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SPECTRA OF SOME OAXACA EARTHQUAKE AFTERSHOCKS FROM RESMAC

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RESUMEN

Fue calculado el espectro de las ondas S del evento principal y 21 réplicas del sismo de Oaxaca (Noviembre 29, 1978) registrados digitalmente a 500 Km del área epicentral en las estaciones sísmicas fijas telemétricas de RESMAC. Debido al ancho de banda en frecuencias del sistema RESMAC, el espectro de las ondas S del evento principal no muestra ninguna frecuencia de esquina. Este muestra dos pendientes a frecuencias altas (−2.0 y −2.8) intersectándose a una frecuencia de 1.4 HZ. La comparación de los espectros de las réplicas con aquéllos obtenidos con las estaciones portátiles digitales cercanas, muestran un cambio de la frecuencia de esquina a bajas frecuencias típicamente del orden de 0.3 HZ y, en general, un valor pequeño, típicamente 4.3 menor, para el momento sísmico. El espectro de la onda P no muestra ninguna frecuencia de esquina en los sismogramas de RESMAC.

ABSTRACT

S-wave spectra of the main event and 21 aftershocks of the Oaxaca (November 29, 1978) earthquake, registered digitally on a RESMAC fixed seismic telemetry station 500 km from the epicentral area, have been calculated. Due to the bandwidth of the RESMAC system, the corner frequency of the shear wave spectrum of the main event is not observed. We do see two slopes at high frequencies (−2.0 and −2.8) intersecting at a frequency of 1.4 HZ. Comparison of the spectra of aftershocks with those obtained from the nearby portable digital stations shows a shift of corner frequency to the lower frequencies, typically of the order of 0.3 HZ and in general, a smaller value, typically 4.3 smaller, for the seismic moment. The corner frequencies of the P-wave spectra are outside the observed frequency band.

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INTRODUCTION

The Oaxaca earthquake of November 29, 1978, (Ms = 7.8, 16.07N, 96.48W) yielded an opportunity for detailed study of an earthquake in a subduction zone. This is the first earthquake in Mexico recorded with a great variety of instruments in the near and far field both before and after the main event. This event had been forecast in a gap (Ohtake *et al.,* 1977), and later trapped (Ponce *et al.,* 1979).

Although the network that trapped the event (Ponce *et al.,* 1979) consisted of smoked paper recorders, 5 digital telemetering stations were running at a distance of about 500 Km from the epicentral area. These digital data may provide a greater understanding of the source mechanisms of the event. The spectra and some of the source parameters of the mainshock and 21 aftershocks were obtained from the data recorded at the Cerrillo station (CRX). Due to the instrument response of the RESMAC system (see figure 1), source parameters for larger events are obscure. However, it was possible to get the slope at high frequencies and source parameters for events of magnitude between 3.6 and 5.0. The source parameters at the CRX station were compared with the spectra of some events from the nearby CICESE-UCSD portable stations (Munguía *et al.,* 1979).

In order to deduce parameters of the focal mechanism from these spectral parameters it is necessary to accept a theoretical source model. Theoretical spectral studies have associated the low-frequency spectral amplitude with the seismic moment of a dislocation source. The high-frequency amplitudes are predicted to be inversely proportional to some power of frequency. This high-frequency asymptote is related to details of the fracture mechanism or build-up function (Savage, 1972). The corner frequency is defined as the intersection of the high-frequency and low-frequency trends and is related to the characteristic time constant (roughly fault length divided by rupture velocity), or dimension of the source.

It has been observed in general that the corner frequency of P-waves is larger than the corner frequency of S-waves (Molnar *et al.,* 1973; Tucker and Brune, 1977; Thatcher and Hanks, 1973). This agrees with theoretical models of earthquakes as equidimensional faults (Brune, 1970; Madariaga, 1976). Theoretical models of long and narrow faults predict similar P and S corner frequencies (Savage, 1972). Unfortunately these models, although they are mathematically sophisticated are less than perfect in modelling the complexities of seismic wave propagation.

Fault slips for small events obtained using spectral analysis have been found to vary substantially with the distance at which observations are made. In deep mines they can be several orders of magnitude less than those measured directly (McGarr

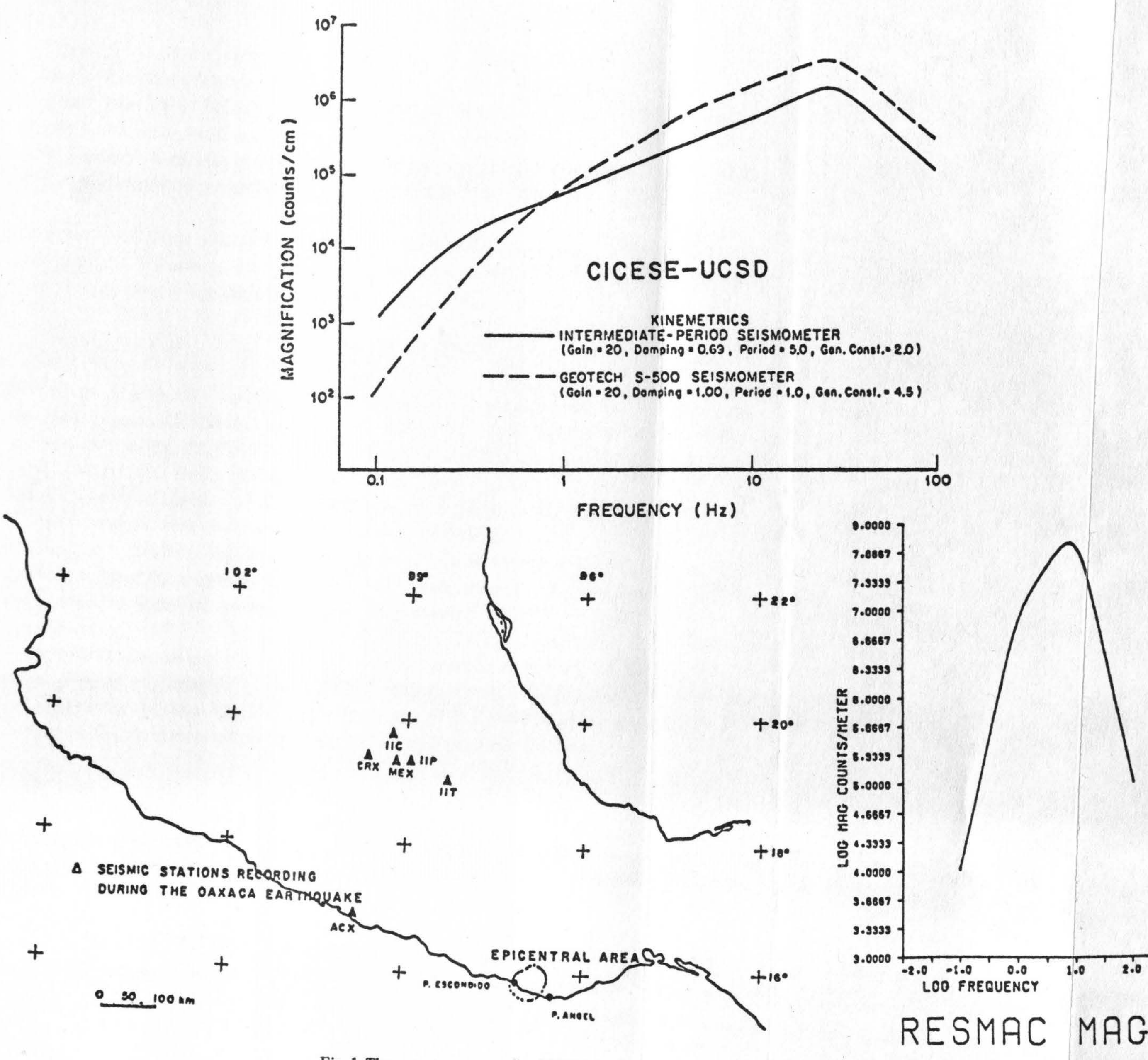

Fig. 1. The response curve for RESMAC and UCSD stations and an index map of the area.

et al., 1979). However, fault slip calculated from spectra of large events usually agree with geological observations.

Stress drops of the order of kilobars have been found in laboratory experiments of brittle fracture of rocks, while stress drops of natural earthquakes lie in the range of a few bars (1 – 100). McGarr *et al.,* 1979), found that tremors in deep mines appear to be associated with stress drops of the order of 1 kilobar. Consequently, they postulate a certain amount of stress inhomogeneity for failure to occur. This may imply large concentrations of stress in localized regions.

In view of these uncertainties the results reported here should be interpreted with caution. Effects of inhomogeneity are not modelled in the interpretation and they are apparently significant.

INSTRUMENTATION

This study is primarily based on data registered at RESMAC stations. The response curve of a typical RESMAC station is shown in the figure 1, as well as the magnification curve for the CICESE-UCSD stations. A RESMAC station consists of a Mark seismometer (with period of one second and damping 0.7), an amplifier, two filters in cascade (period of 0.1 sec and damping 0.7), an analog-to-digital converter (A-D). A PDP11 mini-computer used for data recording. The maximum output of the A-D is ± 131072 "counts", which corresponds to an input of ± 10 volts. The maximum velocity magnification is 162 counts-sec/micron. The output of the A-D is recorded 36 times/sec giving a Nyquist frequency of 18 Hz.

Cerrillo is part of a group of stations which transmits data to the RESMAC computer. This group consists of the SISMEX (Prince *et al.,* 1973) network and what will eventually be the RESMAC (Garza *et al.,* 1978) network. The distance from Cerrillo to the epicentre of the mainshock is approximately 515 km.

The configuration of SISMEX and RESMAC stations in November 1978 (figure 1) made it difficult to get reliable epicentre locations in the Middle America trench. The present distribution of working stations is very much improved (Lomnitz, personal communication). The seismograms (figure 2) are very complicated making it difficult to recognize different phases. For studies in Oaxaca, the Tonantzintla (IIT) SISMEX station is one of the best stations of the system. Unfortunately calibration information for the SISMEX stations for 1978 and 1979 is not available to us. SISMEX stations transmit analog VHF signals which are digitalized at the receiver.

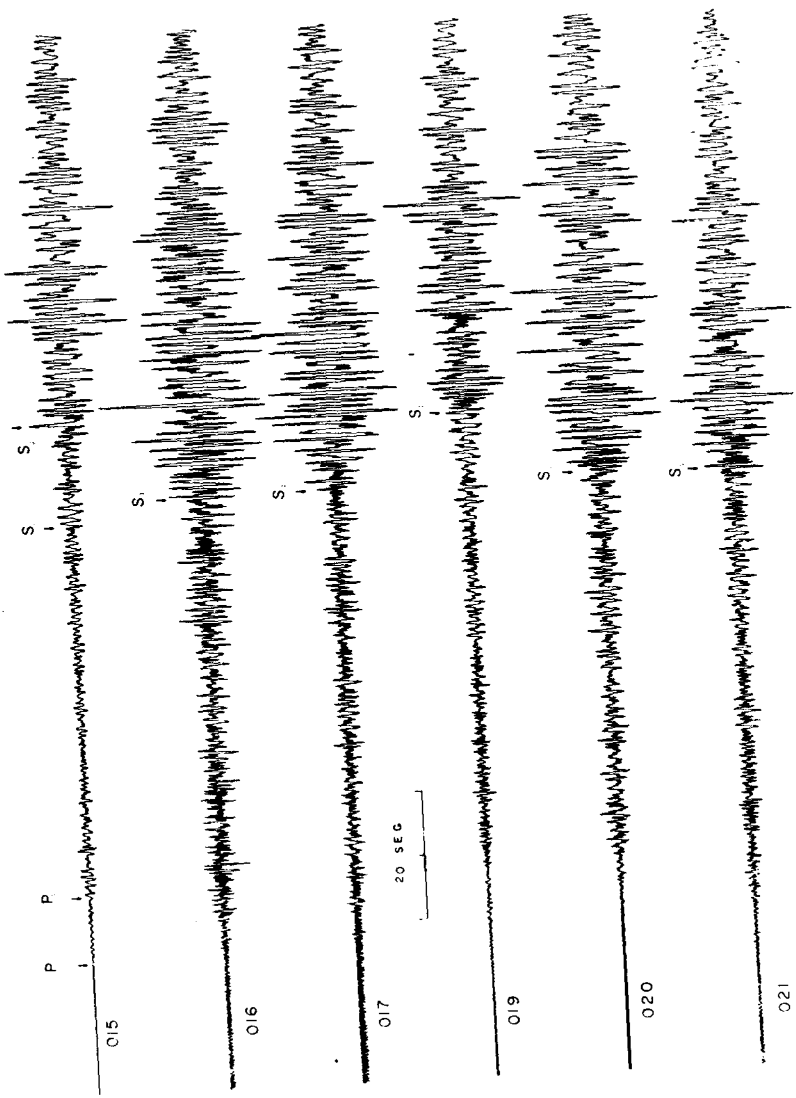

Fig. 2. Examples of Oaxaca seismograms.

DATA ANALYSIS

From the travel time curves for a continental structure at normal depth, the phases that would appear in the seismogram at a distance of 510 Km are: the refracted Pn, the direct wave Pg, the reflection PgPg (very close to Pg), the conversion SgPg, the refracted Sn wave, the direct Sg wave and finally the reflection SgSg. For this distance the surface waves do not appear very soon after the arrival of the S-wave. Consequently, it is unlikely that the energy spectrum is contaminated by surface waves. Instead the spectra will have energy from the phase SgSg and the scattering due to reflection near the station.

Spectra of S and P waves recorded at CRX were obtained. The spectra were corrected for instrumental response and seismic attenuation. The epicentral distance was estimated from the average Sg-Pg times assuming a Vp velocity of 6.5 km/sec (based on unpublished refraction results at Pinotepa Nacional). This distance has an error of ± 35 km. The uncertainty in the distance yields an error of one order of magnitude in the moment. Several values of Q were tested to gain more insight into the value of this parameter in the region. Since very little is known about Q in this area, anelastic attenuation was approximated with a Q of 500 for S-waves and a Q of 1242 for P-waves (as suggested by Anderson *et al.,* 1978). From the analysis of the spectra, a fairly reliable bandwidth of frequencies between 0.2 to 7.0 Hz was estimated. Consequently, the earthquake signal was band pas filtered outside this range of frequencies.

Figure 3 shows the different time windows that were used in calculating the shear wave spectra. Some increase in the spectral amplitude was observed with the increase of the sample length. All spectral calculations were made with 2 000 data points (55.6 seconds) of data. This indicates the presence of scattered P and S energy.

In order to compare RESMAC spectra with CICESE-UCSD data, the spectra must be corrected for radiation pattern and free surface reflection of Sv waves. Figure 4 shows a comparison of these spectra. Reyes *et al.* (1979) used hypocentral determinations of aftershocks to establish 2 trends in the distribution of aftershocks. One part of the aftershock zone dips at an angle of 20^{o} while another part suggests a reverse fault zone dipping at 70^{o} toward the trench. There are a large number of aftershocks on the first portion, on the second activity is scarce and is supported by a composite focal mechanism. Two of the events used in our comparison to CICESE-UCSD results are associated with the zone that dips at 20^{o}. This admittedly weak result is the basis for assuming that all events analyzed here slipped on fault planes parallel the main thrust zone in a down dip direction. This corresponds to a dip of 20 degrees and an azimuth of 60 degrees. Nuttli (1961), calculated the amplitude of S-waves at the free surface for different angles of incidence. Using Nuttli's formulas the ratio of the displacement amplitude at the free surface to the amplitude of the incident wave is 0.82. The previously mentioned unpublished refraction results (Singh, personal communication) were used to arrive at this number. An average depth of 35 km was assumed. At 60 degrees azimuth the average radiation pattern correction for Sv waves (assuming a rupture velocity of 0.9 Vs) is 0.84 (Madariaga, 1977).

Table 1A shows values of spectral amplitudes, corner frequency and slope at high frequencies for different values of Q. At high frequencies both the spectral amplitude and slope decrease with Q. The corner frequency also tends to decrease but in an erratic way. Table 2 shows all the spectral parameters we have calculated to date.

Because of the response of the RESMAC system it was only possible to get the slopes at high frequencies of the mainshock (−2.0 and −2.8, fig. 5). The intersection for these slopes is at 1.4 Hz. The first aftershock of magnitude 5.6 was recorded nearly 13 minutes after the main event, a corner frequency at 0.7 Hz was found, although this means a small source dimension for a relatively large event. The second large aftershock of magnitude 4.8 was recorded approximately 74 minutes later, this spectrum does not show any corner frequency at all in contrast with the first aftershock, instead it is possible to see a slope of −1.3 at high frequencies (figure 5).

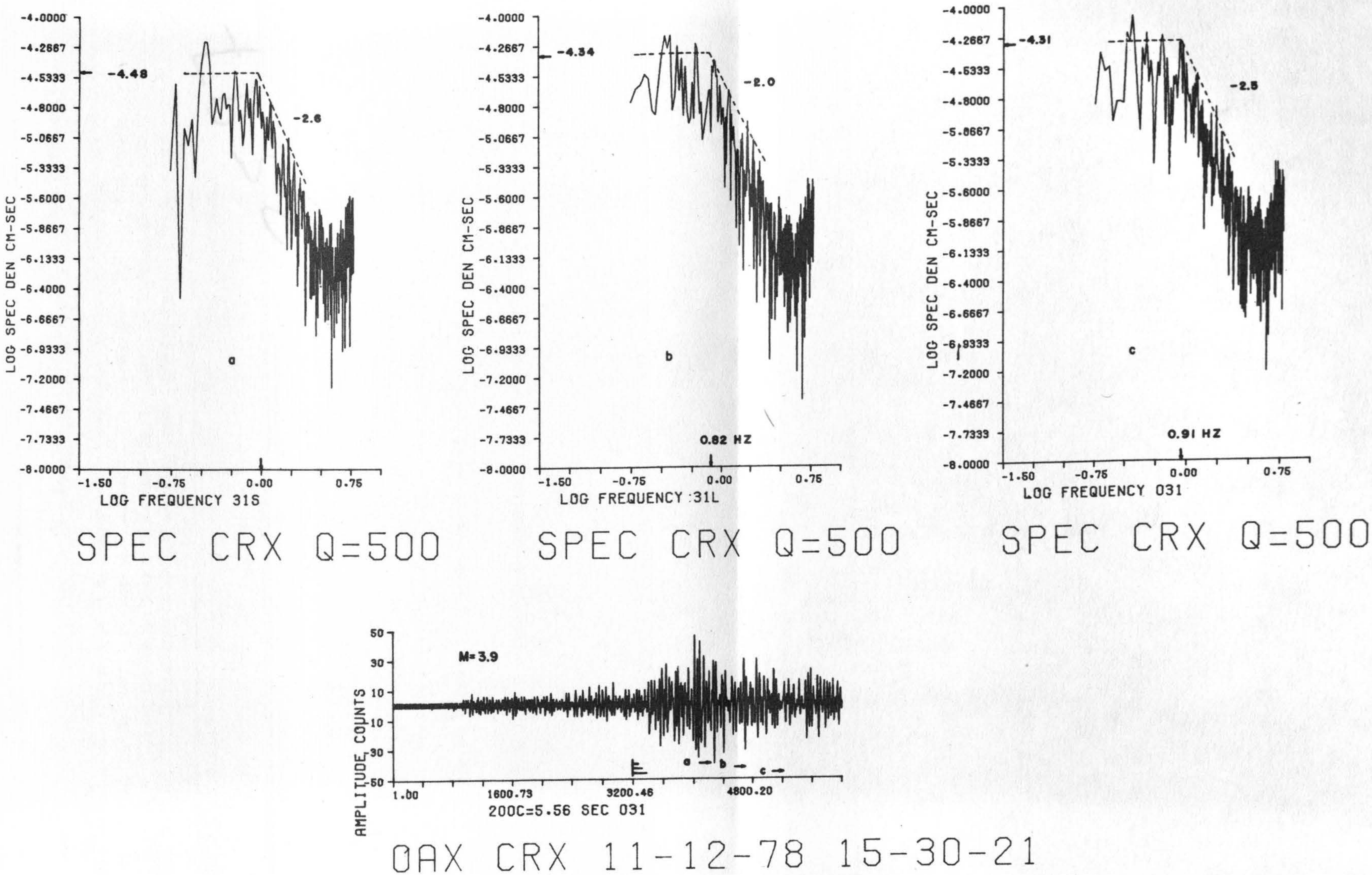

Fig. 3. Variation of spectra with increasing sample length.

TABLE 1A

CICESE-ULSD DATA					RESMAC DATA												
MAG	Q	$\log\Omega_m$	f_{cm}	∂	Q	$\log\Omega_R$	f_{cR}	∂_R	Q	$\log\Omega_R$	f_{cR}	∂_R	Q	$\log\Omega_R$	f_{cR}	∂	AFTERSHOCK
4.2	1000	-2.26	1.55	-1.50	1000	-4.12	0.87	-2.40	300	-3.92	0.91	-2.0	350	-3.86	0.98	-1.4	60 019
4.7	1000	-1.68	0.49	-2.00	1000	-4.00	0.69	-2.30	500	-3.90	0.71	-1.60	350	-3.89	0.81	-1.10	021
4.5	1000	-1.73	1.35	-2.50	1000	-3.56	0.43	-2.20	500	-3.48	0.51	-2.00	350	-3.46	-0.47	-1.40	020
4.4	1000	-2.00	0.68	-1.1	1000	-3.97	0.78	-1.80	500	-3.74	0.66	-1.10	350	-3.60	0.71	-1.00	035

TABLE 1B

CICESE-UCSD DATA								RESMAC DATA							
ΔM_o	Q	$\log\Omega_M$	f_{cM}	∂	M_{oM}	T_o	$\Delta\delta$	Q	$\log\Omega_R$	f_{cR}	∂	M_{oR}	T_o	$\Delta\delta$	
4.87	1000	-2.26	1.55	-1.5	6.86×10^{22}	0.83	52.49	500	-3.92	0.91	-2.0	1.41×10^{22}	1.52	1.17	019
1.1	1000	-1.68	0.49	-2.0	1.63×10^{22}	2.61	0.40	500	-3.90	0.71	-1.6	1.47×10^{22}	1.95	0.58	021
4.32	1000	-1.73	1.35	-2.5	1.67×10^{23}	0.95	83.63	500	-3.48	0.51	-2.0	3.87×10^{22}	2.72	0.57	020
2.63	1000	-2.00	0.68	-1.1	5.65×10^{22}	1.88	3.71	500	-3.74	0.66	-1.1	2.13×10^{22}	2.1	0.67	035

NOTES

$\Delta M_o = \frac{M_{oM}}{M_{oR}}$; f_c = corner frequency HZ, T_o = source dimension KM , $\Delta\delta$ = Stress drop bars

M_o = Moment dynas - cm ∂ = slope at high frequencies Ω = spectral density

Table 1A. RESMAC spectral parameters for differing Q values compared with the results from the CICESE-UCSD nearby stations.

Table 1B. RESMAC source parameters for Q = 500 compared with CICESE-UCSD results.

TABLE 2

EVENT	$\log\Omega_0$	f_c	∂	M_o	T_0	$\Delta\delta$	MAGNITUDE	DATE
001	-2.54	0.72	-1.2	3.37×10^{23}	1.92	14.1	5.6	
002			-1.3				4.8	21:08:53 29-11-78
003	-4.56	1.0	-1.2	3.22×10^{21}	1.39	0.36	3.7	21:50:10 29-11-78
004	-4.11	0.93	-1.7	9.08×10^{21}	1.49	0.81	4.1	22:06:56 29-11-78
005	-4.86	-.89	-1.5	3.53×10^{21}	1.56	0.28	4.3	22:31:25 29-11-78
006	-2.86	0.65	-2.3	1.61×10^{23}	2.15	4.79	5.0	23:08:50 29-11-78
007	-4.36	0.83	-2.4	5.10×10^{21}	1.67	0.32	3.6	23:39:39 29-11-78
008	-4.01	1.0	-1.9	9.29×10^{21}	1.39	1.02	4.2	00:01:53 30-11-78
009	-4.42	1.0	-2.4	4.44×10^{21}	1.39	0.49	3.8	01:32:16 30-11-78
010	-4.06	-.74	-2.1	1.01×10^{22}	1.88	0.46	4.0	02:02:35 30-11-78
011	-4.62	1.12	-1.2	2.8×10^{21}	1.24	0.44		17:41:48 30-11-78
013	-4.44	0.91	-2.4	4.24×10^{21}	1.52	0.36	3.7	17:57:25 30-11-78
014	-4.8	0.89	-2.1	3.45×10^{21}	1.56	0.27	3.6	21:23:45 30-11-78
015	-3.36	0.87	-2.8	5.1×10^{22}	1.6	3.72	4.7	05:37:13 02-12-78
016	-4.06	0.83	-1.7	1.01×10^{22}	1.67	0.65	4.1	20:29:20 02-12-78
017	-4.4	1.0	-2.6	4.65×10^{21}	1.39	0.51	3.8	23:36:34 02-12-78
019	-3.92	0.91	-2.0	1.41×10^{22}	1.52	1.17	4.2	01:11:11 04-12-78
020	-3.48	0.51	-2.0	3.87×10^{22}	2.72	0.57	4.5	06:35:51 05-12-78
021	-3.9	0.71	-1.6	1.47×10^{22}	1.95	0.58	4.7	23:45:49 05-12-78
025	-4.26	1.07	-1.9	6.21×10^{21}	1.30	0.87	4.6	10:54:24 08-12-78
031	-4.31	0.91	-2.5	5.73×10^{21}	1.52	0.48	3.9	15:30:21 11-12-78
035	-3.74	0.66	-1.1	2.13×10^{22}	2.1	0.67	4.4*	21:50:40 18-12-78
039	-3.75	0.5	-1.7	2.08×10^{22}	2.77	0.29		08:53:50 28-12-78
040	-4.34	0.91	-1.9	5.34×10^{21}	1.52	0.45		18:40:07 28-12-78
041	-3.64	0.74	-1.5	2.68×10^{22}	1.88	1.2		19:19:47 28-12-78
042	-4.13	0.78	-1.7	8.67×10^{21}	1.75	0.48		19:46:09 28-12-78

Table 2. Source parameters derived from RESMAC data recorded at Cerrillo.

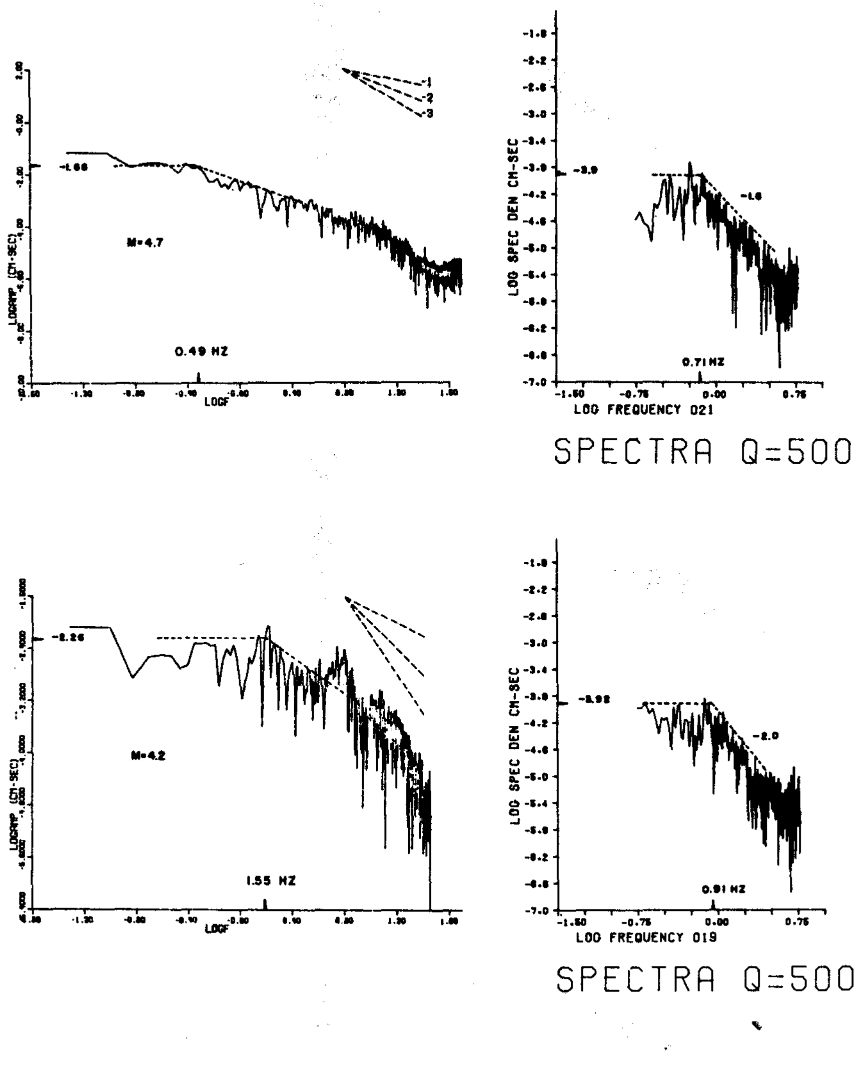

Fig. 4. Two examples of spectra for events recorded both by CICESE-UCSD and RESMAC.

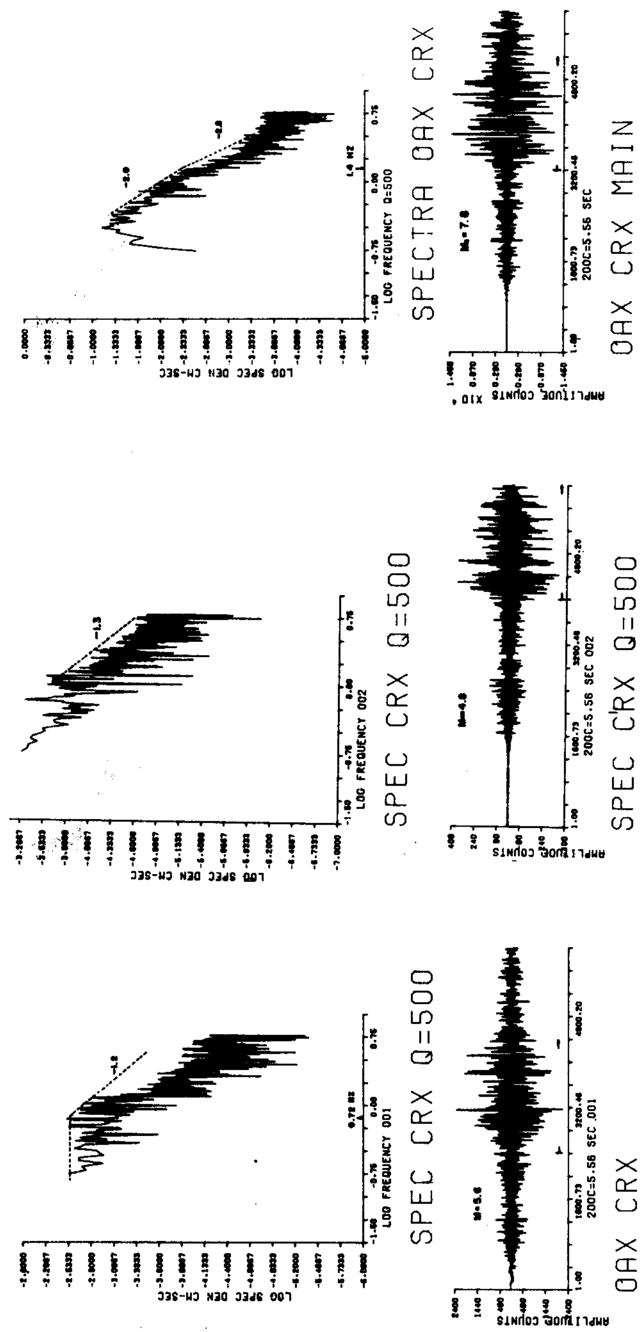

Fig. 5. Spectra for the mainshock and the first two aftershocks recorded by RESMAC.

SOURCE PARAMETERS

Using Brune's (1970) model, the far-field spectral parameters are related to the source parameters as follows:

$$M_o = 4\pi\rho R\beta^3\Omega_o/0.69 \quad \text{Dynas-cm} \tag{1}$$

$$r = 0.37\beta/f_c \quad \text{km} \tag{2}$$

$$\Delta\sigma = 106\rho R\Omega_o f_c^3 / 10^6 \quad \text{bars} \tag{3}$$

The constants used in this work are: s wave velocity = 3.75 km/sec, density ρ = 2.35 gr/cm, R = epicentral distance (km), Ω_o = spectral density cm/sec, and f = corner frequency Hz, r = source dimension, $\Delta\sigma$ = stress drop. Table 2 shows the results of these calculations.

Two (figure 6) of the 21 aftershock spectra show no recognizable corner frequency. Table 1B shows parameters of the spectra and source of some events registered at both RESMAC and CICESE-UCSD stations. In general there is not good agreement between corner frequencies (the largest difference is 0.8 Hz). CICESE-UCSD corner frequencies are larger than the RESMAC corner frequencies. This difference results in a discrepancy of 1.7 km in the source radius and a large discrepancy in the stress drop. This bias could be due to scattering in the crust (Dahlen, 1974), but it seems more likely to be evidence of heterogeneity in the focal mechanisms. We have not yet determined the focal mechanisms for these shocks. Unfortunately only CRX was sufficiently quiet for spectral analysis. It is evident from the seismograms and the time windows which have been used, that the RESMAC spectra contain scattered P and S waves. Consequently, scattering seems to increase the estimated fault size. RESMAC moments are smaller, sometimes by a factor of close to 5, than CICESE-UCSD moments. The disagreement could be due to:

1. Differences in bandwidth between CRX and the CICESE-UCSD stations.
2. The band width of CRX. The station was not originally planned to provide spectral information at teleseismic distances, and our use of it in this way is an unexpected bonus.
3. Uncertainties in the radiation pattern. We have only one station.

4. Energy losses due to conversion of the Sv signal we used and due to scattering in the largely unknown structure between Oaxaca and Mexico.

Consequently calculations of the moment give a possible lower limit. The spectra of P-waves were calculated and do not show any corner frequency. This could be due to the lower amplitude of the P-waves, but it is more likely that the P corner frequencies lie outside the response band of the RESMAC station.

CONCLUSIONS

Source parameters of 21 aftershocks were obtained. Corner frequencies lie near one Hz, showing smaller values than those obtained with the nearby stations. This could be due to scattering along the path length and near the station. Seismic moments for the observed events with magnitudes from 3.6 to 5.6 range from 3.45 x 10^{22} dyne-cm to 3.3 x 10^{23} dyne-cm, with source dimensions from 1.2 to 2.7 km and a maximum stress drop of 4.7 bars. Consequently source dimension and stress drop are lower limits. P-wave spectra do not show any corner frequency, being very sensitive to the scattering and noise level. Seismic moment is the more reliable parameter yielding a lower limit. It should be understood that these limitations are largely related to the use of RESMAC stations for purposes for which they were not originally designed and the use of a system which was, at the time, still under development. Since then considerable improvements, partly stimulated by this and other work on Oaxaca earthquake data, have been made (Lomnitz, personal communication). With upgrading of the RESMAC stations to include three-component short and long period stations, it will be possible to obtain data in a wider dynamic range of frequencies.

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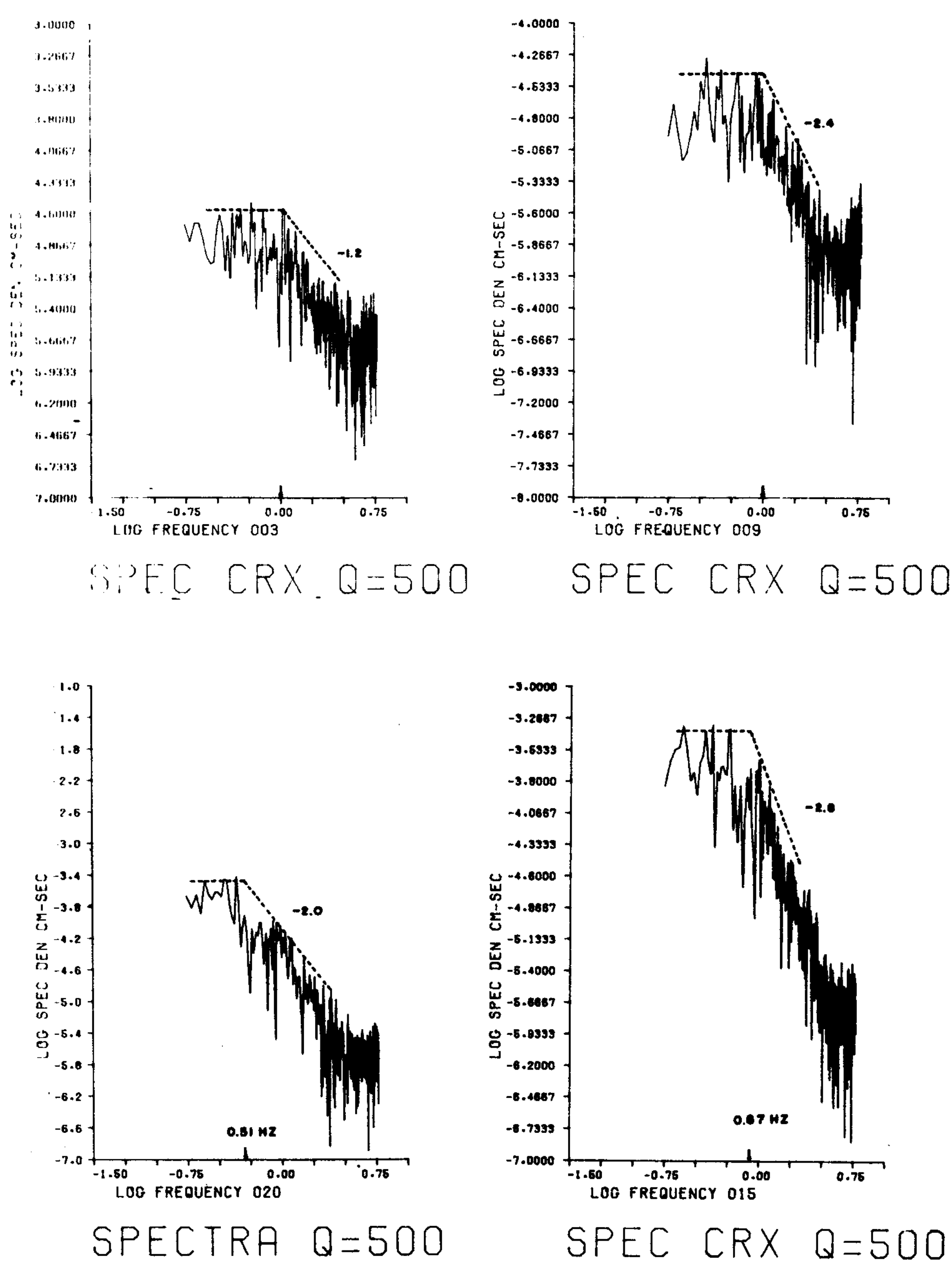

Fig. 6. The two upper spectra show well defined corner frequencies and the two lower spectra are dubious.

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