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SYNOPSIS This paper summarizes the history and rational for installation of the Guerrero accelerograph array. The array is producing unprecedented quantities of high quality digital strong motion data. Recent research using the array data has included studies on attenuation, site effects, scaling of spectra with magnitude, the ratio of vertical to horizontal accelerations, and the source of the September 19, 1985 earthquake.

1 INTRODUCTION

The Guerrero array consists of 30 digital strong motion accelerographs in Guerrero, and neighboring states, Mexico (Figure 1). It was designed to record accelerograms from large earthquakes on part of the Mexico subduction thrust (Section 2). The network has operated for five complete years. Important early data were near field recordings from the September 19 and September 21, 1985 earthquakes. As described in Section 3, the array is located above another mature seismic gap. Within the next few years it is likely to record another earthquake with magnitude near 8.

Most of the data is from moderate sized earthquakes, which are recorded at an unprecedented rate described in Section 4. The magnitudes of these events range from under 3 to over 8. There is no better, more uniform data set to study the effects of magnitude and distance on strong motion recorded on rock.

We have examined the dependence of the Fourier spectrum on earthquake size and distance in some detail in Section 5. Section 7 examines the ratio of vertical to horizontal peak accelerations. All of the stations are nominally on the best rock consistent with the array layout. Nevertheless, Section 6 shows that near surface geology causes important amplifications at some stations. Section 8 shows a model for the source of the Sept 19, 1985 main shock derived from the strong motion records.

2 BACKGROUND

The idea for the Guerrero array originated at the International Workshop on Strong-Motion Earthquake Instrument Arrays held in Honolulu, Hawaii May 2-5, 1978 (Iwan, 1978). The proceedings of that conference identified a seismic gap in Oaxaca, Mexico, but the Oaxaca earthquake of Nov 29, 1978 at least partially filled the gap. Among the seismic gaps along the Mexican subduction zone (Singh et al., 1981), the Guerrero gap (99.7W to

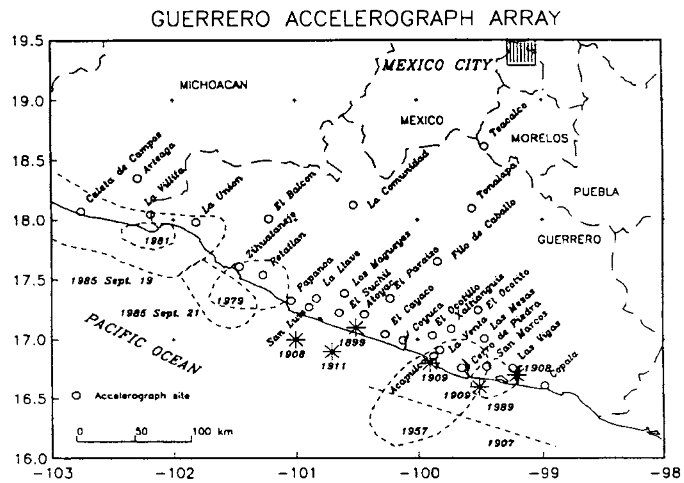

Figure 1. . Map of coastal Mexico with locations of Guerrero Accelerograph stations and rupture zones of some previous earthquakes. Aftershock zones are from the following sources: 1973 - Reyes et al, (1979); 1985 - Anderson et al (1986); 1981 - Havskov et al (1983); 1979 - Valdes et al, (1982); 1957 and 1982 - Nishenko and Singh (1987a); 1989 - Singh (personal communication).

101.7W, Figure 1) and Michoacan gap (101.7W to 103.0W) appeared, to our thinking in 1983, most likely to experience a large earthquake in the near future. Singh et al., (1980a) thought that the Michoacan gap had not ruptured in a large earthquake in at least 80 years prior to 1980 and might be aseismic, but an earthquake on October 25, 1981 (MS = 7.3) ruptured part of it, and implied to us that the remainder of this gap also would probably fail in an earthquake. This is the gap that ruptured on September 19, 1985. The Oaxaca and Michoacan earthquakes again demonstrated the value of the seismic gap hypothesis, as formulated by Kelleher et al. (1973) and others for anticipating the locations of future major earthquakes.

3 GUERRERO SEISMIC GAP

Seven large earthquakes occurred in what is now called the Guerrero gap in 1899, 1908, 1909, and 1911 (Figure 1). From Anderson et al. (1989b), the total moment of these events was about 22 * 10^{27} dyne-cm. Considering that a magnitude 8 earthquake corresponds to a moment of about 10 * 10^{27} dyne-cm, and that smaller events contribute much less moment (eg. a M_S 7.5 event typically has a moment of only 2 * 10^{27} dyne-cm, (Anderson et al.), a Guerrero gap earthquake could attain moment magnitude 8.2, but multiple events somewhat smaller than this (eg. 7.8 to 8.0), distributed over several years, might be more likely.

Nishenko and Singh (1987b) estimate the conditional probability of a major earthquake in the Guerrero gap between 1986 and 1996 to be 56-79%. Every other part of the Mexican subduction zone from Jalisco to Oaxaca has ruptured since 1928. Considering the high overall rate of seismicity in Mexico, the Guerrero gap is clearly an extremely likely site for a large earthquake in the near future.

4 DATA SUMMARY

Table 1 summarizes the rate at which the array has recorded data. Table 2 lists the important events recorded to date. Figures 2 and 3 show selected records from two important earthquakes. Figure 4 shows the magnitudes and distances of events recorded by the network through December, 1988. Data from 1989 and 1990 will contribute to fill in the plot between magnitudes 5 and 7. Figure 5 shows the peak acceleration of each record as a function of magnitude only for 1985 through 1988. Distance is omitted from this figure. Since some events are recorded at short range for all magnitudes, Figure 5 suggests an upper bound for the types of earthquakes recorded so far. Above magnitude 5, there are fewer events, but the figure strongly suggests that the upper bound is concave downwards, indicating saturation of peak acceleration with magnitude. Some of the records have peak accelerations below 1 cm/sec^2. These are recorded on the PDR-1 digital recorders (Quaas et al., 1987; Quaas and Anderson, 1989); because of the gain-ranging capabilities of the instruments, these records still have good signal to noise ratios. Documentation of the data through 1988 are given in a series of reports (Anderson et al, 1987a,b, 1988, 1990a,b). Documentation of the April 1989 earthquake is given by Anderson et al (1989). More complete documentation for 1989 and 1990 data is in preparation. Data are available on floppy disk from UNR or UNAM.

The most important accelerograms to date are from the September 19, 1985 earthquake (Anderson et al., 1986). This event occurred before installation of the array was complete. Since then, installation has been completed, instruments improved, and trigger levels adjusted. Consequently, even magnitude 4 to 4.5 events are now triggering a substantial fraction of the array (Table 2). The average number of records per event has also increased (compare 1985 and 1986 with post 1987, Table 1), but the numbers of small events (magnitudes under 4) that only trigger one or two stations have also increased, so the average number of records per event has only gone up by 50%.

Table 1

Records obtained by the Guerrero Accelerograph Array

Year	Ev[1]	Re[2]	Rt[3]	<3	3-3.9	4-4.9	5-5.9	6-6.9	>7
1985	38[4]	75	1.9	1	18	10	3	0	2
1986	44	83	1.7	5	19	14	5	0	1
1987	47	118	2.7	2	30	14	0	1	0
1988	52	119	2.2	5	30	13	4	0	0
1989	77	217	2.8				4[5]	1	0
1990[5]							2		

Notes:
[1] Number of events.
[2] Number of records.
[3] Average number of records per event.
[4] Magnitudes of four events are unknown.
[5] Incomplete.

Table 2

Most Important Earthquakes Recorded by the Array

Date	M	Re[1]	a_{max} cm/sec^2	R. E. D.[2] (km)
Sept 19, 1985	8.1	16	166	20-388
Sept 21, 1985	7.6	13	625	35-240
Apr 30, 1986	7.0	4	98	32-368
May 29, 1986	5.2	5	79	34-88
June 16, 1986	4.5	6	165	11-70
Mar 26, 1987	4.8	10	33	11-143
Apr 2, 1987	4.8	5	103	10-46
June 7, 1987	4.8	12	78	9-256
June 9, 1987	4.2	10	63	4-132
Feb 8, 1988	5.8	13	440	13-219
Aug 16, 1988	4.6	13	240	6-187
Mar 9, 1989	4.6	8	47	*
Mar 10, 1989	5.3	11	257	*
Apr 25, 1989	6.9	18	346	*
May 2, 1989	5.4	14	116	*
Aug 12, 1989	5.4	8	37	*
Aug 17, 1989	4.9	11	103	*
Oct. 8, 1989	5.1	16	138	*
Nov 9, 1989	4.8	10	54	*
May 11, 1990	5.2	14	153	*
May 31, 1990	5.8	19	392	*

Notes:
[1] Number of records for this event.
[2] Range of epicentral distances.

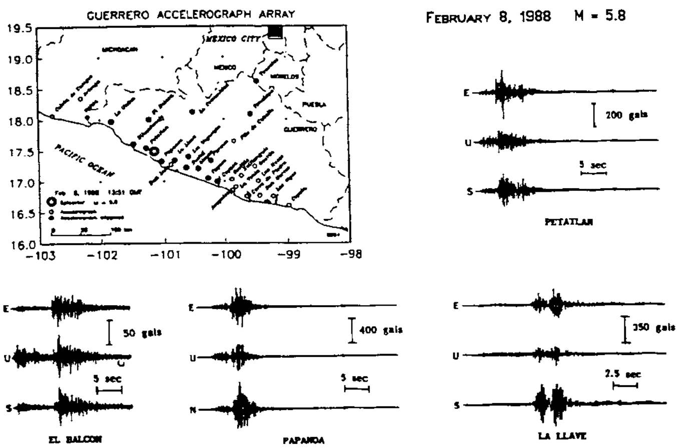

Figure 2. . Important accelerograms from the earthquake of February 8, 1988 (M=5.8). Location of epicenter, stations that triggered, and copy of selected records.

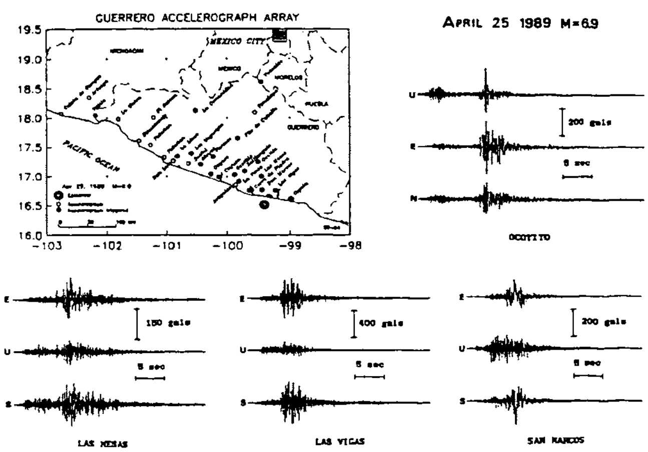

Figure 3. . Important accelerograms from the earthquake of April 25, 1989 (M=6.9. Location of epicenter, stations that triggered, and copy of selected records.

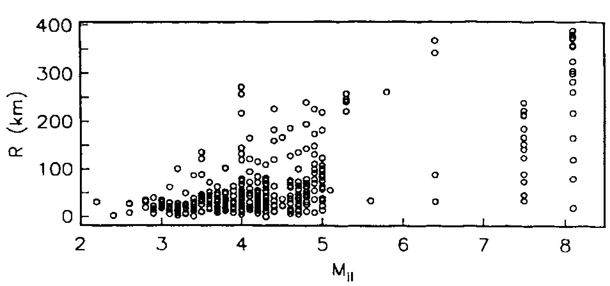

Figure 4. . Magnitude and epicentral distance of all events 1985 through 1988.

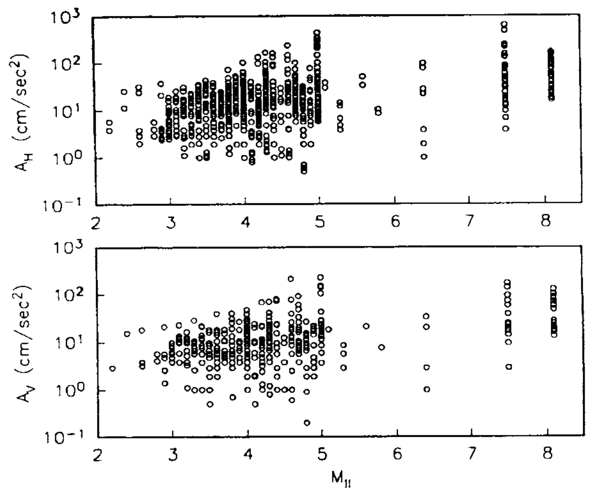

Figure 5. . Peak horizontal acceleration (A_H) (top) and Peak vertical acceleration (A_V), bottom, as a function of coda magnitude for all events 1985 to 1988.

5 ATTENUATION AND SCALING

Castro et al. (1990) used strong motion data from the Guerrero array to estimate Q for 26 frequencies between 0.1 and 40 Hz. The procedure used by Castro et al. should be of general interest. Consider one characteristic of ground motion, A(m,r,s), which may be, for example peak acceleration or a spectral amplitude. The size of the event is represented with parameter m, and the distance with parameter r. The parameter s designates the effects of the recording site. We designate the i^{th} event with notation m_i, a particular distance range with notation r_j, and the effects of a particular site with notation s_k. We write A(m,r,s)=S(s)M(m)R(r). Then we carry out a two step inversion. The first step finds R(r) without making any assumptions about its shape, except a smoothness condition. This step gives R(r) and an estimate for $M(m_i)S(s_k)$ for every recording. The process is like Richter's procedure for the development of the magnitude scale (Richter, 1958).

Castro et al. found R(r) for Fourier spectral amplitudes at 26 frequencies between 0.1 and 40 Hz (Figure 6). Castro et al. also estimated Q relative to reference curves with distance dependences of r^{-1} and $r^{-\frac{1}{2}}$. They find that estimates at individual frequencies can be approximated satisfactorily by the parametric form: 1/Q = c + d/f, as is shown in Figure 7. However, the empirical curves R(r) provide a better estimate of the distance dependence of the Fourier spectrum.

The term $M(m_i)S(s_k)$ was estimated for every record. Assuming that $S(s_k)$ is lognormally distributed with zero mean, these two functions can be separated. $M(m_i)$ for each of the nine events used in this study is shown in Figure 8. Of course attenuation near the surface, which is common to all stations, will appear in the source term $M(m_i)$. Radiation at the source is fundamentally inseparable from any common site effects using data recorded at the surface. Thus the rapid falloff at high frequency on Figure 8 is likely caused by severe attenuation in the rock layers below the station. These curves show a fundamental characteristic of seismic source scaling: that as magnitude increases the low frequency amplitudes increase rapidly but the high frequency increases only slowly.

Another study of the Fourier spectrum, from a different perspective, is nearing completion. Where Castro et al. determined spectral shapes without reference to any model for the shape, Humphrey and Anderson (1990) are fitting a preconceived shape to a large fraction of Guerrero accelerograms. A model for the shape of the Fourier spectrum of acceleration is, after Brune (1970) and Anderson (1986):

$$M(f) = \frac{M_0}{4\pi\rho\beta^3 r} \frac{(2\pi f)^2}{\left(1+\left(\frac{f}{f_0}\right)^2\right)} e^{-\pi\kappa f} \quad (1)$$

In Equation 1, M_0 is seismic moment, ρ is density, β is shear wave velocity, κ is a spectral shape parameter at high frequency presumably related to attenuation (Anderson and Hough, 1984), f is frequency, and f_0 is the corner frequency. Spectra in Figure 8 qualitatively resemble this shape. Given an observed spectrum, Equation 1 is solved for M_0, f_0, and κ. Since M_0 and f_0 characterize the spectrum radiated from the seismic source, a large number of earthquakes can be compared by a plot showing these two parameters, as in Figure 9.

Brune (1970) showed how one can also obtain an estimate for the stress drop from the moment and corner frequency. Stress drops in 26 earthquakes are obtained from the diagonal axes in Figure 9. For these events, stress drops are mostly between 100 and 1000 bars. For large earthquakes, including the Sept 19, 1985 Mexico earthquake, the stress drop is usually near 30 bars (eg. Kanamori and Anderson, 1975). The stress drops inferred here are higher than usual. They may be high because the region is a mature seismic gap.

6 SITE EFFECTS ON ROCK

The terms $S(s_k)$ (Figure 10) reveal the site effects, relative to an average site. Apparently, strong site effects are rather common among the Guerrero stations. As discussed by Castro et al., the estimated site effects at La Union, Zihuatanejo, El Balcon, and Petatlan are less reliable because a smaller amount of data was available to constrain the results.

The stations of the Guerrero array are all installed on rock outcrops. Many are plutonic outcrops, and most others are outcrops of other types of volcanic rock. There is a variable degree of weathering at these sites. The least weathered rock among the stations in Figure 10 is at BALC, MAGY, SUCH and XALT. The most severe weathering affects LLAV, ATYC, MSAS, and CPDR. We cannot see any obvious correlation of site effects with the degree of surficial weathering.

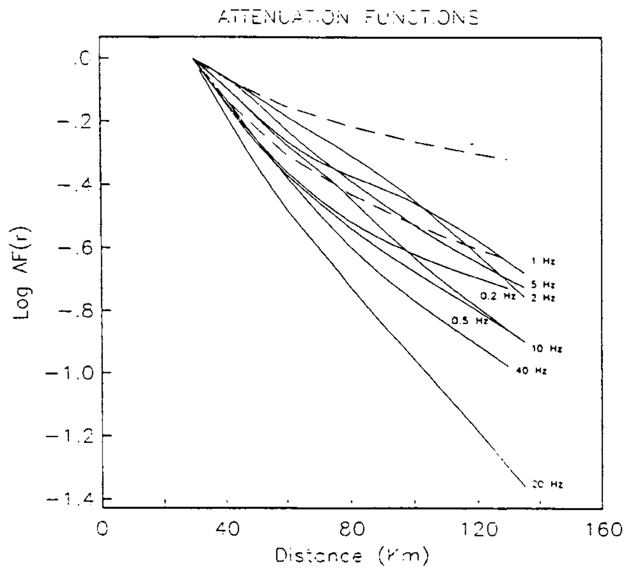

Figure 6. . Attenuation functions R(r) for amplitudes of Fourier spectra as a function of distance, at eight selected frequencies. For reference, curves with distance depencences of r^{-1} and $r^{-\frac{1}{2}}$ are also shown on this figure. (From Castro et al., 1990a)

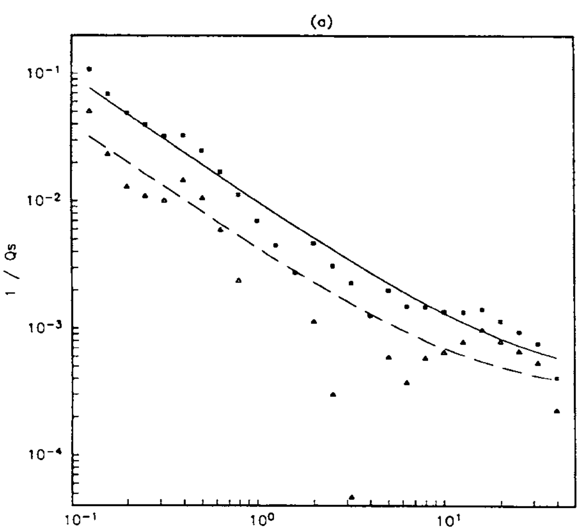

Figure 7. . Estimates for Q as a function of frequency. Solid symbols and upper line are for a reference spreading model proportional to $r^{-1/2}$. Triangles and lower line are for a reference spreading model proportional to r^{-1}. (From Castro et al., 1990a)

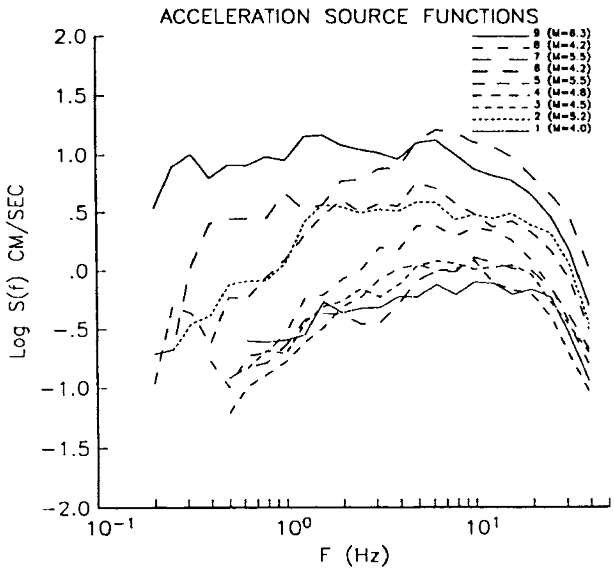

Figure 8. . Acceleration source function normalized to 30 km for nine earthquakes. (From Castro et al., 1990a)

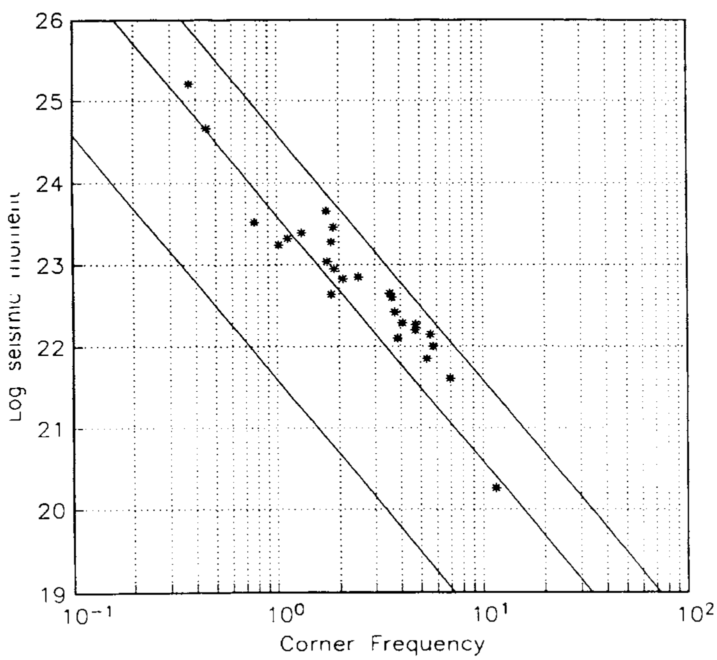

Figure 9. . Symbols on plot show corner frequency of selected events as a function of seismic moment. Solid lines show locus of constant stress drop after Brune (1970). (From Humphrey and Anderson, 1990)

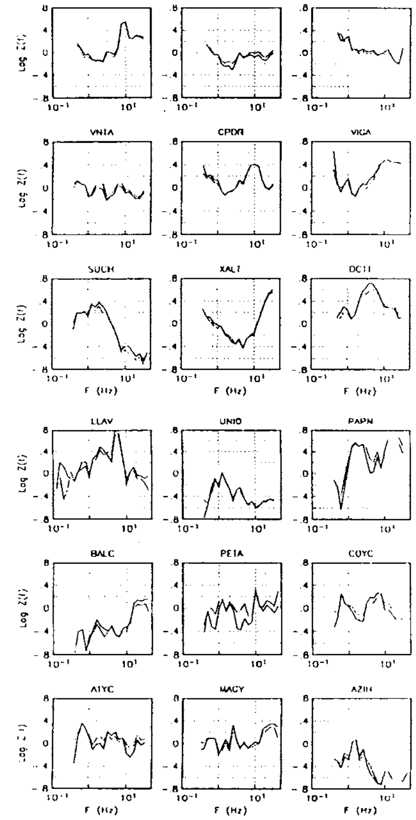

Figure 10. . Site functions for Guerrero array stations obtained by Castro et al. (1990a). The two lines compare two slightly different estimation methods.

7 VERTICAL ACCELERATIONS

The ratio of peak vertical acceleration to peak horizontal acceleration (v/h) is typically assumed equal to two thirds (eg. Newmark and Hall, 1982). Recently, Abrahamson and Litehiser, (1989) reopened the question with a study of United States accelerograms. This paper examines v/h for the Guerrero data from 1985 through 1988. Considering wave propagation and earthquake source theory, the ratio might be expected to depend on distance, source depth, and magnitude. Figure 11 explores these variables.

The highest v/h ratios occur at small distances and small magnitudes where there is most data. However, the ratio follows a skewed distribution, and at large distances or large magnitudes the smaller number of points might not suffice to show the long tail at high v/h ratios. Among several cumulative distribution functions of v/h ratios for selected subsets of the Guerrero data (Figure 12), no two distributions differ significantly based on the Kolmogorov-Smirnov test (as implemented in Press et al, 1986, p472ff.). The subset of events with r<50 contains a large fraction of the events, and is naturally indistinguishable from the complete set. The subsets with r>100 or depth>30 are also indistinguishable. Two subsets appear to have a smaller standard

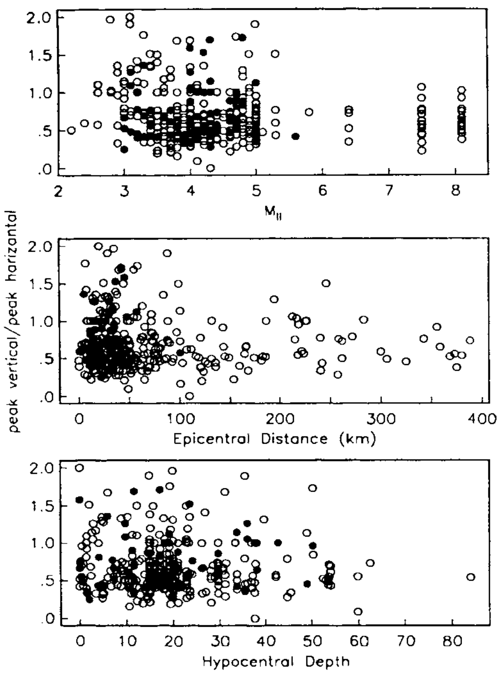

Figure 11. . Ratio of peak vertical to horizontal accelerations for all data, 1985 to 1988, A: as a function of distance from the epicenter; B: as a function of magnitude; C: as a function of distance hypocentral depth. Solid symbols represent events recorded with complete P-wave and S-wave.

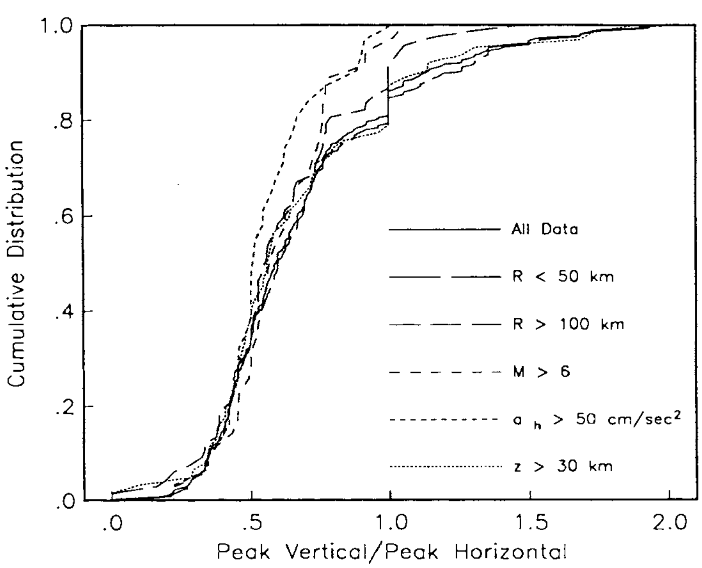

Figure 12. . Cumulative distribution of the ratio of peak vertical to horizontal acceleration for 370 accelerograms recorded between 1985 and 1988, and for selected subsets, as indicated on the legend.

deviation (the subset with M>6.0 and the subset where both horizontal components exceed 50 cm/sec^2), but because these subsets are small the difference is insignificant. In the context of linear elasticity there is no reason for v/h to depend on the amplitude of the record. High ratios of vertical to horizontal acceleration may be a consequence of either wave propagation or source physics; research to understand this phenomenon is underway.

8 1985 MICHOACAN EARTHQUAKE, SEPTEMBER 19

The September 19, 1985 earthquake was one of the most significant earthquakes in the world in the decade of the 1980's. Mendez and Anderson (1990) obtained a detailed model for the source from the strong motion data. Figure 13 shows velocity on the fault for a series of time windows every two seconds starting 10 seconds into the rupture. For the first 10 seconds, there was insufficient station coverage. The solution shows rupture propagating toward the southeast at 2.8 km/sec. Relatively high slip velocities occur at two asperities, one near the epicenter and the other near the southeast limit of rupture. Rupture may have propagated bilaterally outward from both asperities after they failed. An upper bound for the duration of rupture at any one site of the fault is approximately 8 seconds near the epicenter and 10 seconds for the southeast portion of the fault.

9 SUMMARY

This paper has discussed recent results of studies of the Guerrero data obtained primarily by the UNR scientists and students. No attempt has been made to be complete.

There is an abundant supply of data from the Guerrero array,, and important additional data is anticipated. Many questions on strong motion characteristics can now be answered with more confidence than ever before. Acceleration spectra as inferred for the source, after attenuation is removed as much as possible, are consistent with seismic scaling laws, and are now being used to help reduce uncertainties in these models. It is still not possible to totally separate the source effects from attenuation common to all stations; any common effects appear in our source spectra. Site effects that we can separate are strong, even though all the stations are nominally on rock. We have occasional observations of high vertical accelerations; we have not discerned any statistically significant tendency for these to occur at short distances, large magnitudes, deep hypocenters, or high acceleration levels. A model for the source of the Sept 19, 1985 main shock derived from the strong motion records shows that a slip pulse moved across the fault from the northwest to the southeast.

10 ACKNOWLEDGEMENTS

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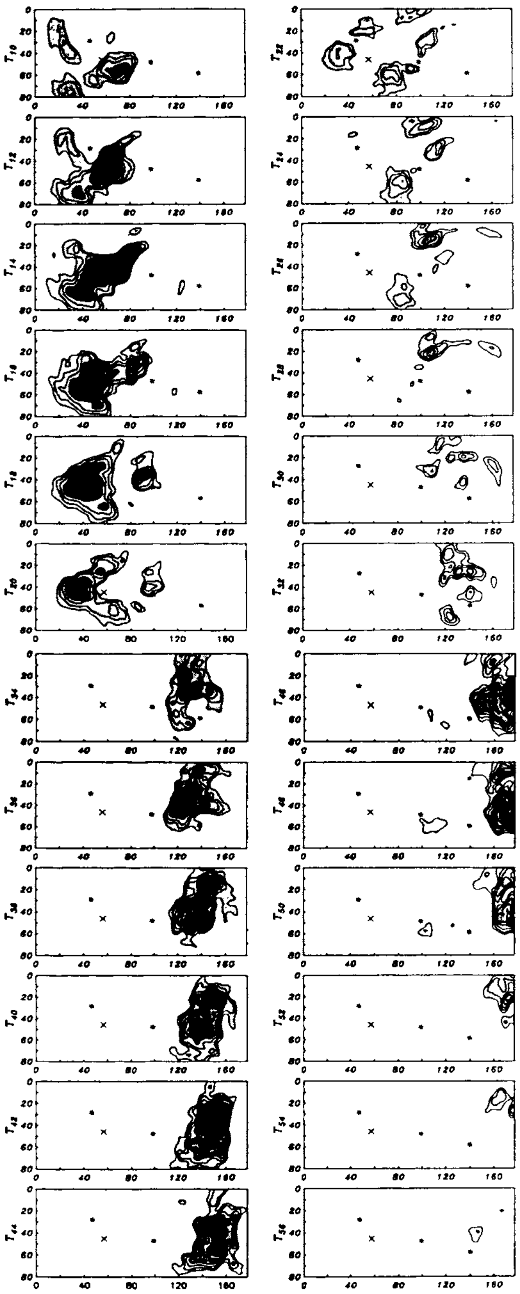

Figure 13. . Series of snapshots of the 1985 source zone, showing the velocity of slip on the fault at the time of each frame. From Mendez and Anderson (1990).

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