GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 1, PAGES 5-8, JANUARY 1987

GEODETIC MEASUREMENTS OF PLATE MOTIONS ACROSS THE CENTRAL GULF OF CALIFORNIA, 1982-1986

M. Kasser [1 2], J.-C. Ruegg[2], Ph. Lesage[2 3], L. Ortlieb[4], J. Pagarete[1 2 8], N. Duch[5], J. Guerrero[6], J. Roldan[6 7]

Abstract. A trilateration network was set up in early 1982 by a team of French and Mexican institutions across the central part of the Gulf of California in order to study the plate boundary related movements in this transition area between the San Andreas fault system and the East Pacific Rise. The reobservation of this network in March 1986 provides a first set of data on the present day deformations in this area. Both surveys used AGA8 Laser geodimeter measurements between 11 stations located on elevated points of Baja California and Sonora and on the islands between the peninsula and mainland coasts. Deformation patterns during the 1982-1986 interval, obtained through three different methods indicate mainly a right lateral shear movement in the Gulf axis direction N46°W. Between Baja California Peninsula and Angel de la Guarda Island 17 ± 4 cm of dextral slip occurred. Between the coast of Sonora and the central islands of the Gulf the mean displacement amount to about 23 ± 12 cm. In the southwestern part of the network, weaker movements seem to have occurred, and are smaller than estimated errors. This may indicate either that the boundary is locked in this part or is deflected towards the ESE. These results, which give an estimation of the relative plate velocity of 8 ± 3 cm/a, are consistent with the generally accepted relative movement between North American and Pacific plates (about 6 cm/a).

Introduction

The Gulf of California is a complex transition zone between the sea-floor spreading boundary of the East Pacific Rise to the south and the San Andreas transform fault system to the north and contains the boundary between the North American and the Pacific plates. Bathymetric, sedimentary, and magnetic studies (Rusnak et al., 1964; Larson et al.,1968; Bischoff et al.,1974; among others) show the existence of short basins linked with NW-SE long fracture zones; on the basis of seismic data, these structures are interpreted respectively as spreading centers and transform faults with right lateral displacements (Sykes, 1968; Molnar, 1973) (Figure 1).

Several estimations of the relative plate motion velocity between Pacific and North American plates, either from global tectonics or from geophysical and geodetic methods, suggest a long term average rate of 6 cm/a (Larson et al., 1968; Minster et Jordan, 1978; Ness et al., 1985), but no direct measurement was available on the Gulf of California. The historic slip-rate since 1918 has been estimated from seismicity data (Reichle et al., 1976) to be 3.7 to 6.1 cm/a.

In the single previous tentative of direct measurement based on a short photographic experiment, Vacquier et Whitmann (1973) found no displacement during 1970-1971 between Angel de la Guarda Island and Baja California.

The Geodetic Measurements 1982-1986

In a cooperative project associating several French and Mexican institutions, a geodetic network has been set up in 1982 and remeasured in 1986. The geodetic network has a large aperture of about 150 km (Figure 1) and includes 25 distances, in the range 18-93 km, between 11 stations located on the summits of the topography on the coasts of Baja California and Sonora, and on the main islands. Distance measurements were carried out using AGA8 geodimeters mainly as these instruments are fully manual and allow to operate measurements with a very weak reflected signal. The refractive index is computed from meteorological data; its determination remains the principal source of errors. Temperature, humidity and pressure are sampled at both ends of the line and the mean refractive index n_m is calculated by assuming a linear variation of them. In order to reduce the variability of n_m, the measurements have been carried out at night. Pressure has been measured with high precision Wallace and Tiernan barometers calibrated before and after the field operation. The modulation frequency has been monitored by comparison, during and/or after the measurements with a frequency standard of 10^{-8} accuracy.

Data Processing

The field geodetic and meteorological data were to be processed to provide reliable geometric elements needed for the deformation analysis.

The relative height of the points are deduced from simultaneous observations of the pressure using Laplace's formula, by a least-squares adjustment which gave a standard deviation of 2 meters.

The aim of the standard reduction procedure is to convert the measured value D_m to the actual distance along the ray path D (Bomford, 1971, p. 60):

[1]Institut Géographique National, 2 Avenue Pasteur, 94160 SAINT-MANDE, France.
[2]Institut de Physique du Globe, 4 Place Jussieu, 75252 PARIS, France.
[3]Centro de Investigacion Cientifica y de Educacion Superior de Ensenada, Baja California, Mexico.
[4]ORSTOM, 75480 PARIS, France.
[5]Direccion General de Geografia del Territorio Nacional, MEXICO DF, Mexico.
[6]Instituto de Geologia, UNAM, MEXICO DF, Mexico.
[7]Estacion Regional del Noroeste, UNAM, Hermosillo Sonora, Mexico.
[8]Faculdade de Ciências da Universidade de Lisboa Portugal.

Paper number 6L7073.
0094-8276/87/006L-7073$03.00

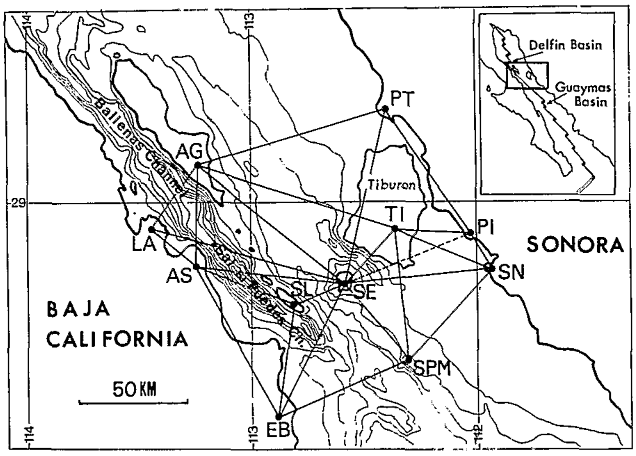

Figure 1. Central Gulf of California trilateration network. Bathymetric contours (100 fathoms) are from Rusnak et al. (1964). In insert, situation of the survey in relation to the tectonic of the region.

$$D = \frac{n_0}{n_m} \times D_m \text{ with } n_m = \frac{n_1+n_2}{2} + (k-k^2)\frac{D^2}{12R^2}$$

where n_m is named mean refractive index along the ray path; n_0 is an instrumental constant, n_1 and n_2 being the refractive index at both ends of the line. k=R/r represents the refraction coefficient along the line, assuming, for a stratified atmosphere, a constant curvature radius r of the light path, R being the local curvature radius of the Earth. The value of k is commonly deduced from n_1 and n_2:

$$k = R\ (n_1 - n_2)\ /\ (h_2 - h_1) \qquad (1)$$

When simultaneous temperature measurements were available on 5 or 6 points, we adjusted a three parameters Kukkamaki law:

$$t = a + bh^c, \qquad (2)$$

where t is the temperature and h the altitude, with the assumption of a null thermal horizontal gradient; then we computed the refraction coefficient. The value of k deduced from this law is more coherent and generally close to 0.16.

The two sets of observations have been compensated using a classical least-squares adjustment method with a priori standard deviations of 5 mm ± 1 mm/km. The observed distances for 1982, the length changes and the residuals are given in Table I.

An estimation of the precision of the network is given by the mean of the residuals divided by the respective distances. This calculation gives 0.75 ppm for 1982 and 0.43 ppm for 1986. Then, the precision deduced from the comparison of the data between the two epochs may be estimated slightly below 1 ppm. It must be noticed that:
- changes in the altimetry generally modify the residuals, but do not significantly alter the displacement vectors.
- the use of refraction coefficients k computed from formula (1) instead of formula (2) yields some small changes in the eastern part of the network, but does not modify the general pattern of the deformation.

TABLE 1: Observed Distances 1982, Variations 1986-1982, and Residuals 1982 and 1986

Line		Slope Dist. (m) 1982	86-82 (mm)	Res. (mm) 82-86	
PI	SN	18046.090	-58	-1	-2
PI	PT	66105.851	-53	-15	-25
AG	TI	93254.059	+3	-105	-25
AG	SE	82789.875	-40	+57	+25
AG	PT	86742.057	+306	-21	-36
AS	SL	48639.394	+59	-10	-31
AS	AG	48005.064	-101	+23	+10
AS	LA	26408.795	+2	-18	-10
AS	SE	65052.097	+17	-28	+25
EB	SL	40488.175	-12	-6	-20
EB	SPM	58537.076	-60	-54	-37
EB	AS	63162.843	+85	-44	-19
EB	SE	56193.830	-45	+61	+67
SE	SL	20245.646	+37	-2	-7
SE	LA	85249.924	+253	+188	+107
SE	SN	67344.814	+305	+197	+22
SE	PT	77520.022	-120	+22	+37
AG	LA	32542.074	+68	-16	-9
TI	SN	47268.866	+4	-54	+10
TI	SE	39673.072	+35	-24	+11
TI	PI	30558.472	-47	-1	-02
SPM	TI	63594.972	+61	+85	-30
SPM	SN	56102.582	-113	-86	-16
SPM	SE	43611.295	-54	-14	+21

Results

The displacement field resulting from the comparison of original and further measurements has only a relative meaning depending either on fixed elements in the network (one station and/or azimuth, or one group of stations) or on the minimization criterium which has been used in the analysis (Gu and Prescott, 1986). The resulting displacement pattern and associated error ellipses are strongly dependent on the selection of the fixed parameters and of the analysis methodology, in such a way that the interpretation of deformations may be obscured by an improper choice. The analysis of the Gulf of California defor-

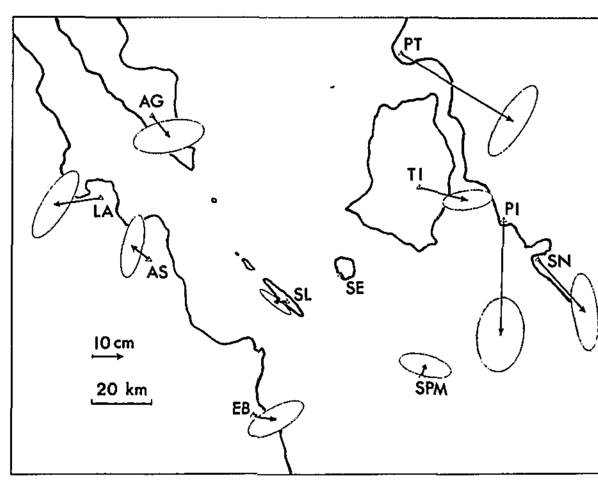

Figure 2. Displacement vectors obtained by fixing station SE and azimuth SE-AG, with associated error ellipses corresponding to 1 standard deviation.

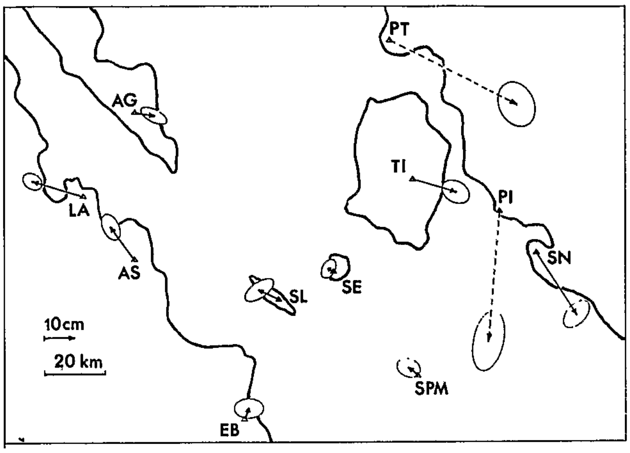

Figure 3. "Outer coordinates" displacement vectors with a direction of reference N46°W and associated 1 σ error ellipses. This solution has been calculated excluding the point PI and PT from the minimization.

mations has been conducted using the following solutions:
- Displacement vectors fixing one point and one azimuth from the original coordinates of 1982 in the 1986 adjustement minimizing the distance residuals. This solution is shown in Figure 2 with station SE and azimuth SE-AG fixed.
- The "outer coordinate" method proposed by Prescott (1981), specially adapted to the detection of strike-slip displacement, minimizes the displacements perpendicular to a given azimuth. The solution with a reference azimuth of N46° W (direction of the Gulf axis) is shown in Figure 3; the points PI and PT were discarded of the minimization in order to better satisfy the criterium proposed by Darby (1982), i.e. the displacements perpendicular to the reference direction should be small.
- The representation of the mean strain tensors for triangles (or subregions) of the network provides an intrinsic representation of the deformation and can be used either with observed distance variations or with compensated data. This last solution is illustrated in figure 4 for selected triangles and polygones.

The errors on the displacement vectors and strain tensors are estimated by using the values given by the planimetric compensations, σ_r=0.75 ppm (1982) and σ_r=0.43 ppm (1986). The errors on the relative displacement between two points are computed from a solution where one of these points is fixed in order to eliminate the effect of error propagation.

The examination of figures 2, 3 and 4 leads to divide the network into four areas:
- In the northwestern part, a dextral strike-slip movement is evidenced between Angel de la Guarda Island (AG) and the Baja California coast (LA, AS). The relative displacement parallel to the N46°W direction amounts to 17 ± 4 cm, between 1982 and 1986.
- In the southeastern area, a dextral strike-slip movement is detected between SPM/SE and TI/SN; the relative displacement amounting to 23 ± 12 cm between SE and SN.
- In the southwestern area, between EB, SL, SE, and SPM, the deformations appear to be small, and anyway smaller than the estimated errors. At a low confidence level one may suspect a slow dextral shear.
- The displacements of stations PT and PI are not well constrained because of the lack of data for the distance TI-PT. Nevertheless, their movements seem to be in the same direction than that of the other points on the eastern coast, and the strain tensors in the northeastern region have the same magnitude and direction than in the northwestern and southwestern areas.

The strike-slip movement between Sonora (PI,-PT,SN) and Baja California (AS,LA,EB) has been calculated using the mean of the relative displacements parallel to the N46° W direction between the stations on each side of the Gulf, and yields 32 ± 12 cm.

It could be noticed that the EW or NE-SW extension component is weak in almost all the network.

Tectonic Implication

The observed strike-slip deformation across the Ballenas Channel depicts the present day activity of this segment of the transform fault which presumably links the Delfin Basin and the Guaymas Basin (Rusnak et al.,1964; Bischoff et al.,1974). It has been inferred that this segment of fault has been locked (Vacquier and Whiteman, 1973) for about 20 years, probably until the July 8, 1975, M_s=6.5 strike-slip earthquake (Munguia et al., 1977). The 1982-1986 displacements seem to indicate that this structure remained unlocked after this event, and that fault creep occurs in this part of the transform plate boundary.

On the contrary, no significant deformation is observed in the southwestern area, between Baja California (EB) and the central islands (SE, SPM, SL). It may be inferred that the Sal-si-Puedes Channel structure between San Lorenzo (SL) and Baja California (EB) has been locked during the last few years as it is indicated from the lack of seismic activity; alternatively the plate boundary may be interrupted north of San Lorenzo, and strongly deflected towards the ESE.

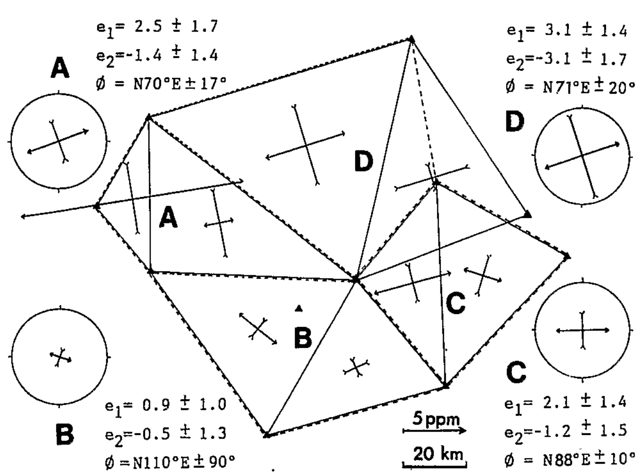

Figure 4. Strain tensors for selected triangles of the network. In the circles, mean strain tensors for the four subregions delimited by dashed lines, and principal values of extension and contraction axis, and orientation of the extension axis.

In the area between the Tiburon and Sonoran points and the San Esteban and San Pedro Martir Islands a few faults have been described (Bischoff et al., 1974; Sanchez et al., 1985), but no bathymetric or structural clear evidence of a plate boundary has been previously reported. The observed 1982-1986 deformation may be explained by strain accumulation over a large zone across the eastern Gulf of California, or else by local creep release along secondary faults.

Although the geodetic data in the northeastern area have a poor reliability, they seem to be consistent with a strain accumulation distributed over a large area, or with a complex secondary faulting pattern (Bischoff et al., 1974; Sanchez et al., 1975).

In the period 1982-1986, a few earthquakes (M=4.5-5.6) occurred in the central region of the Gulf of California; this seismicity may be associated with the observed deformation but the ISC and NEIS determinations are not accurate enough to study in detail this relationship.

Conclusion

The resurvey in 1986 of the trilateration network set up in 1982, provides the first geodetic description of regional motion in the Central Gulf of California. In the last four years, the mean rate of right lateral displacement between Sonora and Baja California can be estimated to 8 ± 3 cm/a and thus is consistent with previous geophysical and geological published data.

The geodetic measurements shed a new light on the distribution and on the regime of the deformation, and lead to distinguish four subregions.

Dextral strike-slip motion along a narrow fault zone is evidenced only in the Ballenas Channel, while the Sal-si-Puedes Channel fracture seems to have remained locked.

An unpredicted large motion is occurring between the Sonora coast and the islands, either as result of strain accumulation or along some secondary faults.

Aknowledgments. This study was supported by numerous French and Mexican Scientific Institutions and Governmental Agencies, among which: INSU, IGN, ORSTOM, Centre Scientifique Français of Mexico, Instituto de Geologia (UNAM), DGGTENAL, CICESE, Comision Federal de Electricidad, Universidad de Sonora. One of us (J.P.) is supported by a grant of Calouste Gulbenkian Foundation. The authors thank all the other participants in the field work: B. Colletta, J.L. Guichard, G. Verrier, F. Castellanos, T.R. Montano, J.L. Rodriguez, T. Calmus, E. Castillo, T. Valdez, V. Navarro and the crews of the helicopters (from CFE in 1982, and from DGGTENAL, in 1986). Their gratitude is also due to the staff of the Instituto de Geologia (UNAM) at Hermosillo and to A. Resendiz at Bahia de Los Angeles. Special mention should be made of J. Angelier and B. Colletta who actively initiated the project but were not able to participate in the 1986 remeasurement of the network. Contribution LS 8609 IPG 943.

References

Bischoff L. and T. Henyey, Tectonic element of the central part of the Gulf of California. Bull. Geol. Soc. Amer., 85, 1893-1904, 1974.

Bomford G., Geodesy, 3d Ed., 731 pp., Oxford Un. Press, 1979.

Gu G. and W.H. Prescott, Discussion on displacement analysis: detection of crustal deformation. J. Geophys. Res., 91, 7439-7446, 1986.

Darby D., The analysis of variance of an underdetermined geodetic displacement problem. Geophys. Res. Lett., 9, 641-644, 1982.

Larson R.L., H.W. Menard and S. Smith., Gulf of California: a result of ocean floor spreading and transform faulting. Sciences, 161, 851-884, 1968.

Minster, J.B. and T.H. Jordan, Present day plate motions. J.Geophys. Res., 83, 5441-5354, 1978.

Molnar P., Fault plane solutions and direction of motion in the Gulf of California and Rivera fracture zone. Bull. Geol. Soc.Am., 84, 1651, 1973.

Ness G.E., M.W. Lyle and A.T. Longseth, Revised Pacific, North America, Rivera and Cocos relation motion poles: implications for strike-slip motion along the trans-mexican volcanic belt, EOS Trans. AGU, 66, 849-850, 1985.

Prescott W.H., The determination of displacement fields from geodetic data along a strike-slip fault. J. Geophys. Res., 86, 6067-6072, 1981.

Rusnak G.A., R.L Fisher, F.P. Shepard, Bathymetry and faults of Gulf of California in Marine Geology of the Gulf of California. Am. Assoc. of Pet. Geol. Mem., 3, 59-75, 1964.

Sykes L., Seismological evidences for transform faults, sea floor spreading and continental drift. In: History of the Earth's Crust, NASA Symposium, R.A. Phinney Ed., Princeton Univ. Press, 120-150, 1968.

Vacquier V. and Whiteman, R.E., Measurements of faults displacement by optical parallax. J. Geophys. Res., 78, 858-865, 1973.

Munguia L., M. Reichle, A. Reyes, R. Simons and J.Brune, Aftershocks of the 8 july, 1975 Canal de Las Ballenas, Gulf of California, earthquake. Geophys. Res. Lett., 4, 507-509, 1977.

Reichle M.S., G.F. Sharman and J.N. Brune, Sonobuoy and teleseismic study of Gulf of California transform fault earthquake sequences. Bull. Seism. Soc. Am., 66, 1623-1641, 1976.

Sanchez Z.O., G.E. Ness, R.W. Couch and J.P. Dauphin, Present-day faulting and major structural blocks of the northern Gulf of California, EOS Trans., AGU, 66, 844, 1985.

(Received October 20, 1986;
accepted October 31, 1986.)