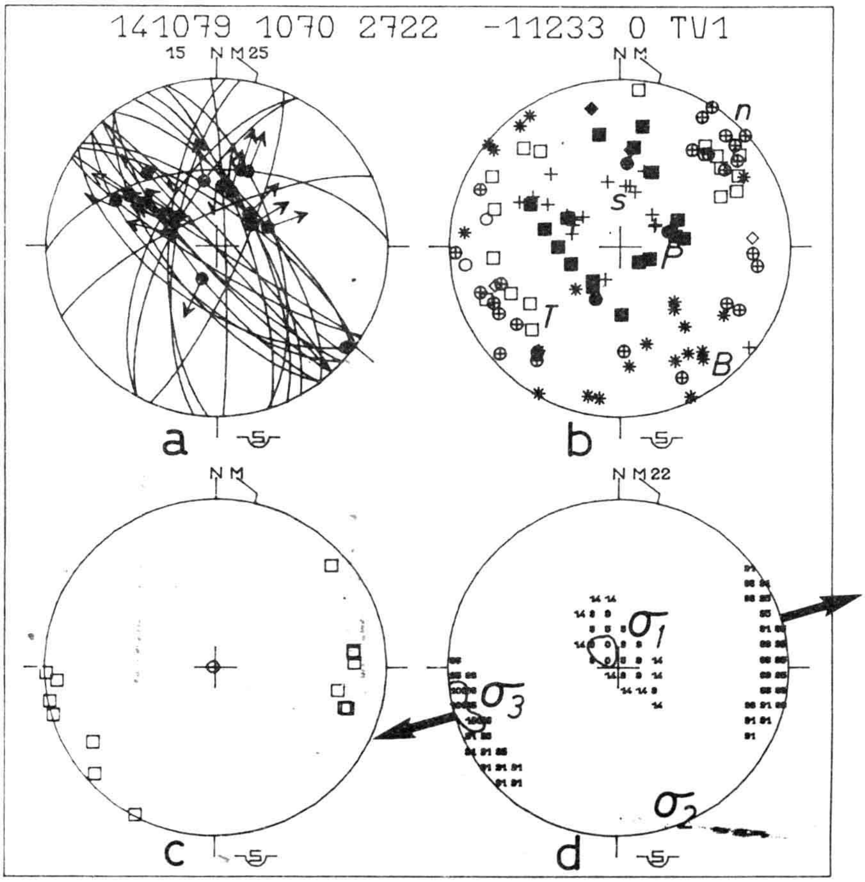

Fig. 8. Normal faults in the Comondu Group (Tres Virgenes). For Legend see Fig. 7. Diagram (c) shows the poles of tension gashes (squares).

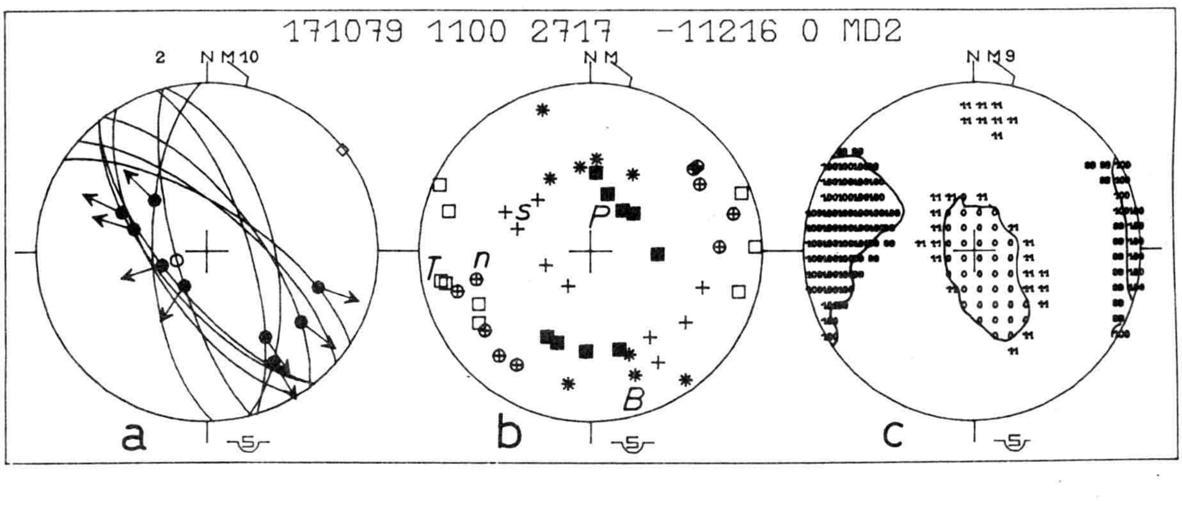

Fig. 9. Normal dextral oblique-slip faults (Gloria Formation, Arroyo Montado, Santa Rosalia Basin). For legend see Fig. 7.

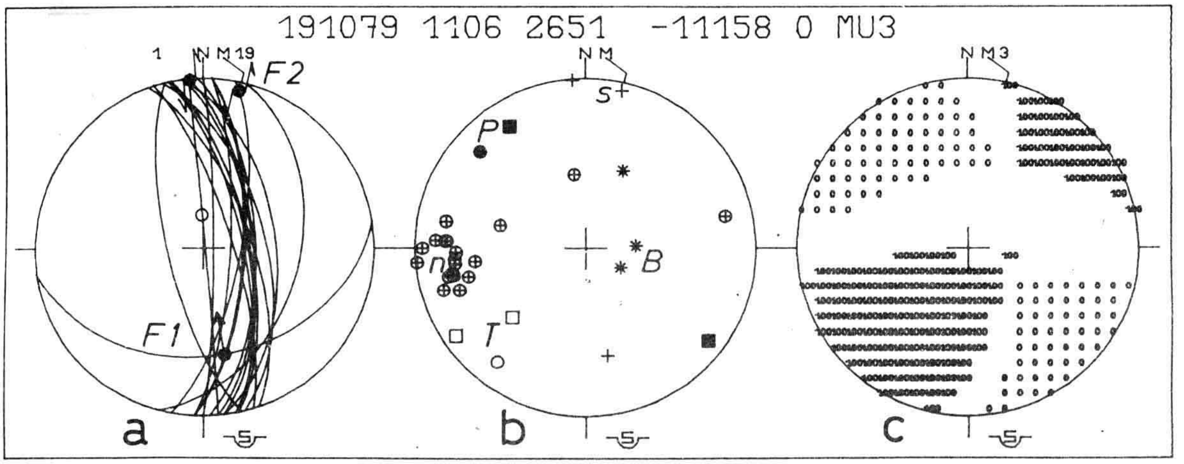

Fig. 10. Sinistral strike-slip faults in Pliocene and Quaternary sediments near Mulege. For legend see Fig. 7.

to NNW–SSE, the second strikes N–S to NNE–SSW (Fig. 11). These successive extensional deformations do affect Pliocene sediments, for example the Gloria and Infierno Formations of the Santa Rosalia Basin. Although our measurements of faults and tension gashes are less numerous in Quaternary rocks than in Pliocene formations, it is likely that the importance of strike–slip relative to dip–slip increased during Late Pliocene–Quaternary times and may have been related to a clockwise rotation of the subhorizontal minimum stress from NE–SW to E–W.

Older fault populations were observed at several places in Baja California. One of the most common assemblages is illustrated in Fig. 12. In addition to normal faults, which resemble those previously described, numerous conjugate strike–slip faults also formed and moved during E–W extension and N–S compression. The fault pattern shown in Fig. 13 is more complicated because pure reverse faults are also present: both strike–slip and reverse faults are compatible with a NNE–SSW compression, although the presence of normal faults and limited plastic deformation (rare small-scale folds) renders the geometrical analysis difficult. The most recent sediments in which similar compressional mechanisms of faulting could be identified belong to the Boleo Formation of the Santa Rosalia Basin; we were unable to find similar populations of faults in the overlying Gloria Formation. Moreover, criteria for the relative tectonic chronology show that these mechanisms are older than the large normal fault related to NE–SW to E–W extension, which affected the Pliocene sediments. We consequently infer that most of these populations of strike–slip and reverse faults were created by a compressional event of latest Miocene to Early Pliocene age. As these compressional faults are rare and small, relative to the extensional faults already described, it is obvious that the compressional event had much less quantitative importance than the ensuing normal and strike–slip Plio-Quaternary faulting.

The oldest fault populations we have studied affect the Comondu Group, principally in the Santa Rosalia Basin. Large blocks are faulted and tilted, so that commonly the normal faults themselves are rotated until they appear to

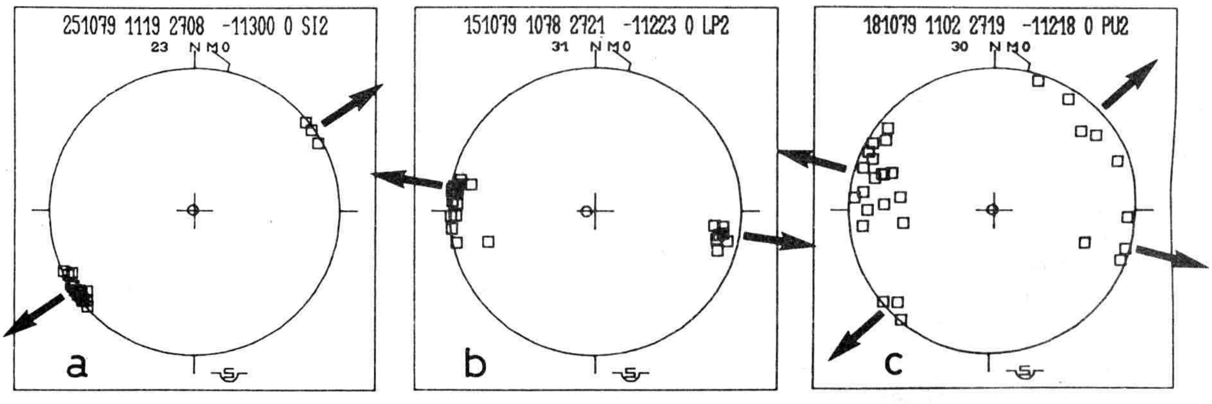

Fig. 11. Examples of populations of tension gashes. (a) San Ignacio. (b) Las Palmas, Santa Rosalia Basin. (c) Arroyo Purgatorio, Santa Rosalia Basin. Squares are poles to tension gashes, open circles are poles to bedding.

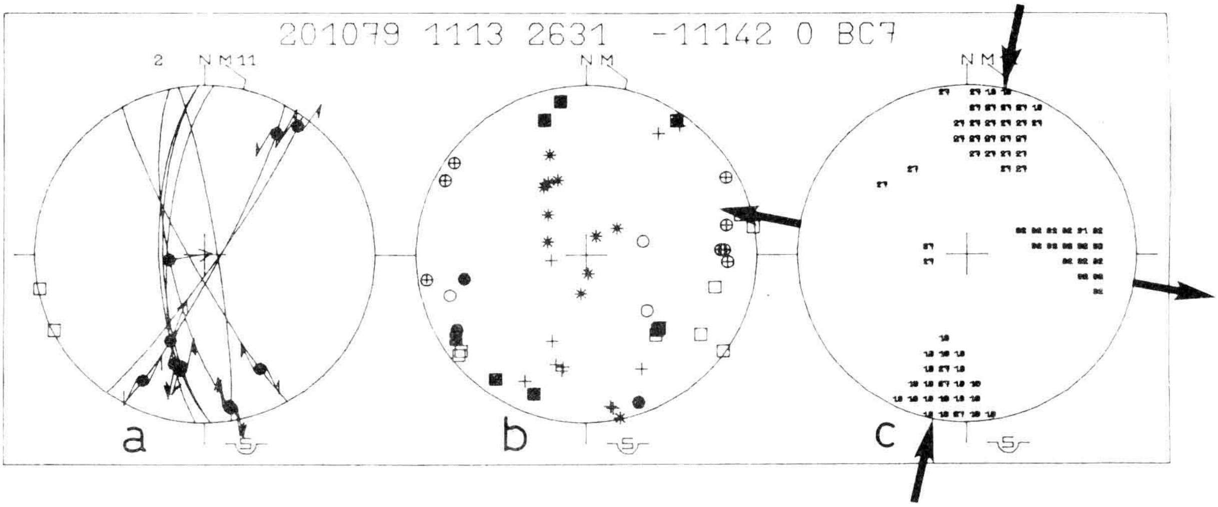

Fig. 12. Conjugate strike–slip faults in the Comondu Formation (Bahia Concepcion). For legend see Fig. 7.

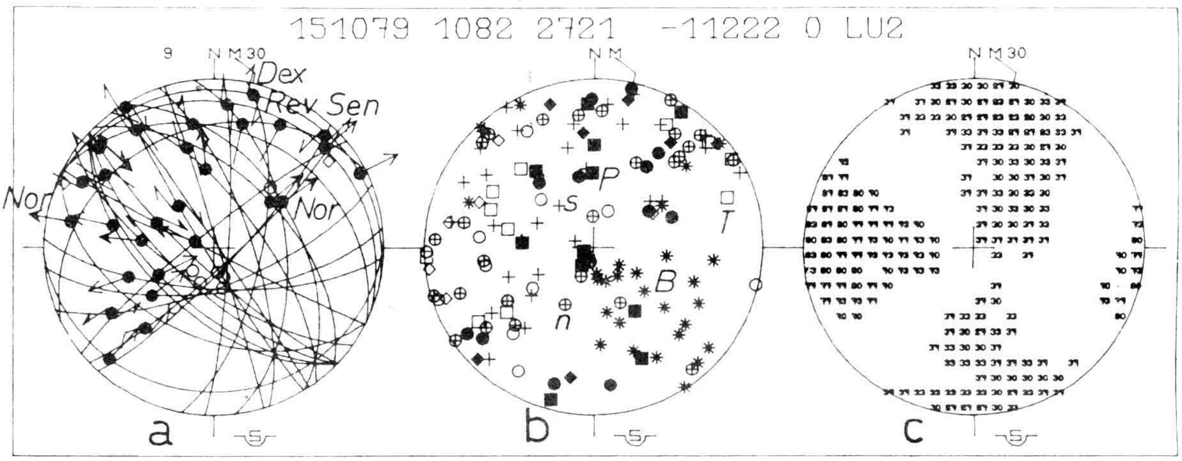

Fig. 13. Complex fault pattern in the Boleo Formation near Mina Lucifer (Arroyo Infierno, Santa Rosalia Basin). For legend see Fig. 7. Dex- and Sen-dextral and sinistral strike–slip faults respectively. Rev., reverse faults; Nor, normal faults.

be reverse faults. Figure 14 shows an example of such a rotated system of conjugate normal faults. The directions of stress axes are easily computed by geometrical and mathematical methods, and may then be rotated back to their previous positions: the extension direction being originally NE–SW (Fig. 14d). Both tectonic and stratigraphic criteria indicate that this pattern of normal faults is older than all previously mentioned tectonic structures. Major normal faults and tilted blocks in the Comondu Group are unconformably overlain by the Boleo Formation, as previously reported by Wilson (1948). On the other hand, we should point out that this pattern of large normal faults dipping at 40–50° to the S or SW, and of tilted blocks dipping at 25–40° to the N or NE, implies an important component of extension, at least locally.

DISCUSSION

Figures 15 and 16 show the directions of stress that we have been able to determine from field measurements in central and southern Baja California. Local results are given in Fig. 15 for both minimum stress (σ_3) and maximum stress (σ_1) while inferred regional directions of subhorizontal σ_1 and σ_3 are schematically shown in Fig. 16, regardless of their age. Divergent arrows (σ_3) are more numerous than convergent ones (σ_1), because normal faults (subvertical σ_1) are common while reverse faults (subvertical σ_3) are rare; strike–slip faults moved when both compression and extension were horizontal (subvertical σ_2). The density of observations partly depends on the density of fractures, which decreases from east to west across the peninsula, as shown by aerial photographs and orbital images as well as by field observations. To the west, however, a NW–SE fault system, dominated by dextral strike–slip faults, is still active in the Vizcaino Peninsula. Young Quaternary deposits are faulted there (dextral strike–slip in the city of Bahia Tortugas), and the stress directions obtained by tectonic analysis in Neogene basins around Bahia Tortugas resemble those obtained near the gulf coast (com-

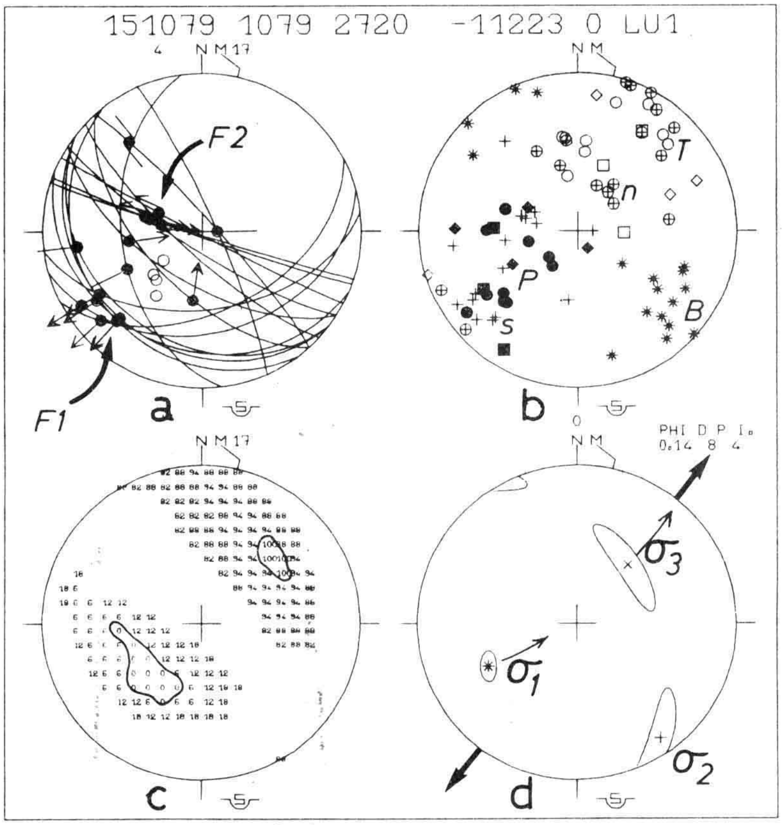

Fig. 14. Tilted conjugate normal faults in the Comondu Group (Mina Lucifer, Arroyo Infierno, Santa Rosalia Basin). For legend see Fig. 7. Note that faults *F*1 are still normal, while faults *F*2 now seem to be reverse.

pare Figs. 15). Motion still continues along the western margin of Baja California, as pointed out by Spencer & Normark (1979).

In the eastern part of the Baja California Peninsula, the two main directions observed in the field as well as on orbital images are N–S and NNW–SSE. The first one corresponds to normal faults and sub-vertical tension gashes, and the second direction corresponds to normal–dextral oblique–slip faults. Another important structural direction is NW–SE, that is parallel to the Gulf of California; it corresponds to dextral strike–slip or normal faults. The NNE–SSW direction, dominated by sinistral strike–slip, is much less abundant. We interpret this general fault pattern as a system of NNW–SSE and NNE–SSW Riedel shears (dextral and sinistral respectively), associated with N–S en échelon normal faults and tension gashes. This system is related to dextral strike–slip along two main NW–SE fault zones; the Gulf of California to the east and the San Benito–Tosco–Abreojos fault system to the west. The whole area has acted as a complex NW–SE trending transform-extensional zone since the Late Miocene–Early Pliocene; variations occurred, as there was an increase of the dextral strike–slip motion relative to the transverse extensional motion. The generation of oceanic crust south of the gulf, at approximately 4 Ma (Larson *et al.* 1968, 1972), probably more recent than the beginning of the intracontinental transform-extensional process. It is likely that part of the intense faulting of the Comondu Group is due to this initial intracontinental extension in Late Miocene–Early Pliocene times, prior to the development of the present pattern of spreading basins and transform segments in the Gulf of California.

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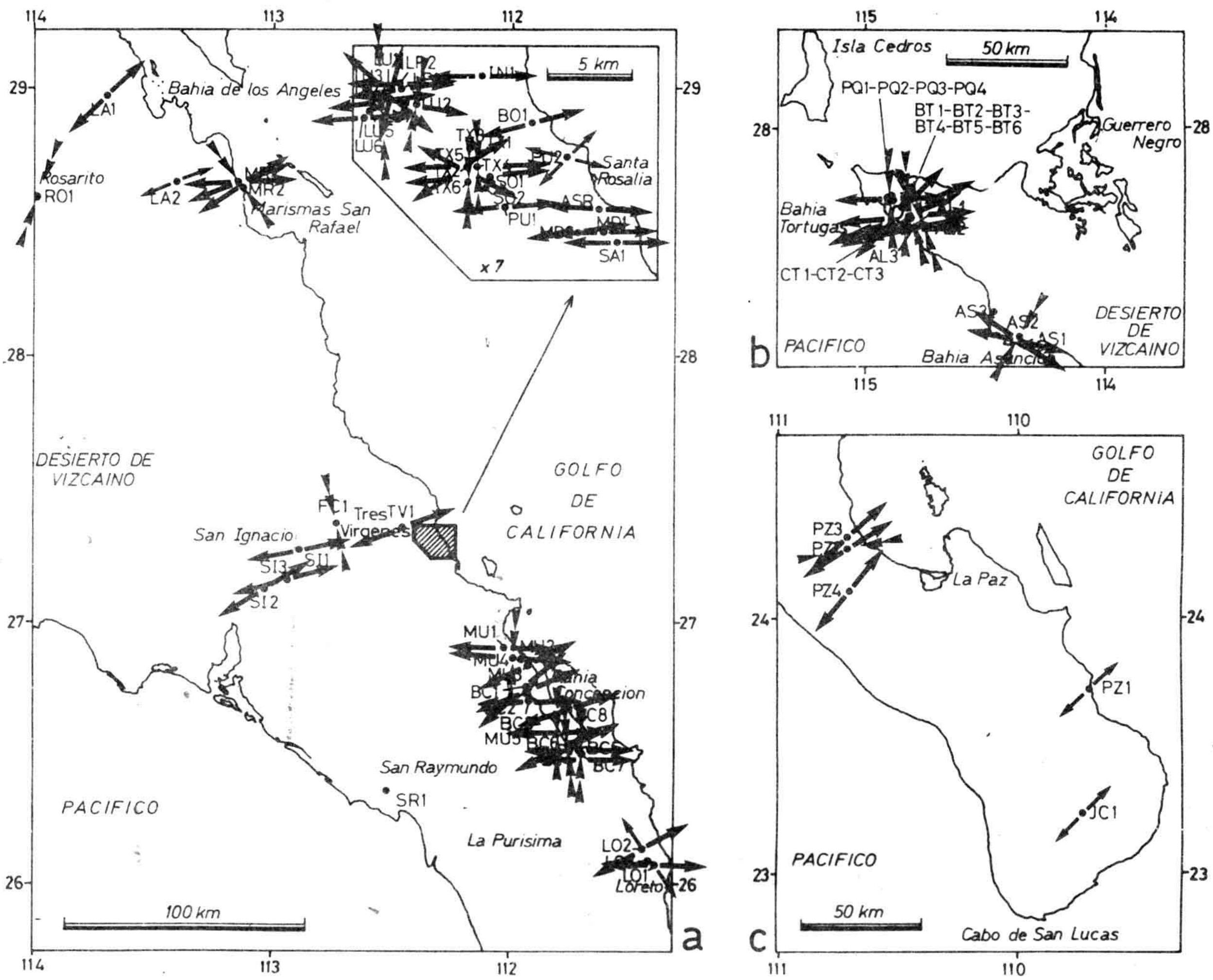

Fig. 15. Results of fault analyses in terms of horizontal compressions (convergent arrows) and extension (divergent arrows), in the shaded areas of Fig. 2.

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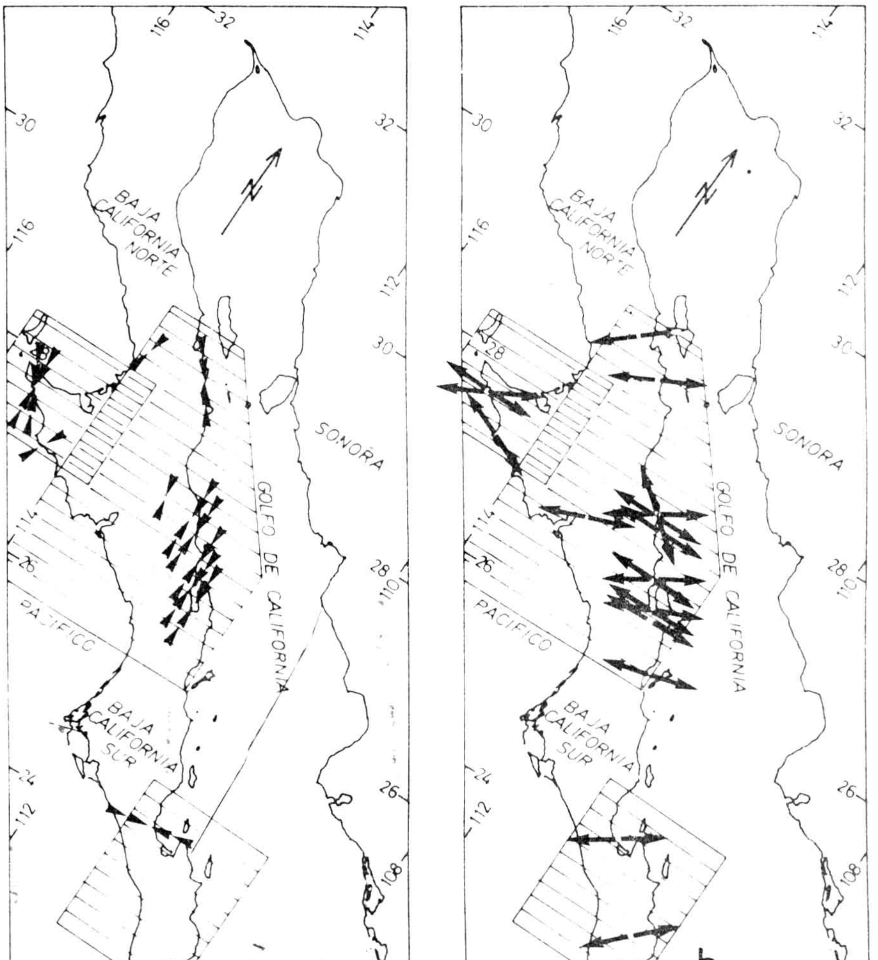

Fig. 16. Regional pattern of compressional (a) and extensional (b) stresses, σ_1 and σ_3, as inferred from field analyses of faulting.

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