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OAXACA, MEXICO, EARTHQUAKE OF 29 NOVEMBER 1978: A PRELIMINARY REPORT ON SPATIO-TEMPORAL PATTERN OF PRECEDING SEISMIC ACTIVITY AND MAINSHOCK RELOCATION

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RESUMEN

El análisis de la actividad sísmica ($m \geqslant 2.8$) --registrada por medio de una red local de 6 sismógrafos durante 3 semanas previas a la ocurrencia de un fuerte temblor (29 de noviembre de 1978, $M_s = 7.8$) en Oaxaca--, revela los siguientes aspectos: (1) Las distribuciones espacial y temporal de la actividad sísmica precedente sugieren que ella ocurre a lo largo de una dirección con rumbo N66°±6°W y probablemente a lo largo de otras dos direcciones con rumbo N39°±6°E que cruzan los flancos occidental y oriental de la zona de réplicas. (2) En una área de 3000 km^2 que rodea al temblor principal se presenta una calma sísmica (para temblores de $m \geqslant 2.8$) excep-

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to durante dos periodos en que ocurren "temblores precursores" (a menos de 24 km del epicentro del temblor principal): el primero, 2 semanas antes de la ruptura, el segundo, 21 hrs. antes de la ruptura y luego la actividad declina durante 17 hrs. hasta la ocurrencia del temblor principal. Este comportamiento de la actividad sísmica en el tiempo, observado inmediatamente antes de la ocurrencia del temblor principal, es similar a otros casos observados mundialmente. Mientras que los temblores precursores ocurren en la mitad norte de un círculo de radio de 24 km centrado en el epicentro del temblor principal, 5 de las 12 réplicas más fuertes ($m_b > 4.0$, 30 nov–8 dic.) ocurren dentro de este pequeño círculo, al sur de los temblores precursores. Además 8 de dichas réplicas, los temblores precursores, el temblor principal y 2 de los mayores temblores precedentes (m = 3.9 y 3.4) se encuentran alineados a lo largo de la dirección N–S. Se observa que existe una aceptable correlación entre los lineamientos definidos por la información sismológica y las fallas activas encontradas en base a estudios geomorfoestructurales. Un resultado importante de este estudio es la documentación de la actividad sísmica precedente a niveles de energía menores que los umbrales de detección acostumbrados ($m_b \simeq 4$). La relocalización del temblor principal se encuentra aproximadamente a 50 km al sureste del epicentro publicado por NEIS; las relocalizaciones de las réplicas difieren entre 40 y 100 km de los epicentros publicados por NEIS.

ABSTRACT

An analysis of earthquake activity ($m \geqslant 2.8$) recorded by a local field array of 6 seismographs during 3 weeks prior to a large earthquake (29 November 1978, $M_s = 7.8$) in Oaxaca, Mexico reveals the following: (1) Spatio-temporal patterns suggest a lineation in the preceding seismic activity which trends N66°±6° and possibly 2 other parallel lineations oriented N39°±6°E and crossing the western and eastern flanks of the aftershock area. (2) Seismic quiescence prevailed (for earthquakes $m \geqslant 2.8$) within an area of 3000 km^2 surrounding the mainshock except for two periods of "foreshocks" (within 24 km of the mainshock): the first, 2 weeks before the mainshock, the second 21 hours before the mainshock and then activity subsided for 17 hours until failure. The last temporal pattern of activity observed immediately preceding the mainshock is similar to foreshock patterns observed world-wide. While foreshocks occurred in the northern half of a circle with radius of 24 km centered at the mainshock epicenter, 5 of 12 largest aftershocks ($m_b > 4.0$, 30 Nov–8 Dec) occurred within this circle but south of the foreshock activity. Also 8 of these aftershocks, the mainshock, foreshocks and 2 of the largest preceding earthquakes (m = 3.9 and 3.4) are clustered along a N–S trend. An acceptable correlation between lineations defined by seismic data and active faults delineated from geomorpho-structural analysis is found. A significant result of this study is the documentation of preceding activity at energy levels below standard detection threshold ($m_b \simeq 4$). Relocation of the mainshock yields a new epicenter about 50 km to the southwest of the published NEIS location; relocated aftershocks fell from 40-100 km from the published locations.

INTRODUCTION

Three weeks prior to the occurrence of the Oaxaca, Mexico, earthquake M_S = 7.8 of 29 November of 1978, the Instituto de Geofísica, UNAM, in collaboration with California Institute of Technology installed a local network of 6 smoked paper portable seismographs in the coastal range of Oaxaca (Figure 1). The project was to define spatio-temporal patterns of local earthquakes $m_b < 4.0$ which can not be resolved from standard world-wide network. The data obtained could provide new information relevant to the Oaxaca seismic "gap" (Kelleher *et al.*, 1973; Ohtake *et al.*, 1977). Last authors observed that from the middle of 1973 the frequency of shallow earthquakes (H<60 km) was unusually low in the area of Oaxaca, Mexico (95.5° W-98.0° W). This area experienced two major earthquakes in its eastern (M_S = 7½ – 7 ¾ 1965) and western (M_S = 7.5, 1968) sides and both were preceded by intervals of quiescense (α stage) and following reasumption (β stage) of local seismicity in advance of the mainshock. The separation between those two previous aftershock zones was comparable with their dimensions. On this basis Ohtake *et al.* (1977) forecast the occurrence of a large earthquake (φ= 16.5° ± 0.5°N, λ=96.5° ± 0.5° W, M_S= 7½ ± ¼)) although they did not predict the time of occurrence. In Mexico, among academic and government circles, this forecast was a matter of controversy (Garza and Lomnitz, 1978), local well controlled microearthquake data could help to clarify the tectonic significance of the Oaxaca gap and the importance of the earthquake forecast.

We have obtained a unique data set of preceding and aftershock activities (Singh *et al.*, 1980). Here we present the 48 largest preceding earthquakes ($m \geqslant 2.8$), Figures 2 and 3 and Table 1, and discuss their correlation with the mainshock and aftershock locations and the surface geologic data (Sumín de Portilla *et al.*, 1978). Magnitude, m, is "relative" (without specific calibration for this region), and has been determined from earthquake coda duration (Lee *et al.*, 1972).

The mainshock epicenter was relocated (15°46' N; 96°48' W) using master event techniques (Figure 1); 7 large aftershocks well located by the whole local aftershock seismic network (Figure 1, Table 2) and permanent stations operated by the Servicio Sismológico Nacional and SISMEX, UNAM, were used as master event. HYPO 71 was used for hypocenter determinations (Lee and Lahr, 1975). The model for compressional-wave velocities (Table 3) was selected by trials and error as no detailed crustal study of the region is available; our model is a compromise from reversed seismic profile data obtained (1) off-shore along the coast of Guatemala and (2) in continental Mexico between Pinotepa Nacional (about 150 km WNW of mainshock epicenter) and Lake of Alchichica (about 400 km inland perpendicular to the coast) (Shor and Fisher, 1961; Helsley *et al.*, 1975, Mooney *et al.*, 1975). The epicenter of the mainshock given by the Preliminary Determination of Epicenter (PDE), published by the National Earthquake Information Service (NEIS) of the U. S. Geological Survey, differs from our location by 48 km, as seen in Figura 1.

Closest to the mainshock epicenter location (less than 24 km), with the exception of one small event on the 9 November, the preceding seismic activity ($m \geqslant 2.8$) occurred during the periods 15-17 November and 28-29 November. We will call these earthquakes "foreshocks".

Small earthquakes appear to occur in linear patterns during the 3 weeks prior to the mainshock (Fig. 2 and 3): the more active zone trends N66° ± 6° W and runs slightly north of the epicenter of the main event; 2 other zones may exist, trending N39° ± 6° E and crossing the western and eastern portion of the area defined by the aftershock sequence (Singh *et al.*, 1980). A N65° ± 5° W fault is well defined by geomorphostructural data (Sumín de Portilla *et al.*, 1979) and satellite image interpretation (N. Galván, personal communication) which is coincident with the more active seismic zone (Figure 3a). No faults corresponding to the N39° ± 6° E lineations of activity are clearly evident in local surface structures; however these N39° ± 6° E lineations could reflect a system of less well developed enechelon faults subparallel to a 200 km long fault that trends N30° E inland from the coastal line about 120 km west of the mainshock epicenter (Figure 3a). 30 of 48 of the preceding earthquakes might be associated with the direction at N66° ± 6° W (Figure 3d). In contrast, 8 of 12 epicenters of the largest aftershocks ($m_b > 4.0$) from 30 November until 8 December, the foreshocks, the mainshock and 2 largest preceding earthquakes (m = 3.9 and 3.4 appear to trend N-S (Fig. 3a).

Foreshocks occurred within the active zone trending N66° ± 6°W. The final episode of foreshock activity ($m \geqslant 2.8$)began 21 hours before the mainshock and then subsided for 17 hours until failure; no foreshocks of lower magnitude occurred in this last period of quiescence. This pattern has been observed for foreshocks preceding other large earthquakes (Rikitake, 1976; Raleigh *et al.*, 1977; Wu, *et al.*, 1978).

DATA ANALYSIS

Five periods of precursory seismic activity and one period of aftershock activity are shown in Fig. 2. The time periods, although not equal, exhibit the main features of the activity. These features are, generally, the occurrence of close foreshocks and the redistribution of activity to the ESE edge of the aftershock area. For reference we have drawn a circle with radius of 24 km centered on the mainshock epicenter and the contour of the aftershock area (Singh *et al.*, 1980). Figure 3a shows the epicenter location of all 48 preceding earthquakes ($m \geqslant 2.8$)and the 12 PDE relocated aftershocks ($m_b > 4.0$)for the period 30 Nov–8 Dec 1978, a cross section, along a direction perpendicular to the N66°W direction is shown in Fig. 3b. Two plots of the occurrence of seismic activity in time are also shown: the first along a direction N66°W (Fig. 3c) and the second along its perpendicular (Fig. 3d). The preceding earthquakes are numbered in order of occurrence with time (see Table 1).

Figures 2a and 3 show the epicenter locations for a period of 4 days, from 9 to 12 November; 6 events were located. One foreshock (m = 3.0) occurred on 9 November (number 1). 5 events occurred on the 12 November, 3 of them (numbers 4, 5 and 6) occurred in an 11 hour period, first to the south, then to the north. These three events may be related to the N39° ± 6°E lineations; they occurred along a N44°E direction. In the upper left corner we indicate the average number of events per day ($\overline{n}$ = 1.5) and the average magnitude ($\overline{m}$ = 3.04 ± .12).

Figure 2b shows the epicenter locations for a period of 5 days, from 13 to 17 November. Most of the seismic activity lies along the N66° ± 6°W fault. We note that 4 of the larger events ($m \geqslant 3.1$) occurred on the 15 November in a 10 hour period at very regular intervals of time, 3 hrs 25 min ± 47 min, and rate of occurrence, 21.2 ± 2 km/seg (numbers 9, 10, 11 and 14 in Figures 2b and 3). This period most clearly suggests the association of activity with the N66° ± 6°W active trend; they occurred along a N61°W direction. The other 2 larger events ($m \geqslant 3.1$) occurred on 17 November separated by 21 hours (numbers 18 and 19); the first is a foreshock. A total of 5 foreshocks ($m \geqslant 2.8$) are observed clustered along an apparent N-S trend (numbers 10, 12, 16, 17, 18). This period is more active ($\bar{n} = 2.6$) and average magnitudes is the same ($\bar{m} = 3.04 \pm .28$). The regularity of the 15 November events and the cluster of foreshocks are suggestive of underlying processes of crustal weakening.

Figures 2c and 3 show seismic activity for a period of 6 days, from 18 to 23 November. All earthquakes occur near the WNW edge of the aftershock zone and within the limits of the two previously defined zones trending N66° ± 6°W and N39° ± 6°E. This activity could reflect a complexity in the local stress field at the intersection of the two active zones. This period is comparatively quiet ($\bar{n} = 1.8$) and no foreshocks were detected. Average magnitude did not change ($\bar{m} = 3.04 \pm .20$).

In Figures 2d and 3 we show 4 days of seismic activity from 24 to 27 November. The earthquakes are now concentrated at the ESE edge of the aftershock area. Most of the epicenters might be associated with the zones trending N66° ± 6°W and N39° ± 6°E. 3 large events, $m \geqslant 3.1$ (numbers 32, 35 and 36) occurred within a 31 hour period on November 25-27 along a N34°E direction. No foreshock occurred, but the period was nearly as active as the one shown in Figure 2b ($\bar{n} = 2.5$) and average magnitude was slightly greater ($\bar{m} = 3.27 \pm .36$).

In Figures 2e and 3 we show 1½ day of activity prior to the mainshock. The N66° ± 6°W zone is again active in this period; 7 large events ($m \geqslant 3.1$) occurred in a 12½ hour period (numbers 40 to 46 in Figures 2b and 3) along a N71°W direction. The last earthquake was observed 10 hours before the mainshock in the upper right side of the Figure 1e;

it cannot be considered a foreshock according to our definition. This period was very active in relation to the previous ones ($\bar{n}$ = 5.5); the average magnitude was slightly greater ($\bar{m}$ = 3.30 ± .28). Only 2 foreshocks m = 3.3) occurred during this period, separated in time by 3½ hours (numbers 45 and 46). All foreshock activity (m > 1.5, not shown) then subsided for 17 hours until failure.

Figures 2f and 3a show our relocations of the 12 biggest aftershocks reported by the PDE (NEIS) from 30 November–8 December (see Table 2). 7 of them were accurately located with the entire local network and used as master events for the relocation of the other 5 aftershocks and the mainshock (15°46' N; 96°48' W). Depth for the mainshock has been estimated to be 18 km from waveform analysis (Stewart and Chael, 1979).

Figure 2f also shows the foreshocks; they occurred in the northern half of a circle of radius 24 km centered in the mainshock epicenter. It is noteworthy that 5 largest aftershocks occurred in the limits of this small circle south of the foreshock activity. Based on the above observations, we believe that our epicenter relocation, using master event technique, is well constrained in relation to foreshock and aftershock sequences. Figure 3a shows a clear clustering of 8 large aftershocks, mainshock, foreshocks and 2 large preceding earthquakes (numbers 33, m = 3.4, and 36, m = 3.9) along a N-S trend. This trend is well correlated with the N-S direction of old deep faults (Orthogonal system formed by N-S and E-W faults) obtained from geomorphostructural analysis (Sumín de Portilla *et al.*, 1978). Figure 3a also shows that the preceding seismic activity occurring along the N66° ± 6° W lineation is well correlated with the shallow and young faults with N65° ± 5° W trend; also a satisfactory correlation is observed between preceding seismic activity and weakly defined system of sub-parallel faults along N30° ± 5° E. The faults along N65° ± 5° and N30° ± 5° E constitute the diagonal system defined from geomorphostructural analysis (Sumín de Portilla *et al.*, 1978).

The cross section along a direction perpendicular to N66° W (Figure 3b) shows that most of the preceding seismic activity occurred in the continental plate; the dip of 14° of the Cocos Plate beneath Mexico is consistent with the focal mechanism for mainshock (Stewart and Chael, 1979). For reference we have also traced a dip of 20°. Figure 3c. clearly shows that the foreshock region was quiet except for two periods of foreshock activity, and suggests that preceding seismic activity was present in the WNW and ESE flanks of the aftershock area during the 3 weeks of observation before the occurrence of mainshock. Figure 3d shows that most of the activity (30 of 48 preceding earthquakes) also occurred associated with the N66°W direction in the northern half of the aftershock area.

DISCUSSION

A generally acceptable definition of foreshock, in literature, is not available. We have used our own definition to discuss the details of the spatial, temporal, and magnitude distribution of the preceding microearthquakes. Our use of the concepts of foreshock do not contradict previous definitions (Jones and Molnar, 1978). However to identify foreshocks from background activity further study is needed on statistical analysis of preceding seismic activity, stability of first motion of compressional-wave phases (P), and on the ratio of amplitudes of compressional-wave to shear-wave phases (Sadovsky *et al.*, 1972; Chin *et al.*, 1978, Ponce *et al.*, 1978).

Preliminary results on precursory and foreshocks activity near the epicenter of the Oaxaca earthquake suggest that a detailed survey of active faults must be done in the coastal range of Mexico, as the seismic activity ($m < 4.0$) associated with them could define the sizes of tectonic units in the region (Lukk, 1978; Kasahara *et al.*, 1978) and constitute precursory activity to large destructive earthquakes (Cheng *et. al.*, 1979). A more systematic observation of seismic activity and multidisciplinary survey of geophysical, geochemical and geological parameters is recommended for the Oaxaca region in orden to test the validity of the tectonic features discussed here. The local seismic network should permit locations of events as low as $m = 3.0$ in the region of interest.

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TABLE 1

PRECEDING EARTHQUAKES (m ≥ 2.8)

No.	ORIGIN TIME	LATITUDE N	LONGITUDE W	DEPTH KM	MAGNITUDE m	STANDARD DEVIATION SEC	NUMBER OF DATA
1	9 NOV. 11:48:51.0	15° 56'	96° 53'	36	3.0	0.09	6
2	12 NOV 05:03:58.2	16° 10'	95° 59'	5	3.2	0.16	9
3	12 NOV 09:17:41.1	15° 11'	96° 09'	6	2.9	0.25	9
4	12 NOV 10:24:18.6	15° 45'	97° 25'	20	3.1	0.20	8
5	12 NOV. 15:42:17.2	16° 11'	97° 1'	27	2.9	0.19	10
6	12 NOV. 21:25:02.7	16° 4'	97° 4'	11	3.1	0.28	10
7	13 NOV. 18:47:37.9	15° 48'	95° 51'	38	2.9	0.20	8
8	14 NOV. 22:49:58.7	16° 6'	96° 54'	12	3.0	0.37	12
9	15 NOV. 05:09:28.4	16° 13'	97° 27'	12	3.1	0.26	9
10	15 NOV. 08:03:41.2	15° 53'	96° 52'	15	3.2	0.17	9
11	15 NOV. 11:04:47.6	19° 40'	96° 24'	8	3.8	0.34	9
12	15 NOV. 11:50:10.5	15° 54'	96° 51'	9	2.9	0.28	11

No.	ORIGIN TIME	LATITUDE N	LONGITUDE W	DEPTH KM	MAGNITUDE m	STANDARD DEVIATION SEC	NUMBER OF DATA
13	15NOV. 12:18:25.2	15° 18'	96° 11'	46	2.9	0.11	8
14	15 NOV. 15:24:19.5	16° 5'	97° 5'	19	3.1	0.24	12
15	16 NOV. 06:41:23.9	16° 2'	96° 16'	13	2.8	0.20	10
16	16 NOV. 12:26:01.6	15° 57'	96° 49'	20	2.8	0.18	9
17	16 NOV. 23:04:41.2	15° 54'	96° 51'	16	2.8	0.30	6
18	17 NOV. 00:22:45.6	16° 00'	96° 50'	18	3.3	0.12	5
19	17 NOV. 21:58:08.1	16° 11'	97° 00'	9	3.1	0.37	8
20	18 NOV. 09:19:21.7	15° 59'	97° 9'	16	3.2	0.25	8
21	18 NOV. 19:07:49.5	16° 15'	97° 28'	52	3.1	0.27	10
22	18 NOV. 20:01:42.5	16° 13'	96° 3'	53	2.8	0.07	8
23	19 NOV. 12:43:09.0	15° 57'	95° 52'	10	2.9	0.18	7
24	20 NOV. 08:59:55.7	15° 49'	97° 8'	18	2.9	0.29	7

No.	ORIGIN TIME	LATITUDE N	LONGITUDE W	DEPTH KM	MAGNITUDE m	STANDARD DEVIATION SEC	NUMBER OF DATA
25	20 NOV. 09:11:22.1	15° 46'	97° 13'	14	3.2	0.16	7
26	20 NOV. 10:23:06.3	16° 8'	97° 31'	5	3.4	0.30	8
27	21 NOV. 02:24:55.1	16° 10'	97° 24'	9	2.9	0.17	6
28	21 NOV. 06:13:13.7	16° 6'	96° 58'	18	2.9	0.14	6
29	24 NOV. 06:06:00.4	15° 33'	96° 2'	8	3.4	0.27	10
30	24 NOV. 07:23:18.8	15° 40'	95° 56'	8	3.8	0.16	7
31	24 NOV. 14:47:03.7	15° 26'	96° 8'	17	2.9	0.14	8
32	25 NOV. 10:47:23.1	15° 40'	96° 32	16	3.4	0.13	8
33	25 NOV. 11:21:48.2	16° 42'	96° 48'	54	3.4	0.09	9
34	26 NOV. 05:36:09.0	15° 59'	96° 34'	26	2.9	0.13	10
35	26 NOV. 09:56:09.2	15° 58'	96° 11'	15	3.1	0.25	10
36	26 NOV. 17:38:55.7	15° 12'	96° 42'	13	3.9	0.19	6

No.	ORIGIN TIME	LATITUDE N	LONGITUDE W	DEPTH KM	MAGNITUDE m	STANDARD DEVIATION SEC	NUMBER OF DATA
37	26 NOV. 20:34:48.1	15° 49'	96° 25'	22	3.0	0.11	10
38	27 NOV. 12:57:02.6	16° 00'	96° 18	21	3.0	0.30	12
39	28 NOV. 12:39:47.1	16° 4'	96° 7'	28	3.0	0.19	10
40	28 NOV. 14:22:43.7	16° 14'	97° 18'	16	3.4	0.19	6
41	28 NOV. 15:34:22.5	16° 10'	96° 57'	13	3.7	0.21	7
42	28 NOV. 16:12:52.2	15° 57'	96° 29'	25	3.5	0.17	8
43	28 NOV. 18:05:23.1	16° 00'	96° 36'	27	3.1	0.23	10
44	28 NOV. 21:45:50.1	16° 10'	97° 24'	8	3.7	0.16	8
45	28 NOV. 23:15:28.7	15° 54'	96° 46'	21	3.3	0.45	7
46	29 NOV. 02:52:48.2	15° 56'	96° 46'	15	3.3	0.40	10
47	29 NOV. 07:50:17.8	16° 10'	96° 3'	47	2.8	0.22	8
48	29 NOV. 10:05:48.2	16° 21'	96° 13'	58	3.4	0.13	10

TABLE 2

RELOCATED PDE (USGS-NEIS) LARGE AFTERSHOCKS ($m_b > 4.0$)

(*): MASTER AFTERSHOCKS

No.	ORIGIN TIME	LATITUDE N	LONGITUDE W	DEPTH KM	MAGNITUDE m_b	STANDARD DEVIATION SEC	NUMBER OF DATA
1	30 NOV. 00:01:11.6	15° 48'	96° 41'	17	4.7	0.31	6
2	30 NOV. 10:22:40.6	15° 46'	97° 7'	19	5.2	0.36	9
3	30 NOV. 10:42:35.4	15° 48'	97° 13'	21	4.4	0.24	10
4	30 NOV. 13:15:19.7	15° 27'	96° 46'	20	4.1	0.33	9
(*) 5	2 DEC. 03:24:14.2	15° 29'	96° 40'	10	4.6	0.16	20
(*) 6	2 DEC. 05:35:59.4	15° 23'	96° 44'	4	4.6	0.27	18
(*) 7	2 DEC. 20:27:36.2	15° 44'	96° 49'	13	4.2	0.35	13
(*) 8	2 DEC. 23:34:25.0	15° 37'	96° 47'	19	---	0.24	18
9	4 DEC. 01:09:41.9	15° 22'	96° 7'	27	4.2	0.30	19
(*)10	5 DEC. 06:32:26.7	15° 45'	96° 17'	11	4.5	0.22	21
(*)11	5 DEC. 23:41:32.8	15° 38'	96° 45'	36	4.7	0.34	17
(*) 12	8 DEC. 10:51:42.7	15° 41'	96° 47'	16	4.2	0.35	18

TABLE 3

Layer	Compressional-wave velocity, km/sec	Depth to the botton of the layer, km
1	4.4	5.0
2	5.6	12.0
3	6.4	22.0
4	8.2	

Compressional-wave velocity = 1.78 Shear-wave velocity

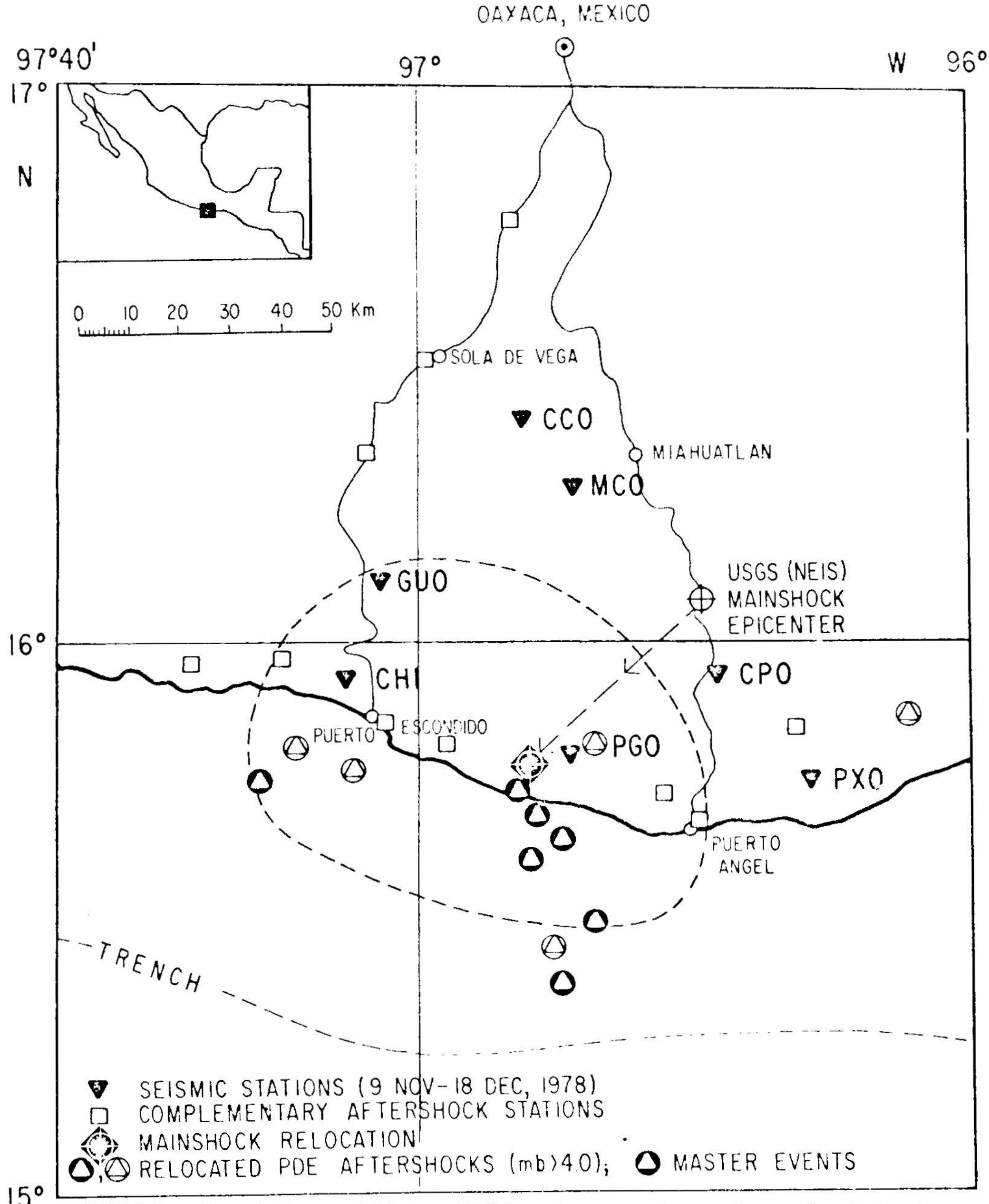

FIGURE 1. From 9 Nov. until 18 Dec. 1978 6 smoke paper seismographs were installed in the coastal range of Oaxaca (GUO, CHI, PGO, PXO, CPO and MCO; CCO was an alternative site for MCO). After the occurrence of the large Oaxaca earthquake ($M_S = 7.8$) on 29 November, 9 additional smoke paper seismographs were installed as shown. 7 large PDE aftershocks (2-8 Dec) were accurately located using the whole aftershock network and used as master events to relocate the mainshock (15°46' N, 96°46' W) and five aftershocks (see Table 2). Our mainshock location differs by 48 km from USGS (NEIS) epicenter.

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