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DEFORMATION NEAR THE EPICENTER OF THE 9 JUNE 1980 M_L = 6.2 VICTORIA, MEXICO, EARTHQUAKE

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ABSTRACT

Geodetic data around the northern end of the Cerro Prieto Fault shows that a positive areal dilatation of 0.9 ± 0.4 μstrain ocurred during a 1 year period ending 18 months before the 9 June 1980 Victoria, México, earthquake. During the 2 year period including the earthquake, relative motion between two stations on opposite sides of the fault was 0.29 ± 0.02 m. Right-lateral slip of 0.5 ± 0.1 m on the Cerro Prieto fault between the surface and 12 km depth would fit 1979 to 1981 length changes in the network. The northern subsection of the network is about 30 km west of the epicenter of the 15 October 1979 Mexicali earthquake. Strain accumulation in this subsection shows a 0.7 ± 0.3 ppm dilatation in the 1978-79 interval which was completely recovered by 1981. The only significant strain accumulation in this subsection between 1978 and 1981 was a 0.4 ± 0.2 μrad east-west shear. Deformation produced by steam extraction at the Cerro Prieto geothermal production field was either not observed, or was masked by earthquake-related changes.

INTRODUCTION

Measurements of a regional trilateration network near the Cerro Prieto geothermal field in Mexico were made in 1978, 1979, and 1981 by the U.S. Geological Survey as part of a U.S. Department of Energy program to monitor deformation produced by both the San Andrès fault system and by steam extraction. The Mexicali strain network (see Figure 1) extends 80 km south from the border between the United States and México, spanning a 25 km wide area centered on the Cerro Prieto geothermal field and an adjacent 30 km wide area across the Laguna Salada Valley to the west.

Measurements of the distance between geodetic monuments in the network are made with a Geodolite, a precise electro-optical distance measuring instrument. The procedures and precision obtained have been described by Savage and Prescott (1973). The standard error in measuring an average distance in the Mexicali network is about 7 mm. In both 1978 and 1979 all lengths within the network were measured twice within a short period of time.

Two moderate strike-slip earthquakes, the Mexicali (14 October 1979, M_L = 6.6) and Victoria (9 June 1980, M_L = 6.2), occurred in areas adjacent to the network between the 1979 and 1981 measurements. The epicenter for the Mexicali earthquake was about 25 km east of the northeastern stations in the Mexicali network. Several of the stations in the southeastern portion of the network are located within the zone of aftershocks from the Victoria earthquake.

GEOTHERMAL AREA

A radial array centered on station Prieto spans the area around the geothermal steam wells. Length as a function of time for lines within this array is shown in Figure 2. Little change is seen between the 1978 and 1979 surveys. Only lines to 36, 1, and BNP 10065 show significant change, a length increase of from 12 to 18 mm. Survey error, fault slip, or steam extraction are possible sources for observed length changes. Steam extraction can be eliminated for stations 1 and 36 since other stations closer to the steam well area show no change. BNP 10065 is closest to the geothermal area and at least part of the 12 ± 5 mm change could be attributed to steam extraction. Fault slip is not evident in other limits which cross the area.

Length changes between the 1979 and 1981 surveys are much greater, especially for stations 3 and 17 which are located near the aftershock zone of the Victoria earthquake. Figure 3 shows that the aftershocks are concentrated in a narrow zone near stations 17 and 3, becoming more diffuse farther northwest. The relatively small changes in lengths to stations 10, 9, 8 and BNP 10065

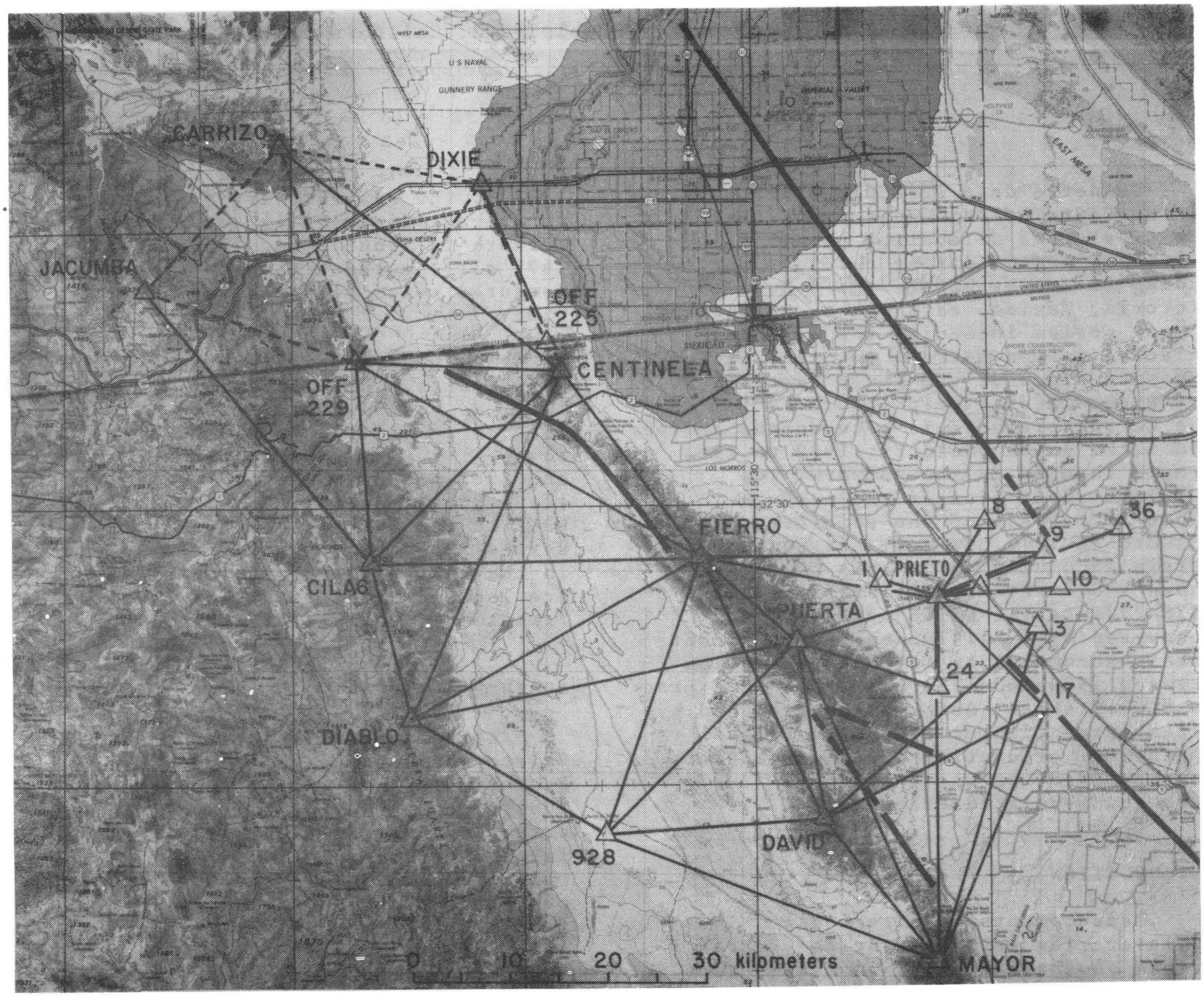

Figure 1. Map of the Mexicali network. Lines connecting triangles represent measured lengths. Dashed lines are lengths from the adjacent Salton network used in the analysis. Epicenters of the 1979 Mexicali earthquake ($M_L = 6.6$) and the 1980 Victoria earthquake ($M_L = 6.2$) are shown by stars.

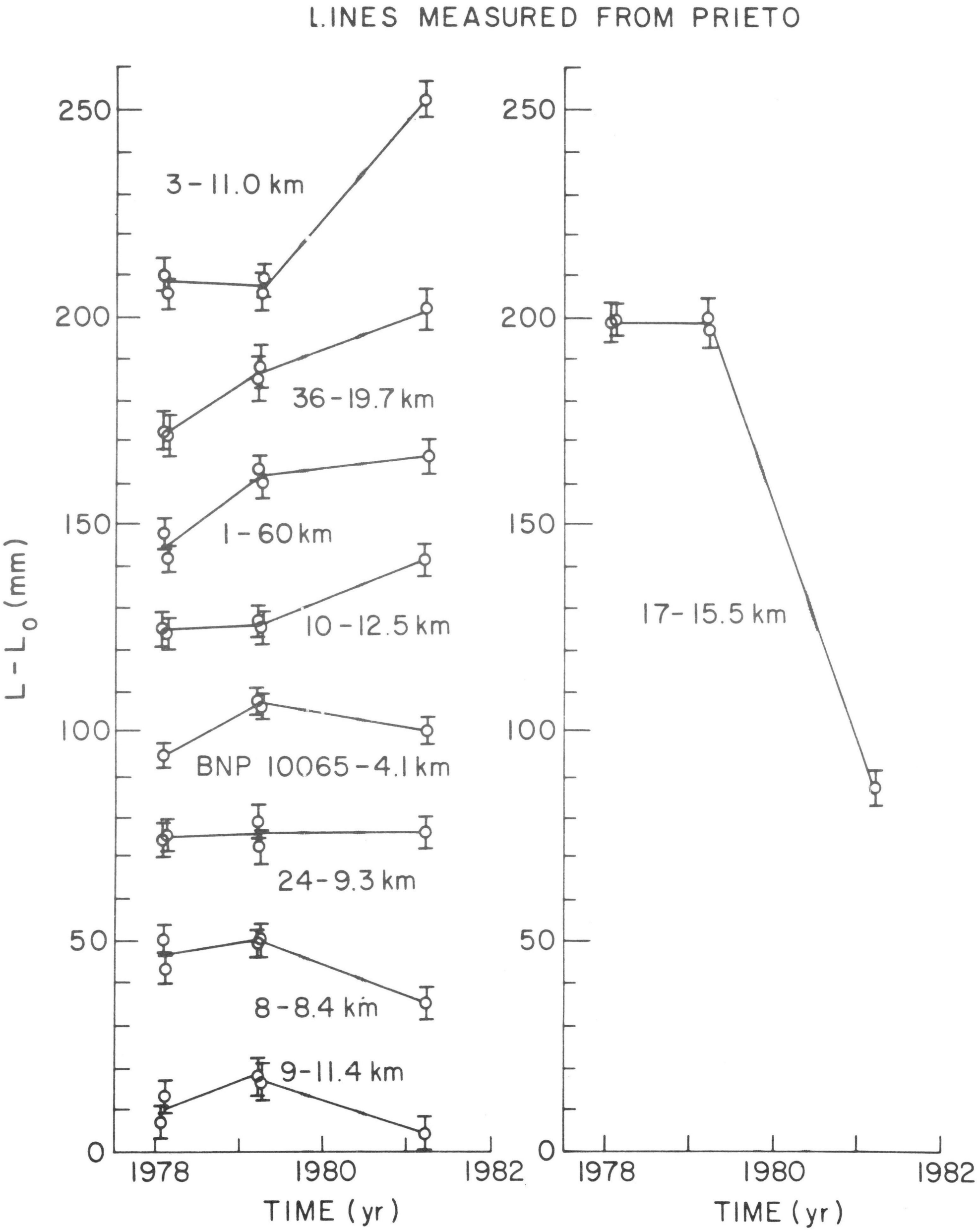

Figure 2. Plot of length as a function of time for lines around the geothermal area measured from Prieto. Error bars represent one standard deviation on either side of the plotted point. The times of the 1979 Mexicali and the 1980 Victoria earthquakes are shown by the thick vertical lines. Each curve is labelled by station number and line length.

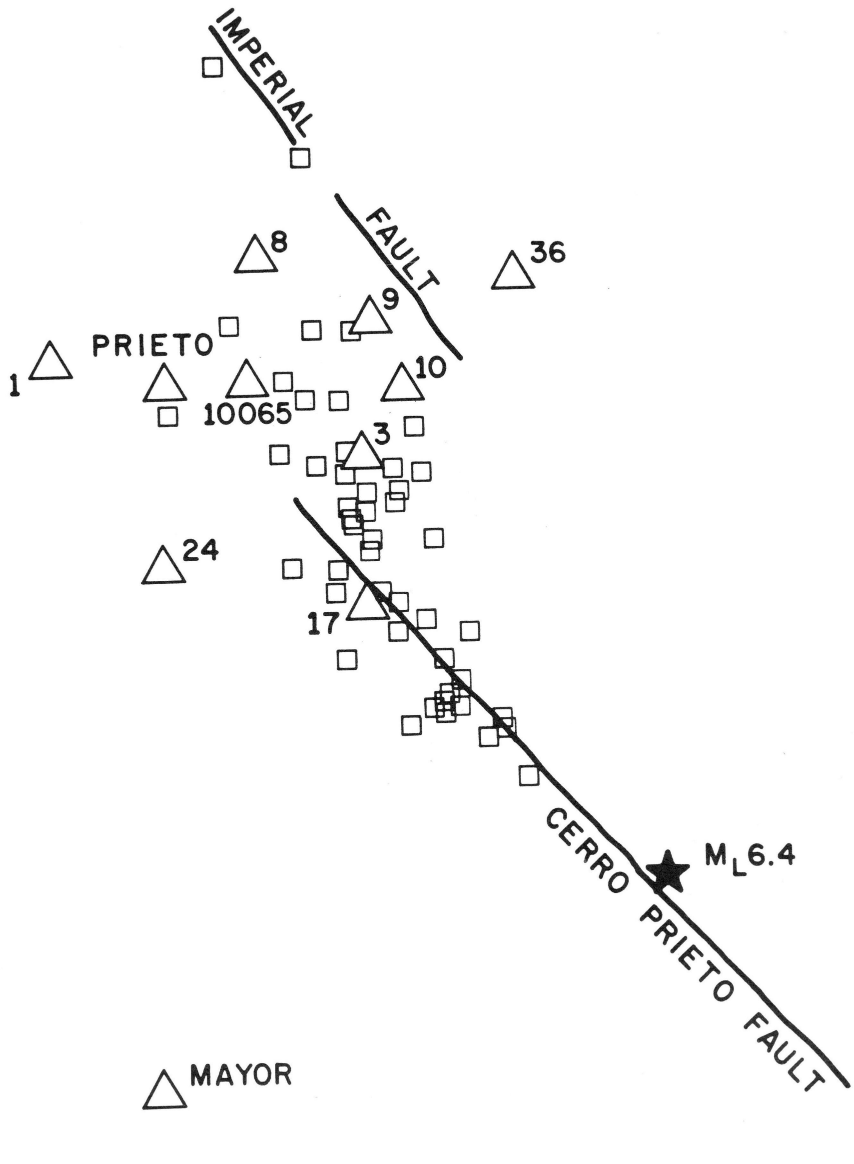

Figure 3.- Map showing the location of epicenters of the aftershocks from the 1980 Victoria earthquake relative to major faults and nearby stations in the Mexicali network.

indicate the rupture did not extend much farther than station 3. To gain a better understanding of the deformation in this area we will examine the relative movements of a larger subset of stations in the Mexicali network.

RELATIVE STATION DISPLACEMENTS

Unlike the radial array around the geothermal area where all measurements are made from station Prieto, most stations in the Mexicali network form a geometrically rigid figure. The relative motion of these stations coordinates adjustment. Because their position is not fixed relative to the others, stations 1, 8, 36, 10, and BND 10065 were excluded from this analysis. To provide a tie between stations Jacumba, Carrizo, Dixie, OFF 229, OFF 225, and Centinela, we use some measurements made during surveys of another network, the Salton network (for details about the Salton network refer to Savage et al., 1979). These measurements were made using the same equipment and procedures and at nearly the same time as the Mexicali network surveys.

Since the network is not fixed to an external reference frame, some constraints have to be applied to eliminate ambiguities arising from rigid-body rotation or translation of the network. We have solved for station position shifts using the "outer coordinate" solution (Prescott, 1981) which requires the center of mass to remain stationary and also minimizes the component of displacements normal to the azimuth of the fault. This method is particularly useful in determining displacements across strike-slip faults. Position shifts are shown in Figure 3.

Between 1978 and 1979 position shifts are small and not significant at the 95 percent confidence level. Between 1979 and 1981 large relative displacements are seen between stations near the Cerro Prieto fault, but elsewhere the movements are small. Relative fault parallel displacement between stations 3 and 17 is 0.29 ± 0.02 mm.

The large displacements across the Cerro Prieto fault are certainly related to the 9 June 1980 Victoria earthquake. The location of aftershocks shown in Figure 3 and the small length changes seen in most lines measured from station Prieto suggests that the end of the fault rupture should be slightly northwest of station 3. The large position shift at station 9 is not well constrained.

We have established that deformation within the Mexicali network is small except in the period containing the Victoria earthquake. For that period large relative displacements are seen in the stations closest to the earthquake epicenter. In the areas of the network where the deformation pattern is fairly uniform we can use the length change to caculate strain accumulation.

SPATIAL AND TEMPORAL STRAIN ACCUMULATION

By assuming that strain is uniform in space over the area covered by a subsection of the network and in time over the interval between surveys, proportional changes in the lines can be used to compute the three components of the surface strain tensor, E_{11}, E_{12}, and E_{22} (the 1 axis is directed east and the 2 axis north) (Prescott et al., 1979). The complete strain field is determined by E_{11}, E_{22} and $\gamma_2 = 2E_{12}$, but additional insight may be gained by examining the shear component $\gamma_1 = E_{11} - E_{22}$ and areal dilatation $\Delta = E_{11} + E_{22}$.

The large coseismic length changes around the earthquake rupture zone violate the uniform strain assumption. We cannot, therefore, use the entire Mexicali network in the analysis. If we eliminate the lines from the 1981 survey which were affected by the earthquake, then to produce a temporally homogeneous data set, we also have to eliminate them from the previous surveys. The subset of lines that remain span the Laguna Salada Basin. Strain accumulation for this subsection is shown in Figure 5. The plots show a 0.9 ± 0.3 μstrain positive dilatation between 1978 and 1979 with a nearly equal, but negative, dilatation between 1979 and 1981. This dilatation consists primarily of an east-west extension, suggesting that the observed dilation is not an artifact of a scale error. The only other significant change occurred between 1979 and 1981 in the γ_1 would indicate right-lateral shear across a plane at N45°W or left=lateral shear across the conjugate plan. N45°W is approximately the strike of the Cerro Prieto and Imperial faults. The observed γ_1 component of shear was -0.6 ± 0.2 μradian, which would indicate left-lateral shear parallel to the Cerro Prieto fault. This is the expected pattern of strain release for an area adjacent to but not crossing a NW-trending right-lateral strike-slip rupture zone.

The earthquake-related changes should be greatest in the portions of the network within and adjacent to the rupture zone. In order to compare and contrast strain

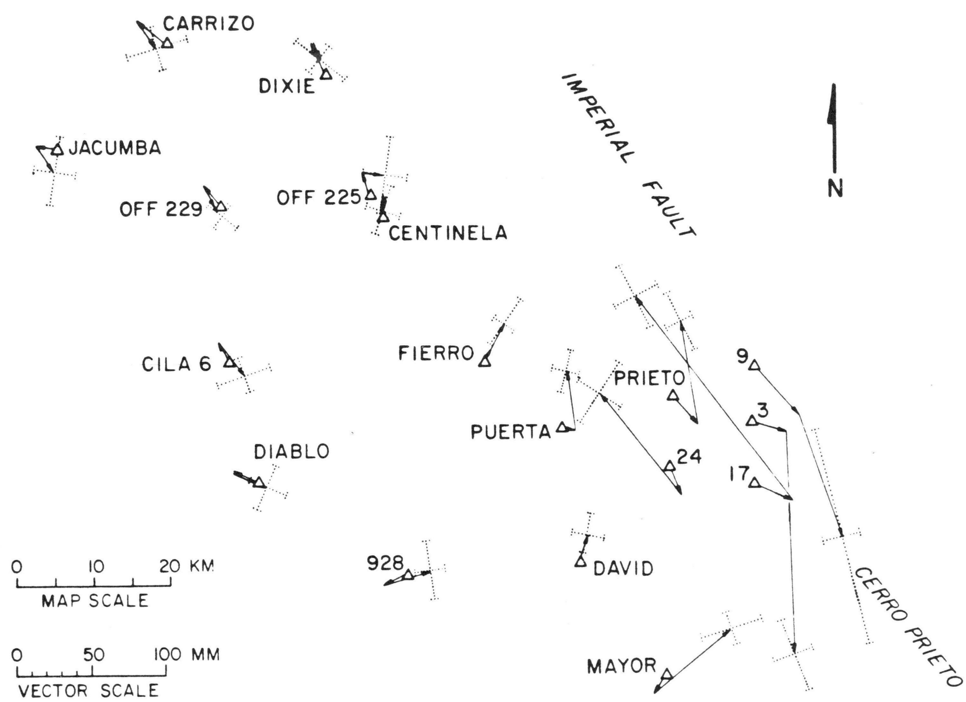

Figure 4. Map showing 1978-1979 and 1979-1981 relative station displacements derived from an "outer coordinate" adjustment. The 1979-1981 vectors are tipped with the major and minor axis of a two standard deviation error ellipse. The size of the error ellipse is the same for both time periods.

TABLE 1. MODEL FAULT PARAMETERS AND COMPUTED RIGHT-LATERAL SLIP FOR THE RUPTURE ZONE OF THE 1980 VICTORIA EARTHQUAKE

Distance NW of Station 17 to End of Fault (Km)	Depth Range, Km	Slip, m	(O-C)2
3	0-12	0.51±0.08	0.06
3	0- 8	0.51±0.08	0.07
3	1-12	1.10±0.11	0.04
3	1- 8	1.18±0.11	0.04
8	0-12	0.46±0.06	0.06
8	0- 8	0.47±0.06	0.06
8	1-12	0.86±0.09	0.04
8	1- 8	1.01±0.10	0.04

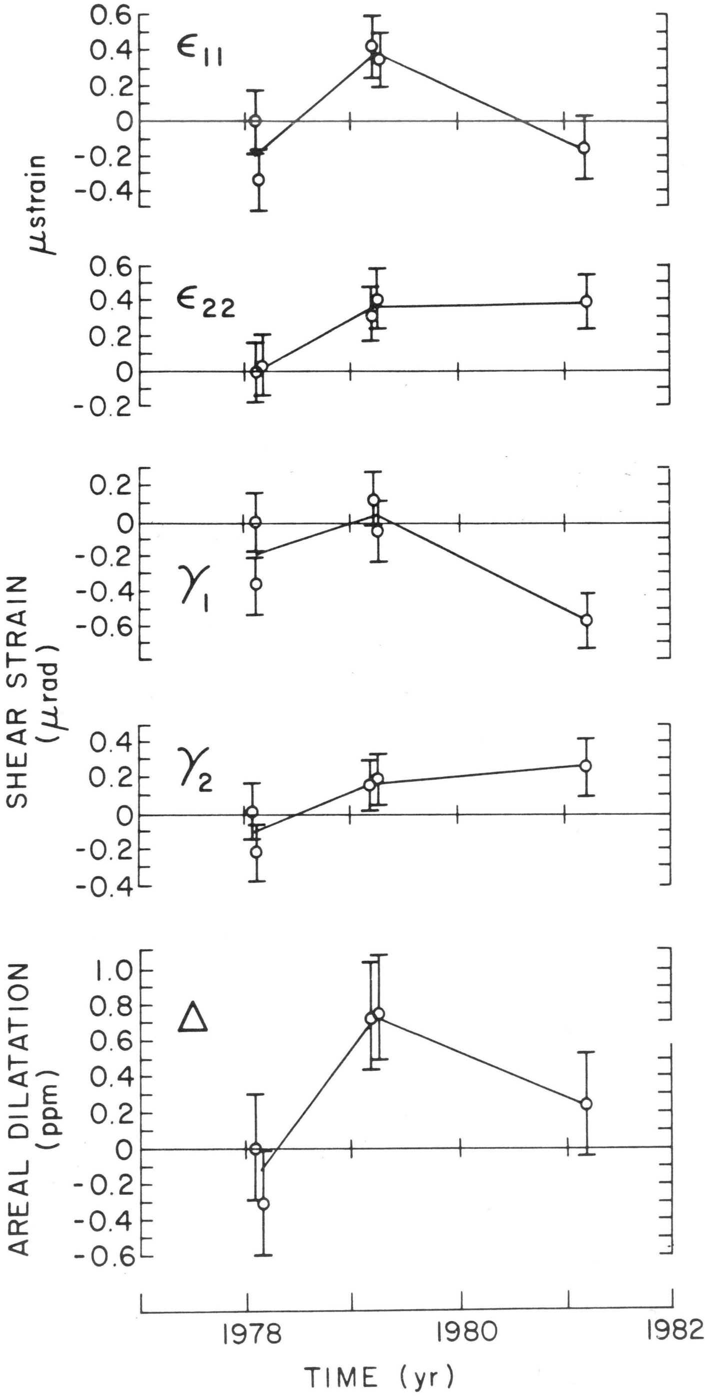

Figure 5. Strain accumulation for the portion of the Mexicali network which spans the Laguna Salada Valley. The strains are referred to a coordinate system with the 1 axis directed to the east and the 2 axis directed to the north. $\gamma_1 = E_{11} - E_{22}$; positive γ_1, measures right-lateral shear across a line striking N45°W or left-lateral shear across its conjugate. $\gamma_2 = 2E_{12}$; positive γ_2 measure right-lateral shear across an east-west line or left-lateral shear across its conjugate. $\Delta = E_{11} + E_{22}$ is areal dilatation. Error bars represent one standard deviation on either side of the plotted point.

changes in different areas, we divided the network into 3 subsections; the north, consisting of all lines along the Laguna Salada Basin north of the line between stations Fierro and Diable; the south, consisting of all lines along the Laguna Salada Basin south of the boundary; and the east, consisting of all lines into stations in and between the geothermal area. Strain accumulation for these three subsections is shown in Figure 6. No strain analysis was made for the 1981 survey of the eastern subsection because of the non-uniform strain field.

Comparing strain accumulation between the subsections we see significant differences in E_{22}, γ_1, and Δ. Most apparent is the -0.7 ± 0.2 μrad change in γ_1 in the south subsection, during the 1979-1981 interval. As expected, the virtual left-lateral strain release is concentrated in the area adjacent to the rupture zone of the Victoria earthquake. The positive dilatation seen between 1978 and 1979 completely recovered in the north subsection by 1981, but only partially in the south. Although both areas returned to the 1978 level in the east-west extension (E_{11}), the southern section continued to show an increase in north-south extension (E_{22}). Both areas show a significant amount of east-west shear, γ_2, but in the north the increment occurred between 1979 and 1981 while in the south it occurred between 1978 and 1979.

A more graphical representation of the strain field can be obtained by examining Figure 7, which shows the orientation and magnitudes of the principal strains E_1 and E_2, where E_1 is the maximum extensional strain and E_2 is the minimum extensional strain. The strain pattern in the south and east subsection between 1978 and 1979 is dominated by a large 0.8 ± 0.2 μstrain extension which is nearly perpendicular to the azimuth of the Cerro Prieto fault. The pattern in the north over the same period is a nearly isotropic positive dilatation. Between 1979 and 1981 the north subsection shows a strain reversal which returns most components to the initial 1978 state. The south subsection shows a left-lateral shear across a NW trending line superimposed on small negative dilatation.

In summary, we find a large positive dilatation between 1978 and 1979 in all three subsections. In the north it consisted of a nearly uniform positive dilatation; in the south it consisted primarily of extension normal to the azimuth of the fault, and in the east it appeared to be an extension normal to the fault superimposed on a right-lateral shear. During the coseismic interval the north subsection nearly recovered to its original level while in the south we see a left-lateral shear across a plane parallel to the Cerro Prieto fault.

DISLOCATION MODELS

Using the length changes observed at the time of the Mexicali network we solved for slip on the rupture surface of the Victoria earthquake. The surface deformation pattern produced by displacements across a fault surface was approximately by a simple model of dislocations in an elastic half space (Chinnery, 1961). The model parameters were taken to approximate the fault rupture surface suggested by seismic data. The observed length changes were then used to determine the amount of fault slip. This determination is fairly weak since the Mexicali network has only a few stations within the rupture zone of the Victoria earthquake. As shown in Figure 3, aftershocks extend from the epicenter along the Cerro Prieto fault to nearly the geothermal area.

The fault used in the dislocation model was a vertical rectangular surface which extends in either direction along the mapped surface trace of the Cerro Prieto fault an equal distance from the point closest to the earthquake epicenter. We varied the location of the ends, top, and bottom of the model fault to find the best fitting solution. The model is an oversimplification of the actual faulting that occurred but a more complex model is not warranted by the measurements. Even though motion on the model fault surface is entirely strike-slip, the displacement vectors of stations near the ends of the fault have a normal component. End effects would be reduced somewhat by a more realistic gradational change at the edge of the dislocation surface. Results from the simple dislocation model are listed in Table 1.

Since the network does not span the southern end of the aftershock zone (Figure 3), the location of the southern end of the dislocation surface is not critical, as long as it is well south of the network. The location of the top, bottom and northern end of the dislocation surface is more critical however. The pattern of aftershocks and the large displacements of station 17 with respect to nearby stations indicate the rupture propogated to at least this point. To test the effect of varying the boundaries of the dislocation surface we tried models that extend 3 and 8 km northwest of 17. We

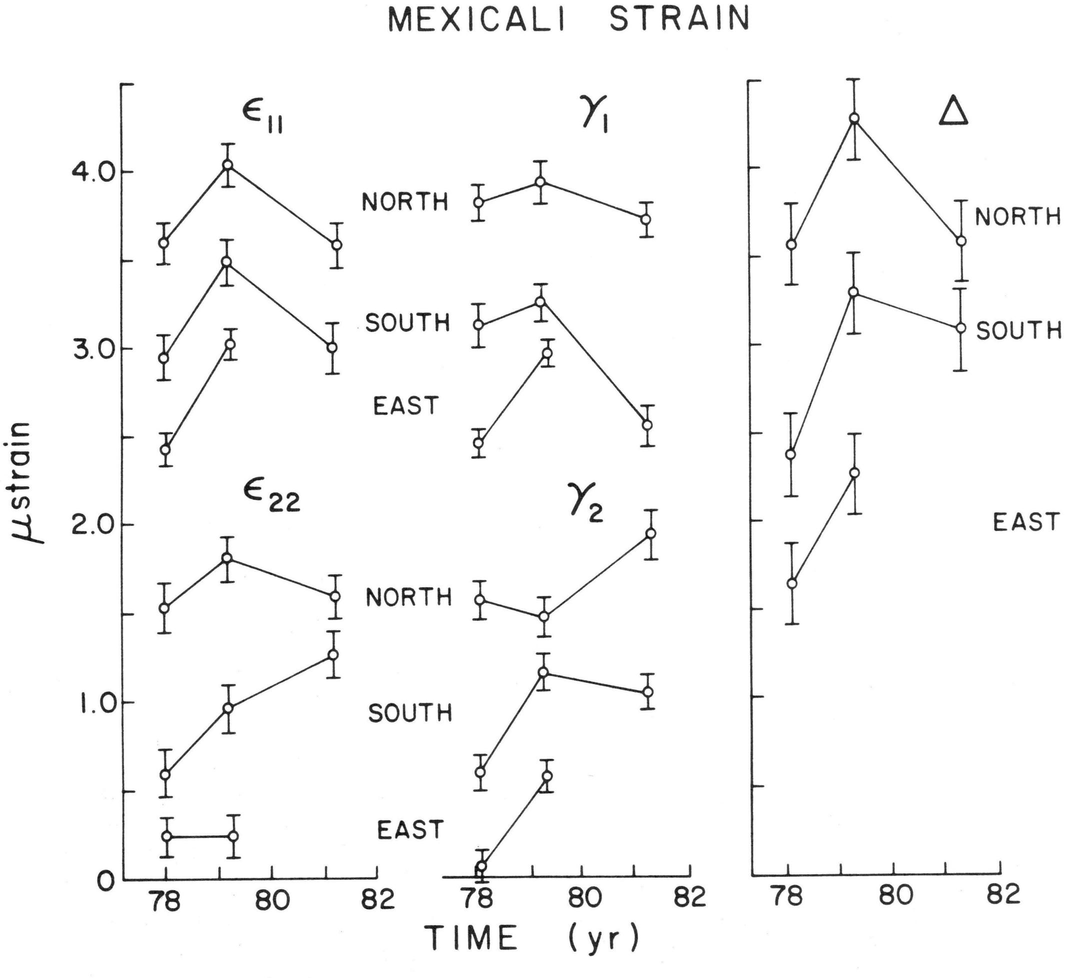

Figure 6. Strain accumulation for 3 subsections of the Mexicali network. North contains all lines north of the line between Fierro and Diablo, south contains all lines to the south of this boundary which cross the Laguna Salada Basin, and east contains all lines into or between stations around the Cerro Prieto geothermal area. Refer to Figure 5 for an explanation of the strain components. Strain components are not shown for the 1981 survey in the east subsection because of large earthquake related changes.

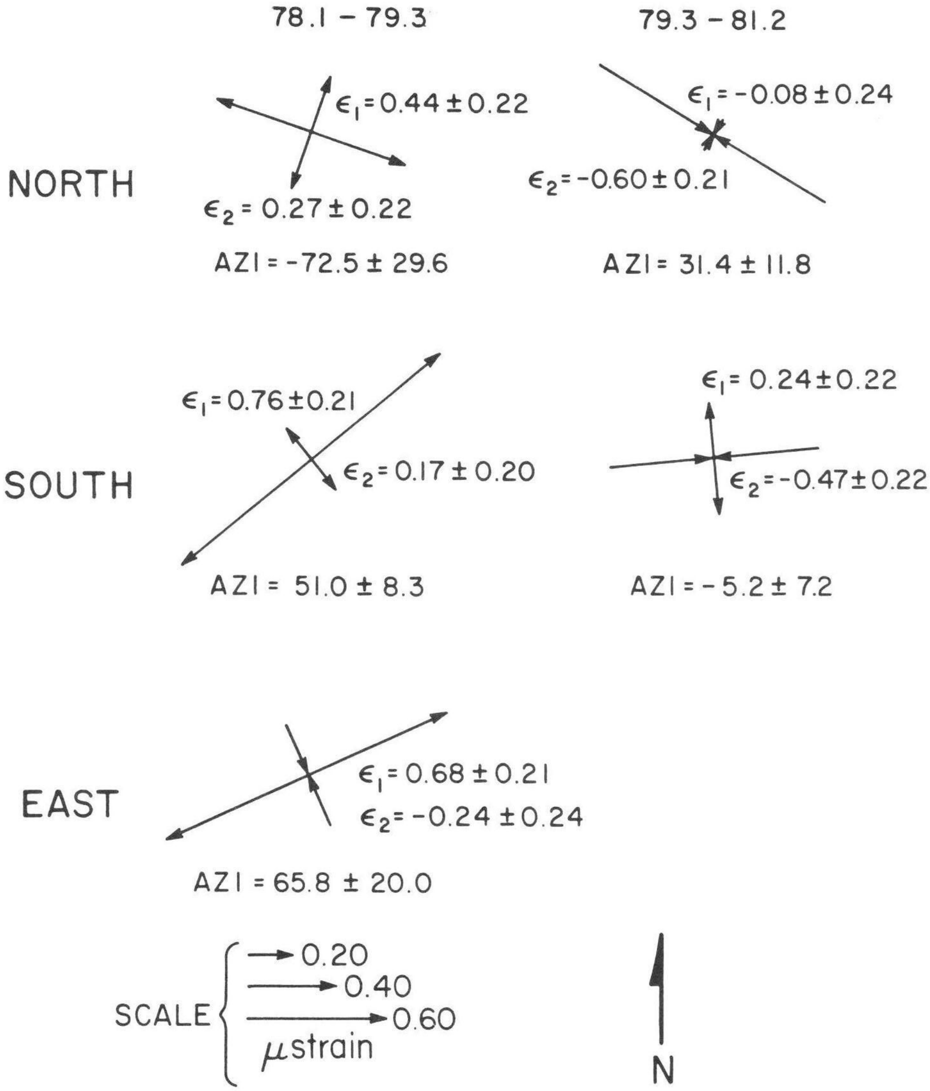

Figure 7. Orientation and magnitude of the average principal strains during two periods for north, south, and east subsections of the Mexicali network. E_1 is the maximum extensional strain and E_2 is the minimal extension strain. Numerical values with stan- dard deviations are shown. Azimuths shown with standard deviation are for the direction of E_1. No principal strains are shown for the east subsection during the 1979.3-1981.2 period because of the large earthquake related changes.

also varied the depth to the bottom of the fault between 8 and 12 km, and the depth to the top of the fault between 0 and 1 km. All models with the upper edge at the surface gave values of slip near 0.5 m. Those with the upper edge buried at 1 km gave slip values near 1.0 m. The best fit for models which extended to the surface had a 12 km depth with the northwest end 8 km from station 17. In this model right-lateral slip was 0.46 ± 0.06 m, not unreasonable for an earthquake of this magnitude.

Since there was no reported surface rupture, a buried rupture surface may be a more appropriate model. The effect of burying the surface is an increase in computed slip to about 1 m. These models fit the observed changes slightly better. Thus the geodetic data are most consistent with a rupture model extending downward from 1 km. The location of the bottom edge and the northern end of the rupture surface are not well constrained by the data. For all such buried rupture models the slip is about 1 m. The amount of slip given by the model is very sensitive to the position of the upper edge of the dislocation surface, and the position of this upper edge is only poorly constrained by the observations. Consequently the amount of slip is more poorly determined than the error bars in Table 1 suggest.

DISCUSSION

The results from a 3 year study of regional deformation around the Cerro Prieto geothermal fields are dominated by coseismic effects from the 1980 Victoria earthquake. The extraction of steam may have introduced small preseismic changes near the steam wells, but these effects, if they exist, are masked by the large earthquake-related changes during the coseismic period.

The expected pattern of deformation from the northwest-ward motion of the Pacific plate relative to the north American plate is right -lateral shear across a vertical plane striking N 48°W. The predicted secular strain accumulation would consist of equal amounts of east-west extension ($E_{11}>0$) and north-south contraction ($E_{22}<0$). There would be no east-west shear (E_{12}) or areal dilatation ($E_{11} + E_{22}$). In stear components, there would be a large $\gamma_1(E_{11} - E_{22})$ and no $\gamma_2(E_{12})$. Deviation from these predicted values might be caused by measurement errors, non-uniform strain, pre-earthquake strain anomalies, and earthquake-related changes.

In the preseismic period, 1978-1979, strain accumulation is dominated by a positive dilatation. As seen in Figure 5 this dilatation in the south and east subsection consisted mainly of an extension normal to the strike of the Cerro Prieto fault, while in the north it was a nearly uniform dilatation. Right-lateral shear parallel to the Cerro Prieto fault is seen only in the east subsection. Two possible causes of the observed positive dilatation are an anomalous strain event or a systematic error in the measurements which results in a relative length increase. It is unlikely that the dilatation is due to error. Savage et al. (1981) in their discussion of strain accumulation in seven Geodolite networks in southern California observed to change in the secular trend of strain accumulation in 1978-1980. Prior to 1978 and perhaps after 1980 the strain has been predominantly a uniaxial north-south compression. This secular trend was interrupted sometime in 1978-1979 by an increment of both north-south and east-west extension in five of the seven networks. They concluded that it was unlikely that this strain increment resulted from systematic error. Comparisons with other systems revealed no appreciable cumulative systematic error. The large dilatation observed prior to the Victoria earthquake could be interpreted as a preearthquake anomaly; however, such a relationship is speculative rather than proven, since similar events in other networks were not followed by earthquakes (Savage et al., 1981).

The coseismic changes are most apparent and easiest to interpret in the south subsection of the Mexicali network. Strain release from the Victoria earthquake produced a large decrease in γ_1 (Figure 6). There was a small negative dilatation relative to 1979, a consequence of the east-west compression being slightly larger than the north-south extension. This negative dilatation increment did not restore the region to the 1978 level. In contrast the net dilatation in the north subsection between 1978 and 1981 is 0.0 ± 0.4 μstrain. The only significant strain accumulation in this subsection is 0.4 ± 0.02 μstrain in the γ_2 component of shear, all of which occurred in the coseismic period. Recall that γ_2 is right-lateral shear across an east-west plane or left-lateral shear across a north-south plane. This shear is not easily explained but perhaps it could result from earthquake rupture end effects or a north-south oriented strain release.

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