The Copala, Guerrero, Mexico Earthquake of September 14, 1995 ($M_w = 7.4$): A Preliminary Report

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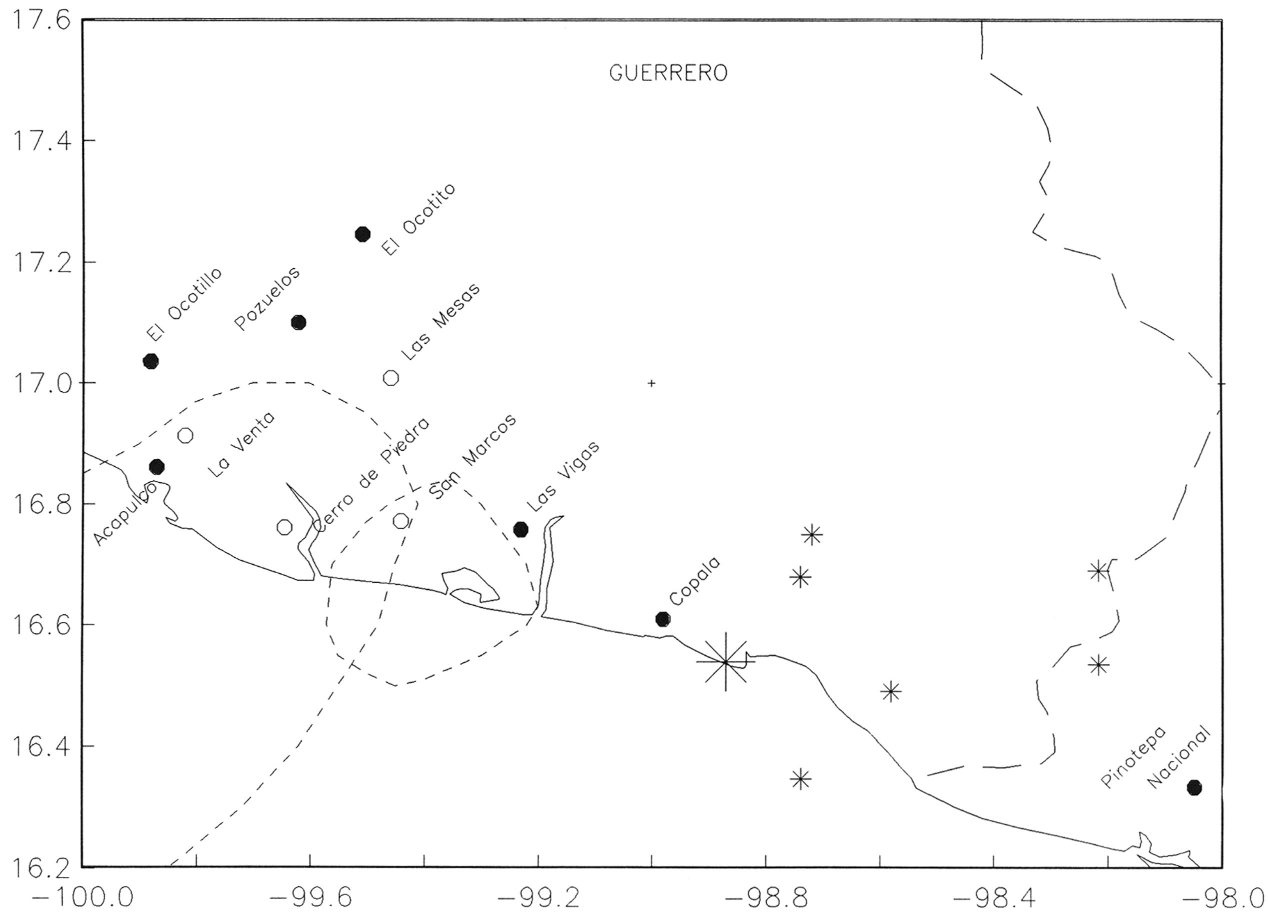
INTRODUCTION

The Copala, Guerrero, Mexico earthquake is the largest earthquake to occur in Mexico since the destructive 1985 events. It occurred at a time when earthquake awareness in Mexico was heightened, as the country prepared for numerous commemorative activities of the 1985 main shock, which were to occur five days later. The strong motion data from this earthquake highlights the enormous progress in instrumentation that has occurred over the past ten years. As in 1985, the accelerogram nearest the epicenter has peak values that are notably smaller than expected, and it seems to display a static offset when integrated. Indeed, accelerations on rock at all distances average below values that were expected based on previous experience in Guerrero.

Table 1 lists hypocentral parameters for the earthquake. The UNAM epicenter is shown in Figure 1. All the hypocenters derived from teleseismic data are demonstrably less reliable. The UNAM hypocenter listed here is consistent with observations that the S-P time at the Copala strong motion station is 3.0 seconds and that the hypocenter is southeast of Copala based on first motions (Anderson *et al.*, 1995). For the teleseismic depth of about 20 km, this implies an epicentral distance of 13 km from Copala, a constraint that plays an important role in the UNAM location. We believe that the fault plane involved is the shallow-dipping plane (Table 1), which strikes parallel to the coast and the subduction zone and dips towards the north. This mechanism is consistent with focal mechanisms that have been observed in numerous previous earthquakes (Suarez *et al.*, 1994), and it is consistent with observed locations of microearthquakes which define a shallow dip to the subduction thrust. Figure 1 shows several aftershock locations, obtained from the US Geological Survey Preliminary Determination of Epicenters.



▲ **Figure 1** Map of epicentral region (modified from Anderson *et al.*, 1995). Large asterisk is approximate epicenter of main shock, as described in the text. Smaller asterisks are epicenters of aftershocks that were located by the National Earthquake Information Service of the U. S. Geological Survey. Accelerographs are identified by a filled circle if data from the main shock has been recovered.

Although locations in this region based on teleseisms are likely to have very large uncertainties, the locations are likely to be reasonably well constrained along the direction parallel to the coast. Thus, the aftershocks can be used to estimate the possible extent of rupture during this event. They suggest that the epicenter was near the northwest limit of rupture and that the rupture may have extended 25–30 km towards the southeast. Field studies by the Instituto de Geofisica and the Instituto de Ingenieria at UNAM will eventually provide an improved description of aftershock locations.

The Copala earthquake and aftershocks on Figure 1 are in the Ometepec seismic gap (Singh *et al.*, 1991) and appear to be a success for the seismic gap hypothesis. A description of the evolution of seismic gaps in Guerrero is presented by Anderson *et al.* (1994). Nishenko and Singh's (1987) best estimate for the probability that an earthquake would recur in this region between 1986 and 1996 was 83% (55%–96%). Previous earthquakes that possibly ruptured within the gap include 1890 (7.5), 1907 (7.9), 1937 (7.5), 1950 (7.3), and 1982 (6.9, 7.0). The 1982 events are very much smaller than the other events and contribute little to the net moment release. The 1907 event ruptured the adjacent part of the trench to the northwest, and may have also ruptured the Ometepec portion. The Sept. 14 event resembles the remaining events reasonably closely in magnitude, at least. It is problematic, however, to characterize any of these events as "characteristic." Like the September 14 event, earthquakes in 1937 and 1950 may not have ruptured the entire Ometepec portion of the trench. Nishenko and Singh (1987) suggest that the 1937–1950 activity was a complicated mode of rupture that took 13 years to complete. Since the 1890 earthquake is pre-instrumental, it is not clear whether the September 14 earthquake was a reasonably close replica of any of the known prior events. These considerations leave some uncertainty as to what Nishenko and Singh predicted. In a sense, those considerations are irrelevant; what is important is that the September 14 event is well within the range of expected magnitudes and is in the Ometepec gap.

STRONG MOTION PROGRAM IN MEXICO

The strong motion program in Mexico has grown enormously since 1985 (Quaas, 1995). This growth, and the current status, are very well documented with two reports by

TABLE 1
Hypocentral Parameters

Institute of Geophysics, UNAM	
Location:	16.54° N
	98.73° W
	20 km depth
U.S.G.S.:	*Preliminary Determination of Epicenters*
Origin	September 14, 1995
Time	14:04:31.7 GMT
	8:04 AM local time
Location	16.830 N
	98.647 W
	21 km depth
Size	$m_b = 6.5$
	$M_S = 7.2$
Harvard	
Centroid	16.82 N
Location	98.64 W
	15 km depth (Fixed)
Moment	Best Double Couple: 1.8 * 10**27 dyne-cm
Tensor	Nodal Plane 1: strike 289, dip 11, slip 85
	Nodal Plane 2: strike 114, dip 79, slip 91
Magnitude	$M_W = 7.4$
University of Tokyo	
Centroid	16.47 N
Location	98.34 W
	17.8 km depth
Moment	Best Double Couple: 1.29 * 10**27 dyne-cm
Tensor	Nodal Plane 1: strike 316.2, dip 8.5, slip 103.9
	Nodal Plane 2: strike 122.2, dip 81.7, slip 87.9
Magnitude	$M_W = 7.3$
University of Michigan	
Location	16.7 N
	98.5 W
	23 km depth
Focal Mechanism	Strike 115.5, dip 77.4, rake 87.1
Source	Total moment: 1.11 * 10**27 dyne-cm
Time	Duration of pulse with this moment: 15 seconds
Function	

Quaas *et al.* (1993, 1995a)[9]. Quaas *et al.* (1993) describe the distribution of stations, and Quaas *et al.* (1995a) catalog the entire set of strong motion records obtained from 1960 through 1993. The various organizations that gather this data are a model for collaboration. They intend to publish the entire set of accelerograms on a CD-ROM sometime in 1996.

Considering the size and quality of the present Mexican network, the Copala event is by far the best documented earthquake with magnitude over 7 that has ever occurred in Mexico. The completeness of the data is likely to rival that from any other subduction thrust earthquake of its size any place in the world.

Table 2
Accelerograph Instrumentation in Mexico

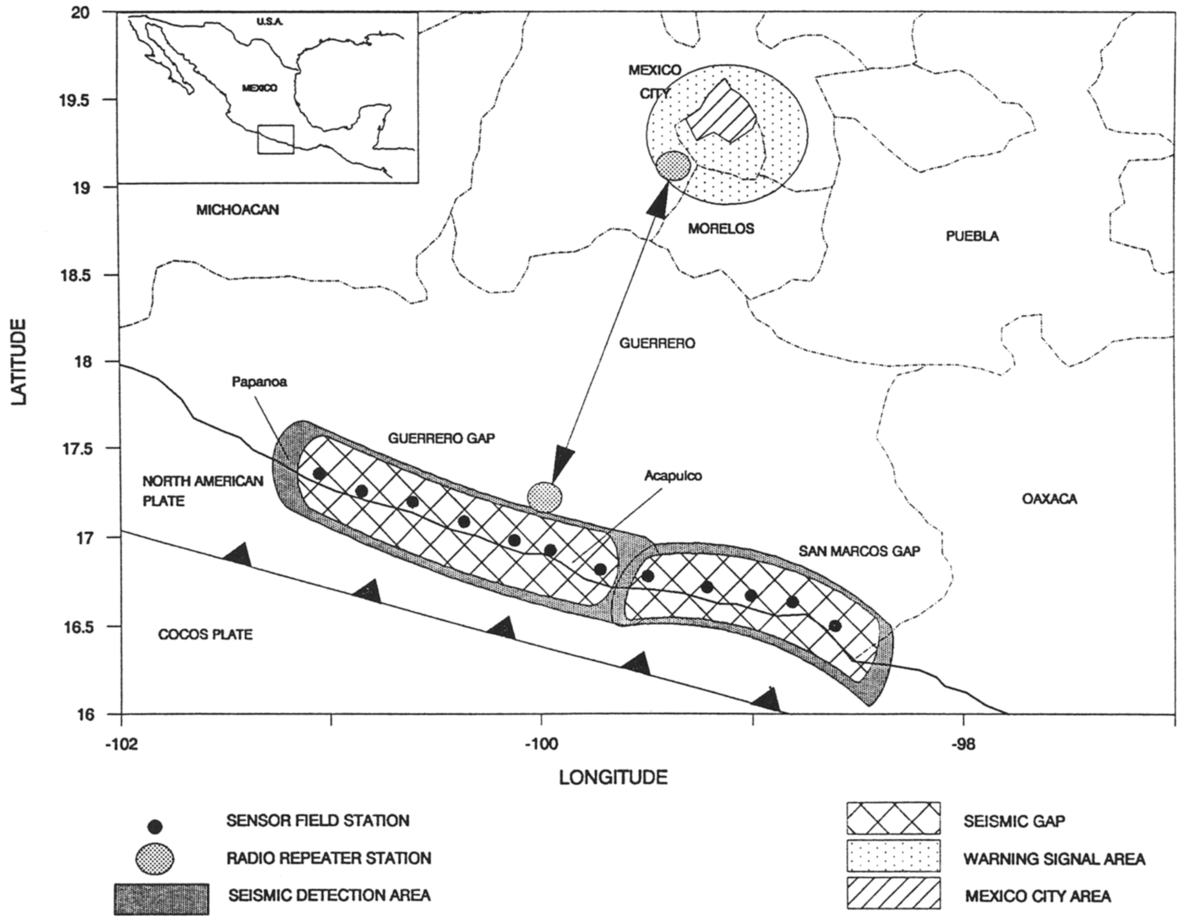
Number & Type of Station	Sept. 1985	Aug. 1995
Free field	95	249
Downhole	0	29
Buildings	5	93
Other Structures (e.g., dams, dikes)	10	67
Total	110	438

TABLE 3
Distribution of Accelerographs in the Valley of Mexico (1995)

Type of Soil/ Setting	Free Field	Downhole	Building	Total
Hill Zone	20	4	0	24
Transition	18	7	17	38
Lake	65	15	66	137
Total	103	26	83	212

In 1985, the main organization involved in strong motion recordings in central Mexico was the Instituto de Ingenieria (Institute of Engineering) at the Universidad Nacional Autonoma de Mexico (UNAM). They were maintaining instruments for some other agencies (e.g., the Federal Power Commision) and operating their own stations. In addition, they were collaborating with John Anderson and Jim Brune to install a network of 30 stations primarily in the Guerrero gap along the coast of Mexico and along the route from Acapulco to Mexico City (Anderson *et al.*, 1994). That network was supported with their internal funds, and by the US National Science Foundation. The Guerrero network was about 70% complete when the September 19 earthquake struck. It recorded several records that were critical to understanding the 1985 main shock (e.g., Anderson *et al.*, 1986).

Tables 2 and 3 (from Quaas, 1995) give statistics of the extension of the strong motion program in Mexico since 1985. Table 2 documents the growth in the total number of stations since 1985. Altogether, the total number of stations has approximately quadrupled. An important feature of this growth is the nearly ten-fold increase of instrumentation of the Valley of Mexico; statistics of the types of sites that are now instrumented are described in Table 3. Through July, 1995, Quaas counted 969 earthquakes that have produced strong motion records, of which 792 are since September, 1985. These have produced over 7600 accelerograms, of



▲ **Figure 2** Locations of seismic alert system sensors (from Espinosa *et al.*, 1995).

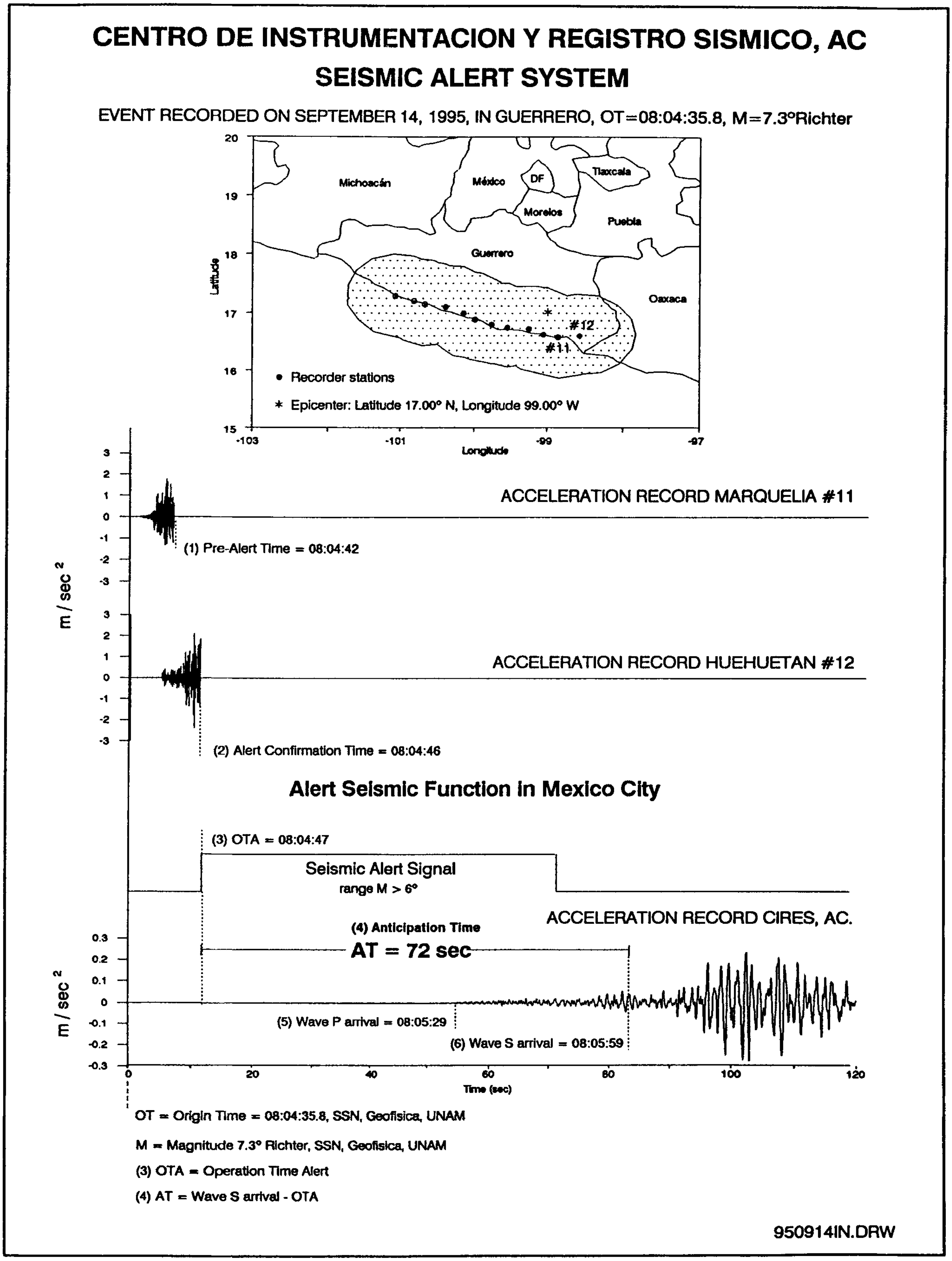
which over 94% are digital. Over 99% of the accelerograms recorded since 1985 are digital. The number of organizations that are recording strong motion has increased. In addition to the Instituto de Ingenieria, Fundacion Barros Sierra and Fundacion ICA installed about 40 strong motion stations each in the Valley of Mexico, and the Centro Nacional de Prevencion de Desastres (CENAPRED), with support from Japan, installed 29 stations in Mexico City and supplemented the linear extension of the Guerrero network along the road from Mexico City to Acapulco. The stations have been thoroughly cataloged by Quaas *et al.* (1993), and the accelerograms have been cataloged through 1993 (Quaas *et al.*, 1995a).

SEISMIC ALERT

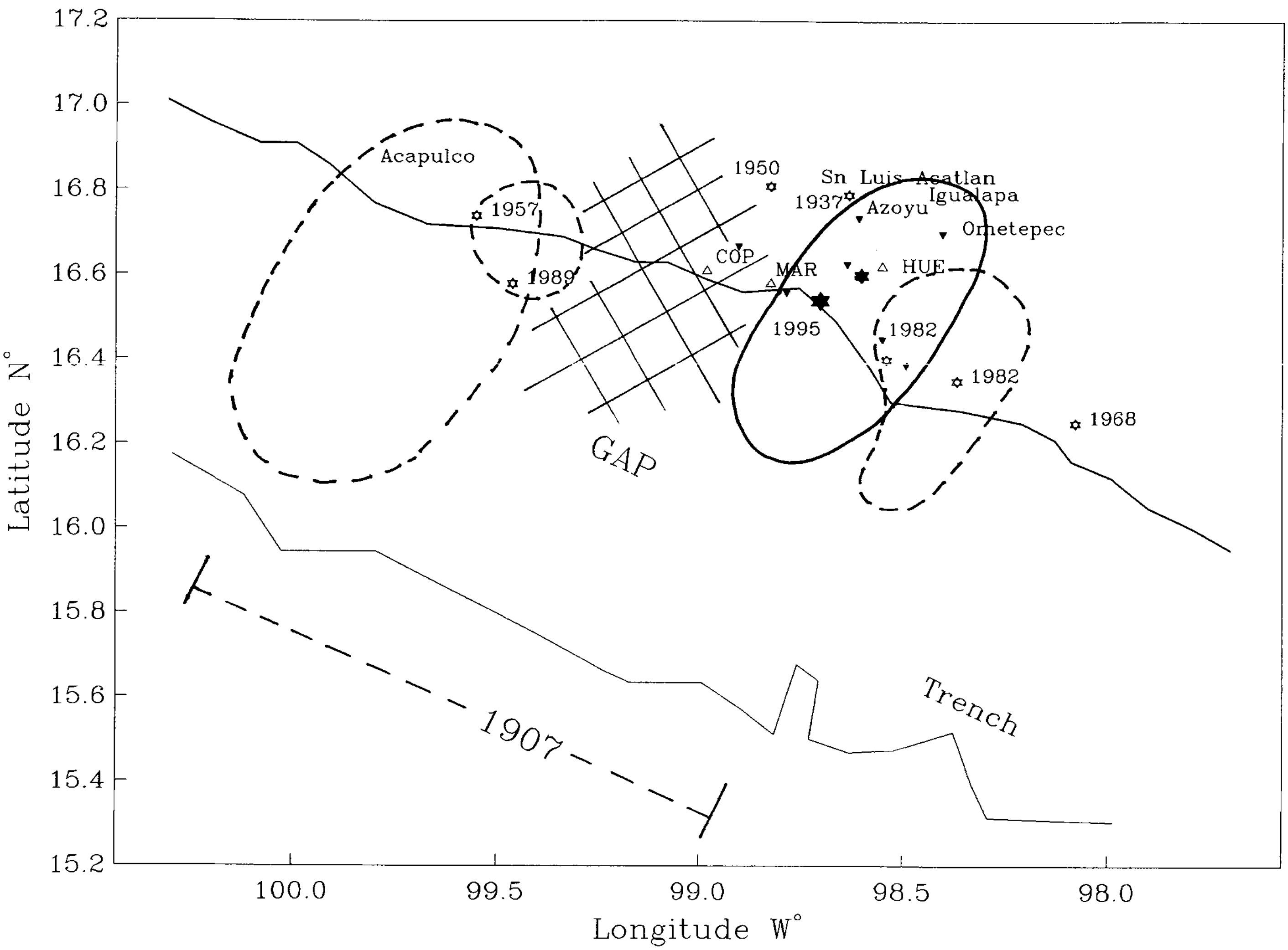
One special supplement to the southern Mexican accelerograph network is the seismic alert system. The main source of damaging earthquakes for Mexico City is the Mexican subduction thrust, which is more than 250 km away at closest approach. Since shear waves travel at about 3.5 km/sec, they take at least 70 seconds to reach Mexico City from the subduction zone. Considering this, seismologists in Mexico have long recognized that if a system on the coast of Mexico could be established to quickly recognize that a strong earthquake had begun, then some warning could be transmitted to Mexico City allowing time for some evasive actions. This concept was implemented in 1991 by the Centro de Instrumentacion y Registro Sismico (CIRES), under the auspices of Fundacion Javier Barros Sierra and under the leadership of Juan Manuel Espinosa-Aranda. The project was sponsored primarily by the Departamento del Districto Federal (Federal District). The seismic alert system is described in some detail by Espinosa *et al.* (1989), Espinosa (1995), and Espinosa *et al.* (1995).

Figure 2, from Espinosa (1995), shows the configuration of the sensors, which are three-component piezoelectric accelerometers with 10 bit digitizers. When a station detects strong shaking that is potentially associated with an event of magnitude over 5, it sends a signal back to the central offices in Mexico City. The triggering algorithm is based on the rate of accumulation of energy, which is classified as over magnitude 6 (M_1) or over magnitude 5 (M_2). Coincidence of two or more stations broadcasting an M_1 alert trigger the alarm system.

One aspect of the system is that the first 10 seconds of



▲ **Figure 3** Timeline for the seismic alert for Copala earthquake (from Espinosa *et al.*, 1995).



▲ **Figure 4** Map of epicentral region showing epicenters of main shock and largest aftershock (filled stars), estimated extent of fault rupture (enclosed by solid line), and estimated ruptures during previous earthquakes (dashed lines). Named cities are sites of significant damage.

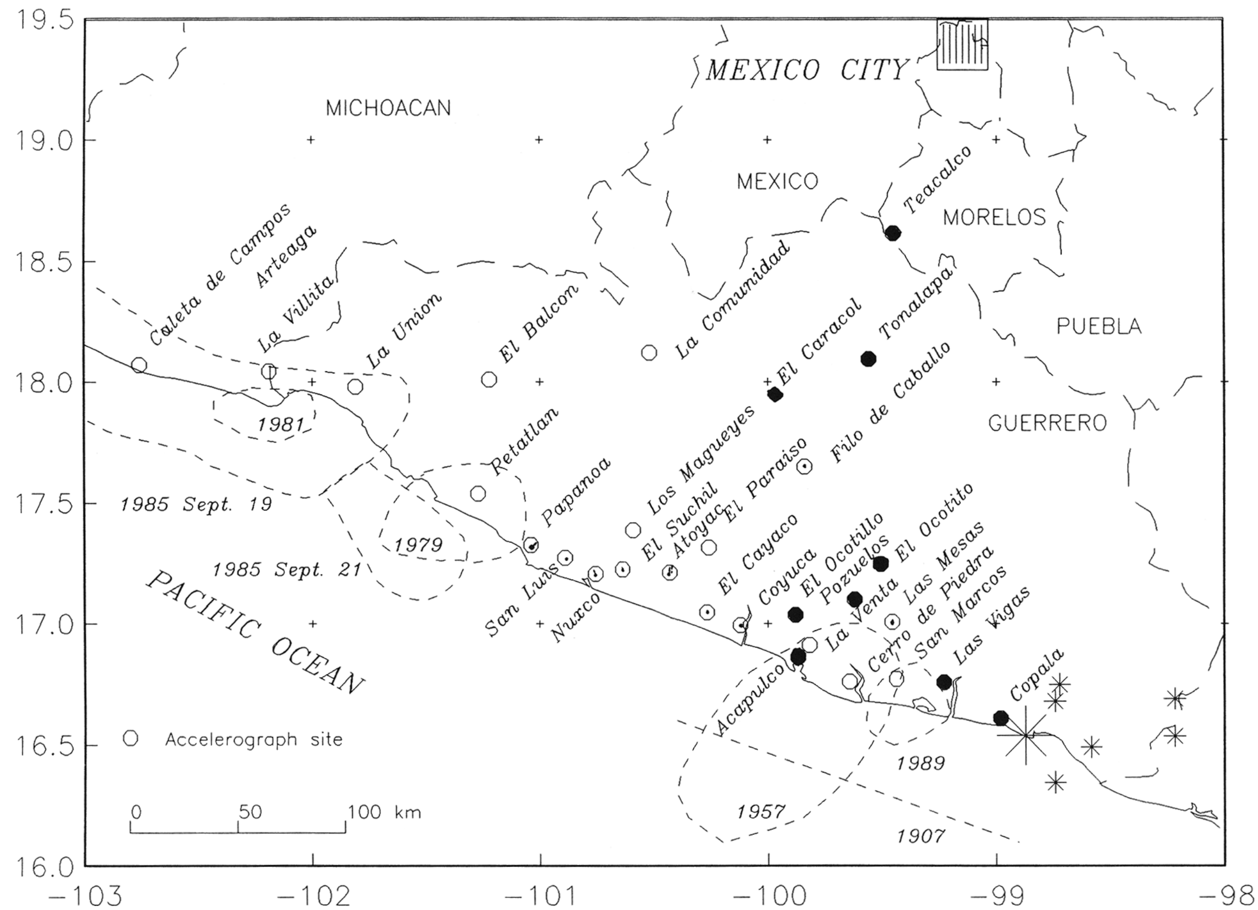
accelerograms to cause a trigger are saved on disk at the remote stations and can be analyzed at a later time. Figure 3 shows the geometry and the sequence of events of the alarm for this earthquake. The alarm was based on stations at Marquelia and Huehuetan. The origin time of the earthquake is estimated to be at 08:04:36. Marquelia issued its alert at 08:04:42, 8 seconds after the origin, and Huehuetan issued its alert at 08:04:46, 10 seconds after the origin. One second later, the alert was broadcast in Mexico City. The seismograms that provide the basis for these alerts are shown in absolute time in Figure 3, terminated at the time each station sent its alert signal. The first strong shaking at the Mexico City station illustrated in Figure 3 arrives about 80 seconds later. The beginning of the earthquake at Marquelia shows a peak acceleration of 15–20% g. These stations are not situated on rock.

Prior to September 14, the alarm had registered one missed alarm, followed by two false alarms. These false alarms had generated considerable skepticism about the value of the alarm. For that reason, the signal was being forwarded to radio and television stations in Mexico City, but it was up to the discretion of the stations whether to broadcast the alert. On Sept. 14, according to one anecdotal account, the announcer at some stations heard the alert signal, and over the air told their listeners that the signal was received, with a commentary of "let's see if we feel an earthquake in the next 50 seconds." Before the countdown was complete, the shaking began. Other stations did not broadcast any kind of alert but told listeners that they had received the signal after they felt the shaking.

Thirty-one schools receive the alarm in addition to the radio stations and various federal agencies. An anecdotal description of the alarm sequence at one school is that the school had practiced drills for an earthquake in advance. The alarm was not automatically broadcast to the entire school; instead some human intervention was needed to relay the information, consuming some valuable time. Students evacuated relatively quickly. One particularly strong student

▲ **Figure 5** (above) Collapsed adobe masonry building in Huehuetan (photo by J. Lermo).

▲ **Figure 6** (below) Damaged jaulillas structure in Huehuetan (photo by J. Lermo).



▲ **Figure 7** Map of Guerrero accelerograph stations (from Anderson *et al.*, 1995). Accelerograms have been recovered from stations with a filled circle. Stations indicated by an open circle with a dot inside are likely to have produced accelerograms but had not yet been inspected.

went to the next classroom to carry a blind student outside; he was still in the building when the shaking began but was outside well before it finished. There is anecdotal evidence that many of the collapses in 1985 occurred late in the ground motion; thus the exercise can be considered a success at that school.

DAMAGE IN THE EPICENTRAL AREA

The Copala earthquake affected a region of Guerrero referred to as the Costa Chica. Some of the cities in the Costa Chica have a very long history. Igualapa City (Figure 4) was founded in 1304, and Azoyu was founded in 1520 (according to Azoyu's Codex). The most important previous earthquake in the history of the Costa Chica is the 1937 event.

The aftershocks of the Copala-Guerrero, Mexico earthquake were recorded using a temporary network of the Instituto de Ingenieria, UNAM, deployed some 24 hours after the mainshock. This network consisted of 7 seismographs and remained in the field during ten days (full triangles in Figure 4). From the location of a few events and damage distribution, an approximate rupture area is proposed in Figure 4. This area covers some 1,800 square km (continuous line in Figure 4) and almost coincides with the estimated rupture of the 1937 (M_s = 7.5) earthquake. Probably, the September 14, 1995 earthquake ruptured the same patch. There is an overlapping of the area proposed in Figure 4 with that for the Ometepec double earthquakes of 1982 (M_s = 6.9 and 7.0, respectively), depicted with broken line in Figure 4. The earthquake did not completely fill the Ometepec gap. Rather, about half of it, west of this event and east of the 1957 Acapulco and 1989 San Marcos earthquakes, appears to remain intact. It is possible that a replica of the 1950 earthquake could fill this remaining gap in the future.

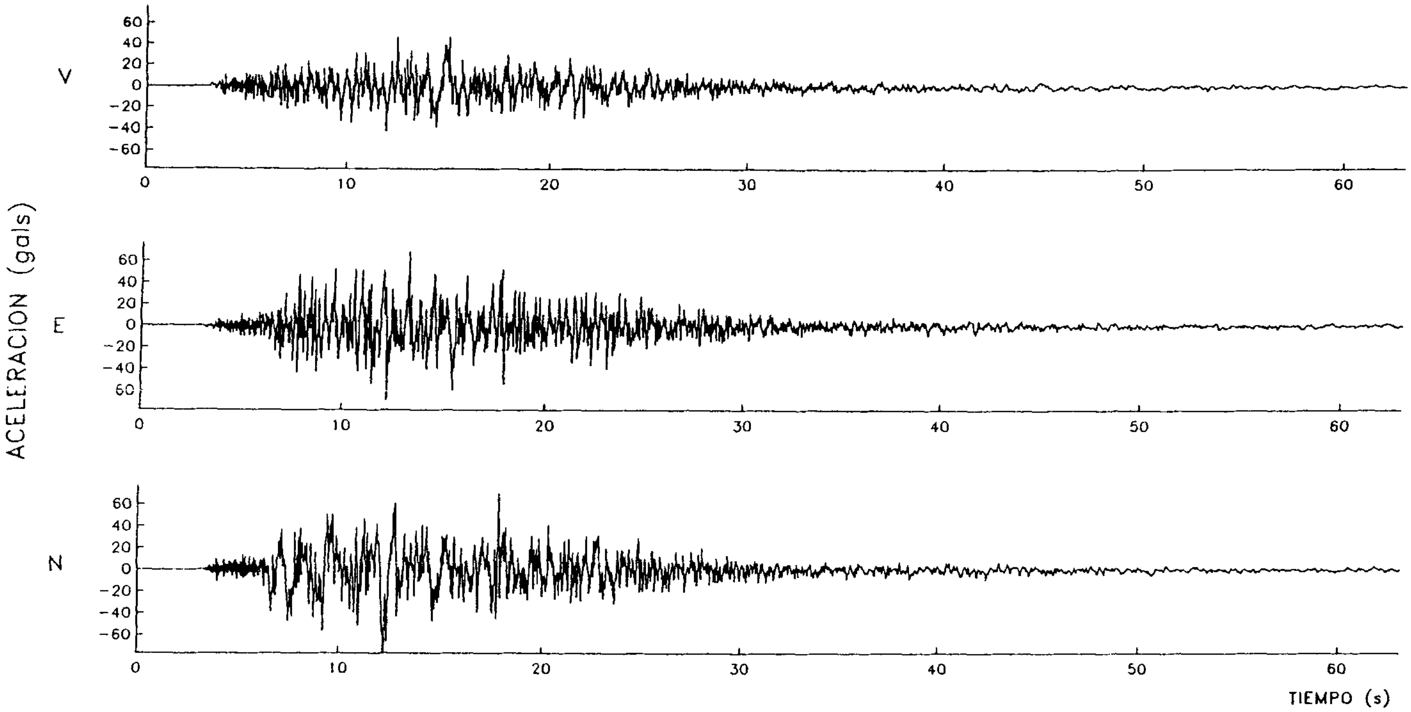
For the Copala earthquake, the epicenters for both the mainshock (16.54N, 98.73W) and the major aftershock (m_b = 5.1) were found to be within the continent, very close to the shoreline, with an approximate depth of 20 km (filled stars in Figure 4). In order to locate the mainshock, the records from three accelerographs were used. Two of them correspond to stations of the Seismic Alert System (SAS) of CIRES and are the stations closer to the epicenter (station

TABLE 4
Sample of Strong Motion Accelerograms from the September 14, 1995 Copala Earthquake

Station	Institution	Lat °N	Long °W	Distance (km)	Amax N–S (gals)	Amax E–W (gals)	Amax V (gals)
Copala	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	16.610	98.980	22.7	77.01	68.95	46.48
Las Vigas	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	16.758	99.230	53.9	-100.14	-79.21	57.44
Acapulco La Salle	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	16.866	99.862	120	14.17	-10.30	-8.00
Acapulco-Diana	Instituto de Ingenieria, UNAM	16.867	99.880	121.8	69.74	-67.50	-15.86
Ocotillo	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	17.036	99.880	129.2	-10.82	-11.37	-9.94
Pozuelos	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	17.10	99.62	109.5	6.44	-8.13	-4.06
Ocotito	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	17.246	99.507	111.5	59.87	-48.62	31.26
Chipancingo	Centro Nacional de Prevencion de Desastres, CENAPRED	17.466	99.452	127.1	-26.31	19.10	-18.55
Mezcala	Centro Nacional de Prevencion de Desastres, CENAPRED	17.930	99.590	178.7	–	-15.32	7.66
Tonalapa	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	18.094	99.559	193.5	-10.56	-11.08	11.04
Iguala	Centro Nacional de Prevencion de Desastres, CENAPRED	18.399	99.506	222.6	-6.84	-6.96	-7.84
Teacalco	Instituto de Ingenieria, UNAM/ University of Nevada, Reno	18.614	99.453	243.4	11.69	-7.69	-6.89
Cuernavaca	Centro Nacional de Prevencion de Desastres, CENAPRED	18.981	99.237	277.8	12.7	12.85	7.78
II, UNAM	Instituto de Ingenieria, UNAM	19.333	99.183	315.4	-12.42	7.65	3.80
Coyocacan	Centro Nacional de Prevencion de Desastres, CENAPRED	19.348	99.169	316.8	16.24	17.61	-5.74
Chapultepec	Centro Nacional de Prevencion de Desastres, CENAPRED	19.416	99.205	324.7	12.45	7.93	6.23
SCT	Instituto de Ingenieria, UNAM	19.393	99.147	321.5	-23.35	-31.76	13.67
Roma	Centro Nacional de Prevencion de Desastres, CENAPRED	19.419	99.155	324.4	-30.98	29.30	-11.23
Zocalo-DDF	Centro Nacional de Prevencion de Desastres, CENAPRED	19.431	99.133	325.5	-21.56	22.99	10.30

MAR at about 12 km and station HUE with 18 km). The third station, COP, belongs to the Guerrero Strong Motion Array (Anderson *et al.*, 1995) at about 30 km from the epicenter. These stations are marked in Figure 4 with open triangles.

This earthquake produced significant damage in four cities of the Costa Chica of Guerrero: San Luis Acatlan, Azoyu, Igualapa, and Ometepec. These cities, which have more than two thousand inhabitants each, are located at



COPALA			I de I, UNAM – UNR	
Fecha:	14 de Septiembre de 1995	Amax (V):	46.48	DCA-333/201
Hora:	14:04:32.25 [GMT]	[gals] (E):	68.95	1g / dec. 1
Duracion:	63.15 seg	(N):	−77.01	COPL9509.141*

▲ **Figure 8** Accelerograms recorded by the station at Copala (from Anderson *et al.*, 1995).

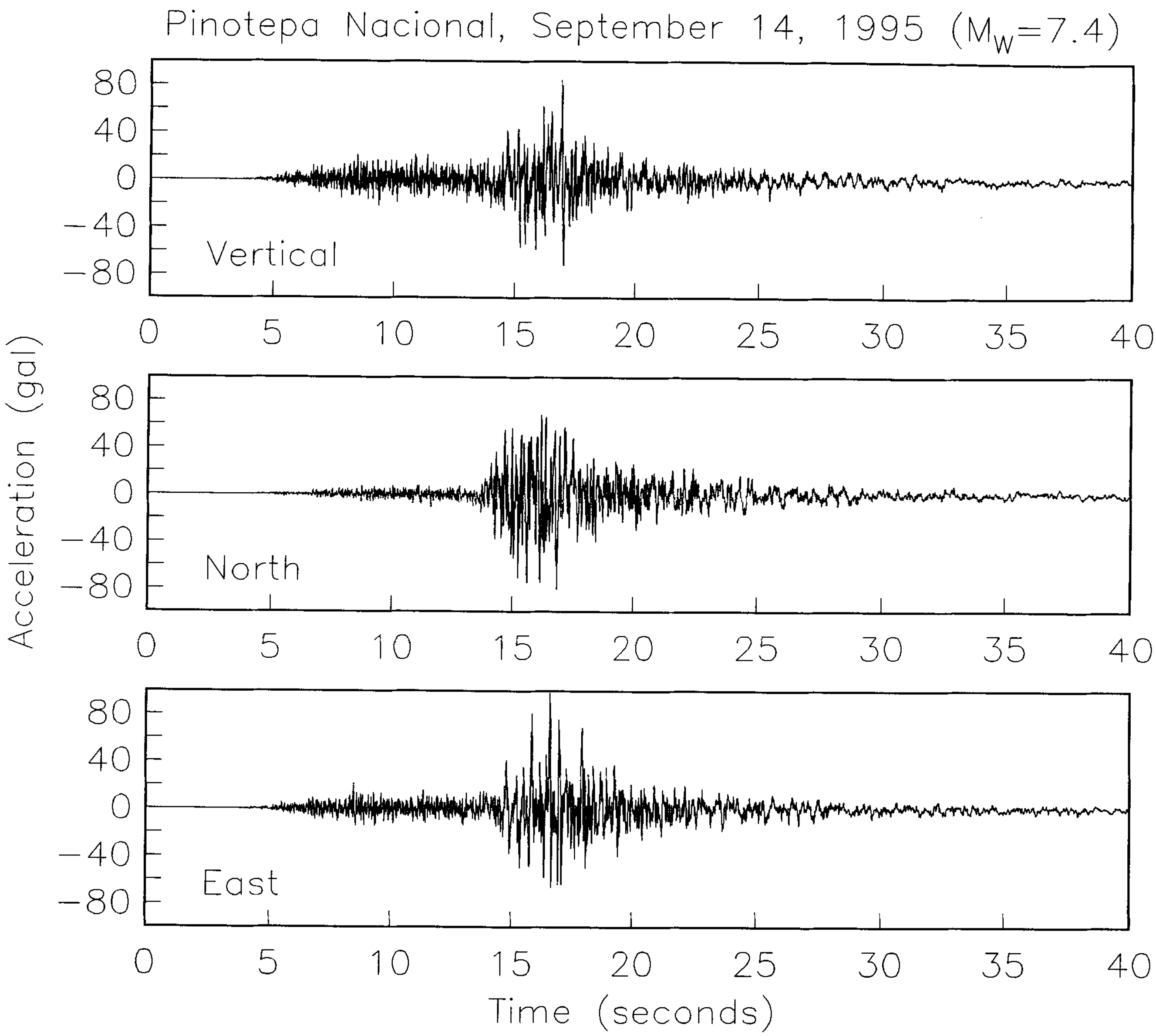
more than 20 km from the coast at an altitude of some 500 m above sea level. The topography for these cities is very irregular with hills and alluvial deposits. Typical construction (between 70 and 80 percent) is adobe-based masonry. Figure 5 shows a collapse of this type of structure in Huehuetan. Somewhat less common is a construction system of wood and mud called "jaulillas." Figure 6 shows damage in the walls of one of these. A minor portion is based upon brick and cement. In any event, only adobe houses collapsed. Damage was concentrated in the hilly sectors. For instance, in Arcelia del Progreso at Azoyu 25 houses collapsed and more than 200 houses had major damage. Extensive microtremor vibration measurements in the area uncovered the predominant periods of the various hilly damaged zones, which have values between 0.1 and 0.2 sec. This is in agreement with experimental studies that show similar values for the the dominant period of these adobe houses (Hernandez *et al.*, 1981). However, many factors may influence damage distribution: age and quality of construction, amplifications due to site effects, directivity and radiation pattern of source mechanism.

EFFECTS OF THE EARTHQUAKE IN MEXICO CITY

Effects of the Copala earthquake in Mexico City are described in a separate contribution by Meli *et al.* (1995). Amplitudes of ground motion were about 20% of those from the disastrous Sept 19, 1985 earthquake. There was some minor damage, but no major damage or casualties. Some of the minor damage could be cause for serious concerns about the potential effects of much larger earthquakes, which are inevitable sometime in the future.

STRONG MOTION DATA

Preliminary reports on strong motion data, as of September 21, included Almora *et al.* (1995), Alcantara *et al.* (1995), Anderson *et al.* (1995), Guevara *et al.* (1995), Gonzalez *et al.* (1995), Quaas *et al.* (1995b), and Centro de Instrumentacion y Registro Sismico, A.C. (1995a,b). The first report by CENAPRED (Guevara *et al.*, 1995) was published the same day of the earthquake. With all of the data, it is only possible to give a brief summary, illustrated with a few of the highlights.



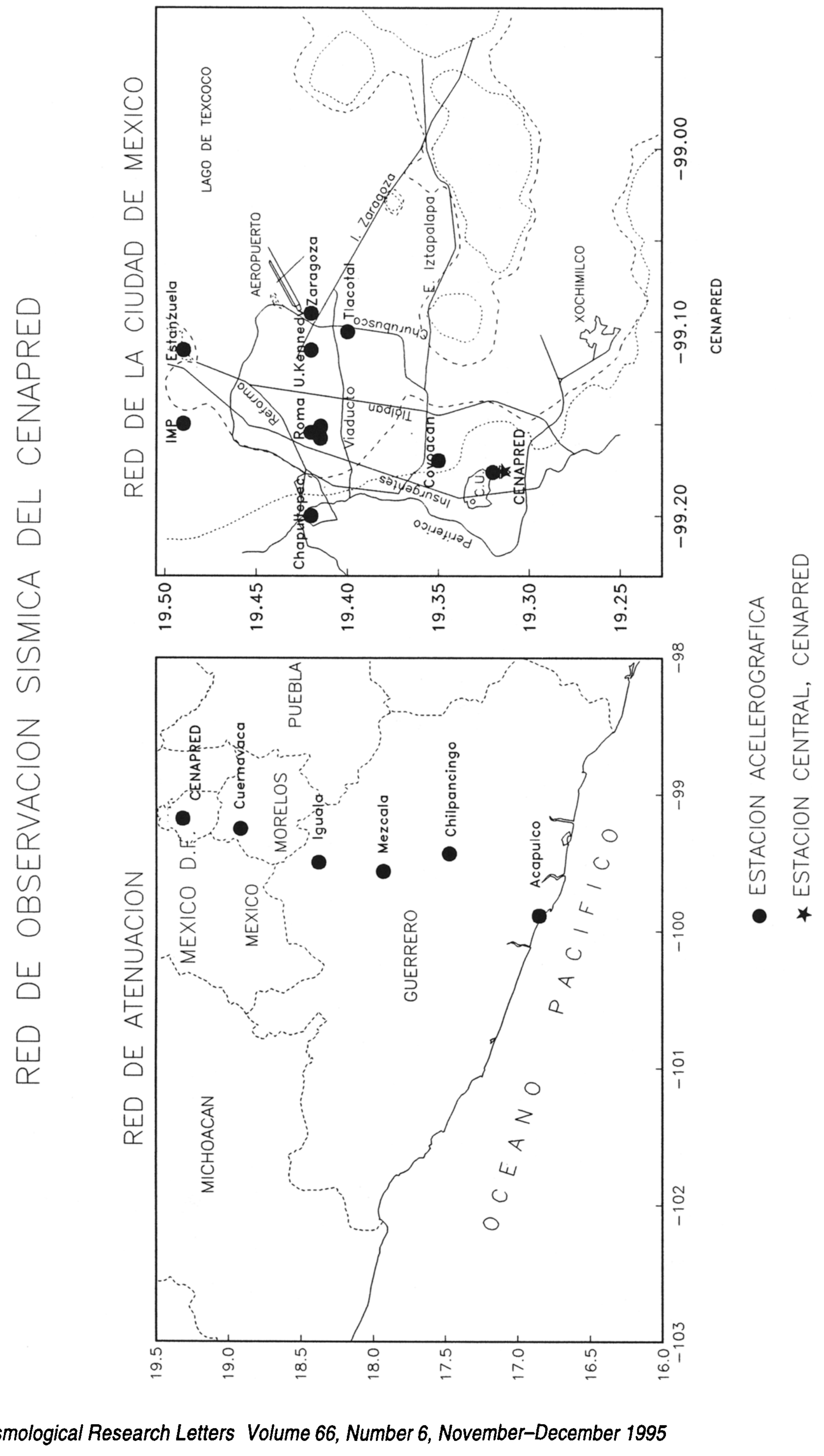
▲ **Figure 9** Accelerograms recorded by the station at Pinotepa Nacional.

Table 4 lists a representative sample of data that had been collected and cataloged within the first week after the earthquake. This represents only a small fraction of the total amount of data that will eventually be gathered from an estimated 300 to 400 stations. Considering the number of stations, coupled with the difficulty and expense of field work, it will probably take the rest of the year to visit all of the stations and to compile a complete picture of the strong motion data. Consequently, the data discussed here was selected to represent some of the more important records obtained from a cross section of the research groups. We also recognize that it would be preferable to prepare combined maps showing stations from the different networks all together, but this again is left for a later compilation.

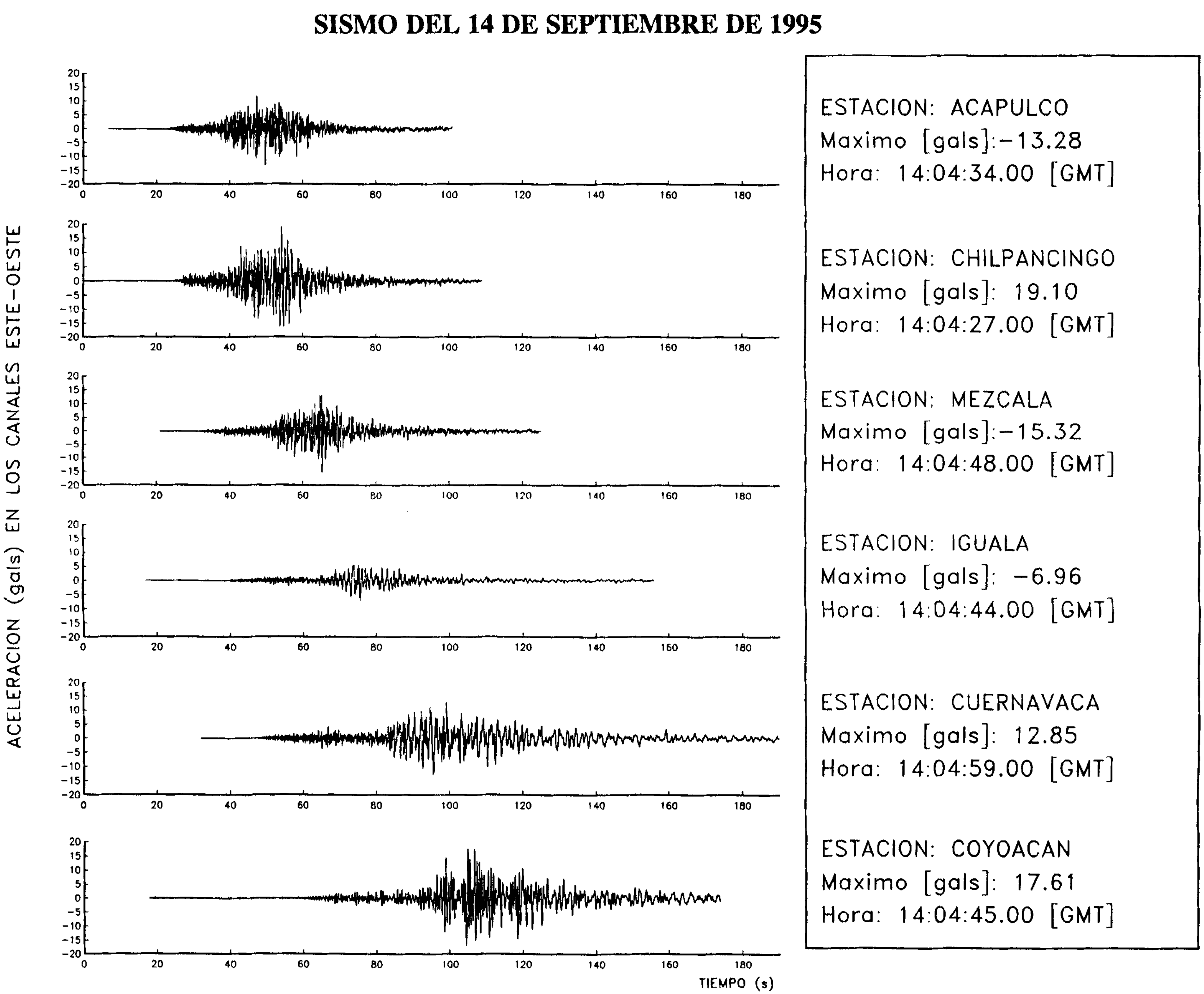
Guerrero Accelerograph Network

We begin with the Guerrero accelerograph network, since it has stations closest to this epicenter. The network has been described by Anderson *et al.* (1994), and in more detail by Anderson and Quaas (1994). Past data from this network is cataloged in a series of reports (GAA-1 to GAA-17), available from either J. Anderson or R. Quaas. Figure 7 shows the distribution of stations in the Guerrero network. Stations from which accelerograms had been recovered by September 17 are shown with solid symbols. Open circles with dots inside had not been checked but are close enough that they might have triggered.

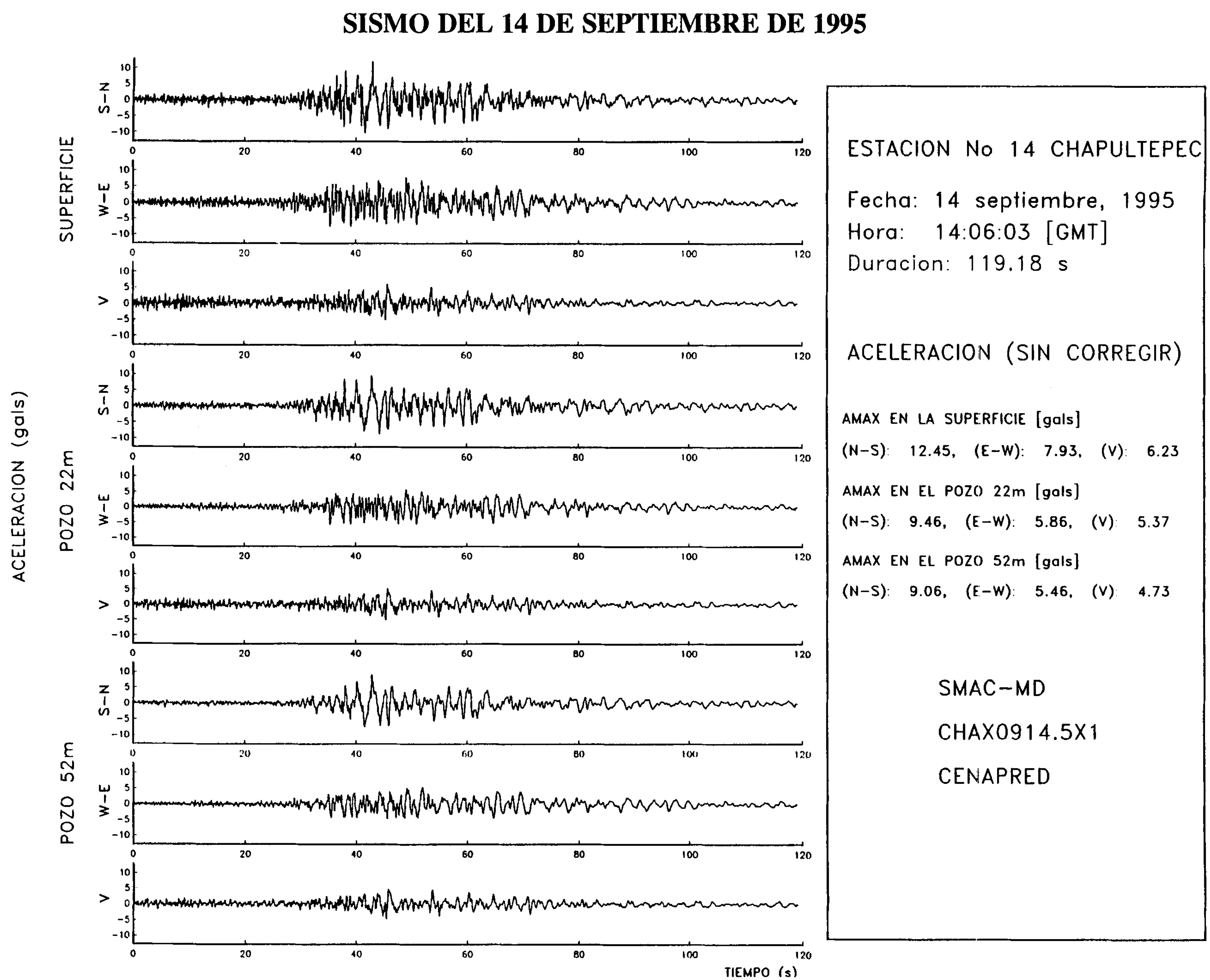
The accelerations at Copala are illustrated in Figure 8. This station, 22 km from the UNAM epicenter, has peak



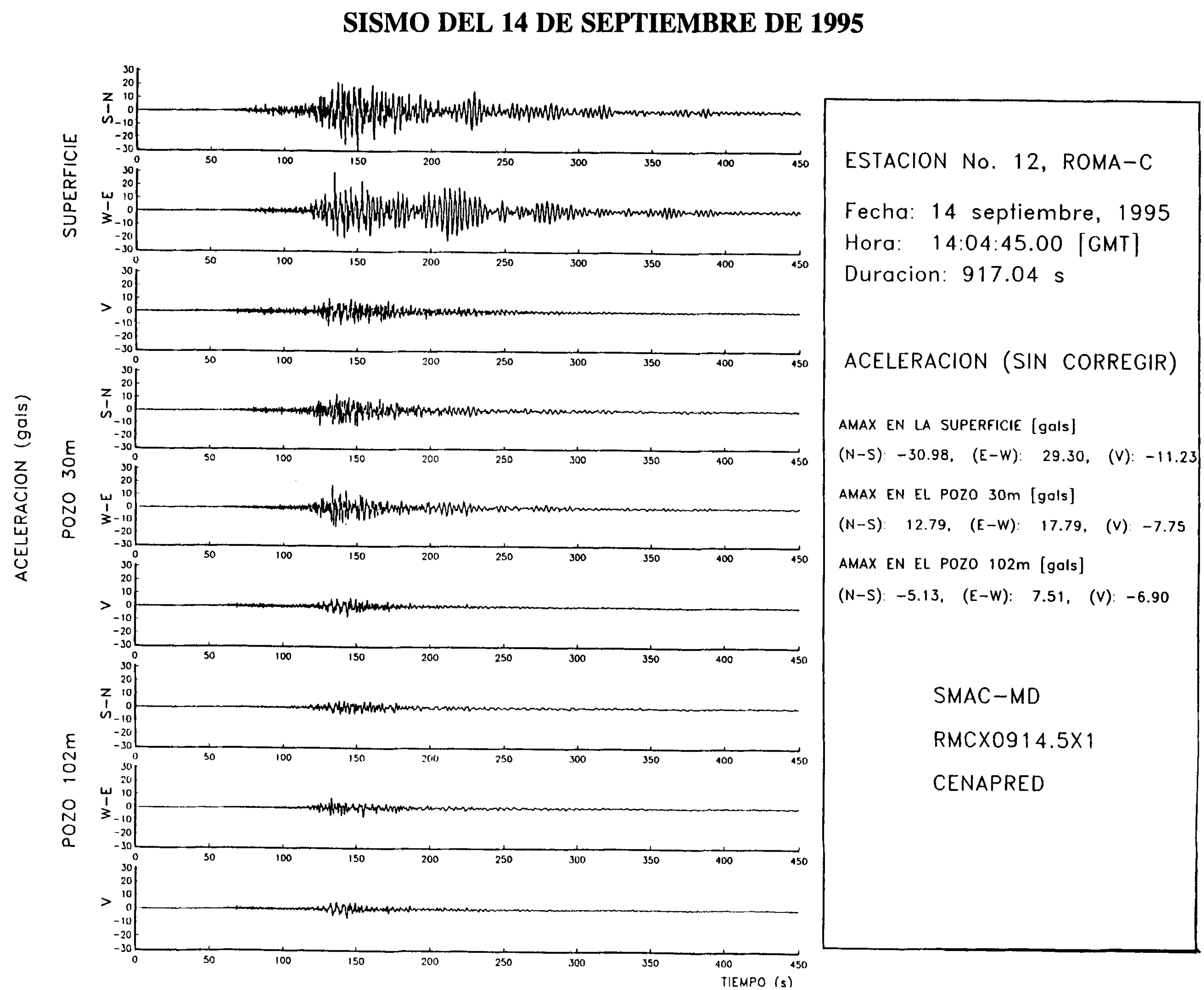
▲ **Figure 10** CENAPRED station locations (from Guevara *et al.*, 1995).



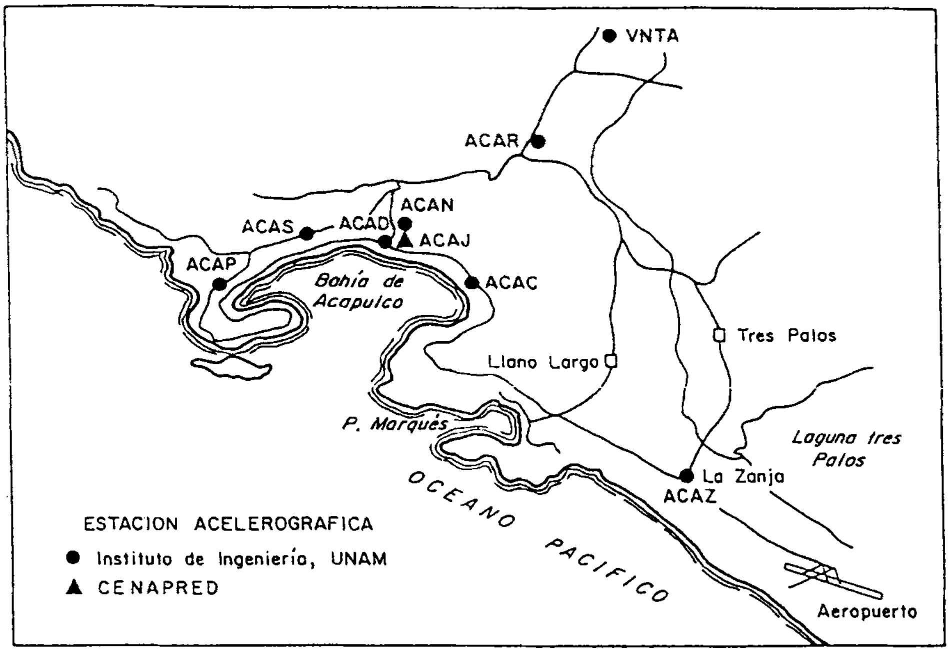
▲ **Figure 11** Accelerograms recorded on the CENAPRED attenuation array between Acapulco and Mexico City (data described in Gonzalez *et al.*, 1995).



▲ **Figure 12** Downhole profile of accelerograms from the CENAPRED station at Chapultepec (from Gonzalez *et al.*, 1995).



▲ **Figure 13** Downhole profile of accelerograms from the CENAPRED station at Roma-C (from Gonzalez *et al.*, 1995).



▲ **Figure 14** Map of accelerograph stations in Acapulco and vicinity (from Quaas *et al.*, 1993).

values of about 77 cm/sec^2. The duration of the strongest shaking at this station, as at the other stations in the cluster near Acapulco (Acapulco, Pozuelos, El Ocotillo, El Ocotito) is about 20 seconds. Since all of these stations are in a narrow range of azimuths from the source, it is expected that all of these stations should have about the same duration. The motions at Tonalapa and Teacalco have somewhat longer durations, as expected because of the larger distance.

Broadband Stations from the Instituto de Geofisica

The Instituto de Geofisica is in the process of installing a network of about 25 broadband, high-dynamic-range stations throughout Mexico. These stations have both high gain velocity recorders and lower gain accelerometers. Twelve of these are operating in the field, and at least eight recorded the Copala earthquake. The nearest of these, at Pinotepa Nacional (Figure 1), is only slightly farther from the rupture zone than the GAA station at Copala. The accelerograms from Pinotepa Nacional are illustrated in Figure 9. Although the duration is shorter than at Copala, indicating strong directivity towards this station and away from Copala, the peak accelerations are still under 100 cm/sec^2 on all components.

Centro Nacional de Prevencion de Desastres Network

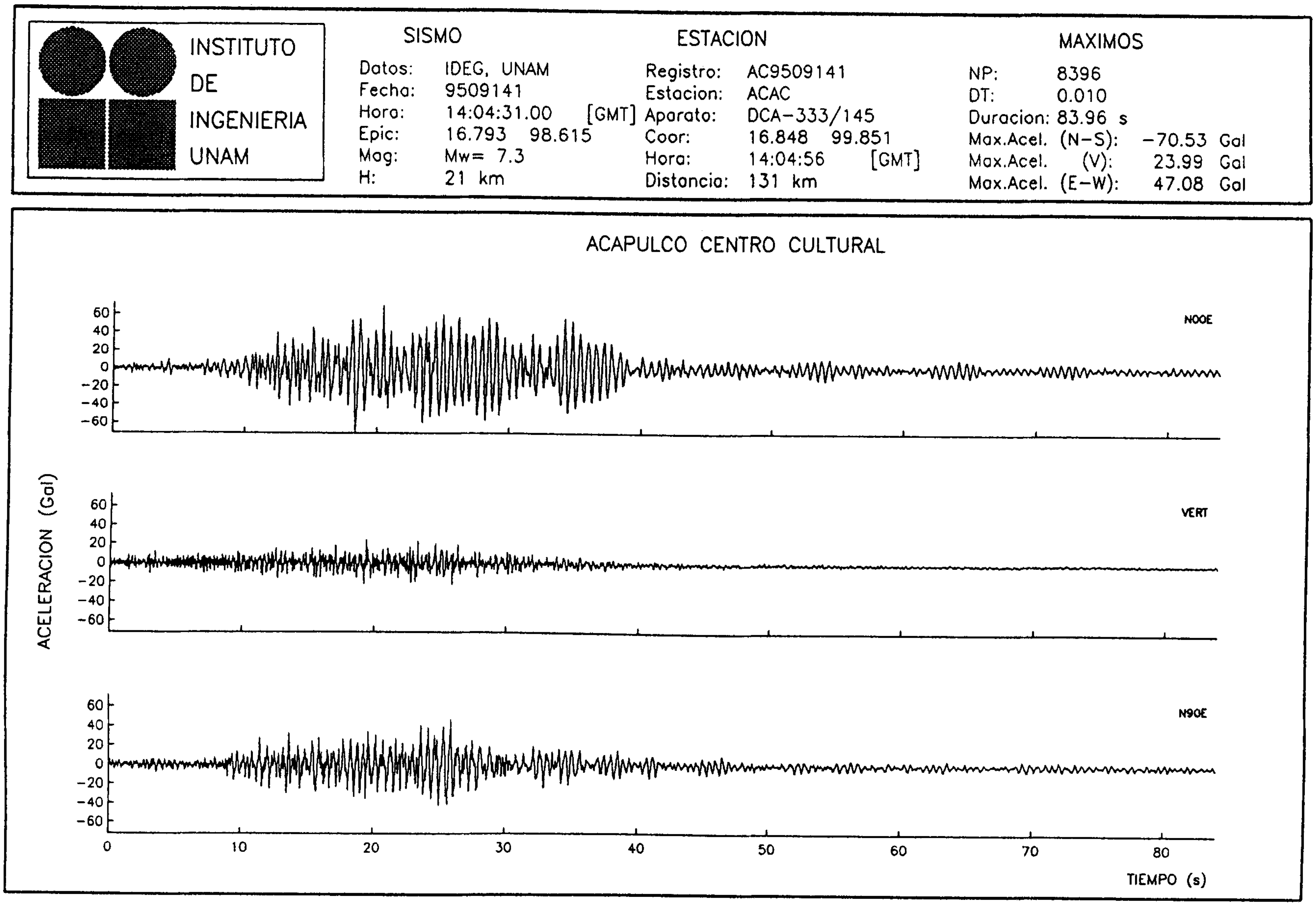
Data from this network of stations are described by Guevara *et al.* (1995) and Gonzalez *et al.* (1995). Figure 10 shows locations of two components of the CENAPRED network. All of the stations in this array are sited on rock and are listed in Table 4. All of the stations use 16 bit A/D converters, have 30 seconds of pre-event memory, and are synchronized to UTC by GPS receivers. Stations in Mexico City are triggered remotely, based on a telemetry signal received from a seismic station located in Iguala, half way from Mexico to Acapulco. Consequently they are all able to recover complete accelerations including the P-wave.

Figure 11 shows the east-west component of accelerograms from the attenuation array, arranged in actual time. The amplitudes are smallest at Iguala, then increase again at Cuernavaca, and at Coyoacan, in the Mexico City basin. This is consistent with prior results. Ordaz and Singh (1992) have noted from previous earthquakes that motions on rock at Cuernevaca and Mexico City tend to be inexplicably large. Singh *et al.* (1995) tested some additional sites near the Valley of Mexico, but so far every station that has been examined shows amplifications over a broad band of frequencies.

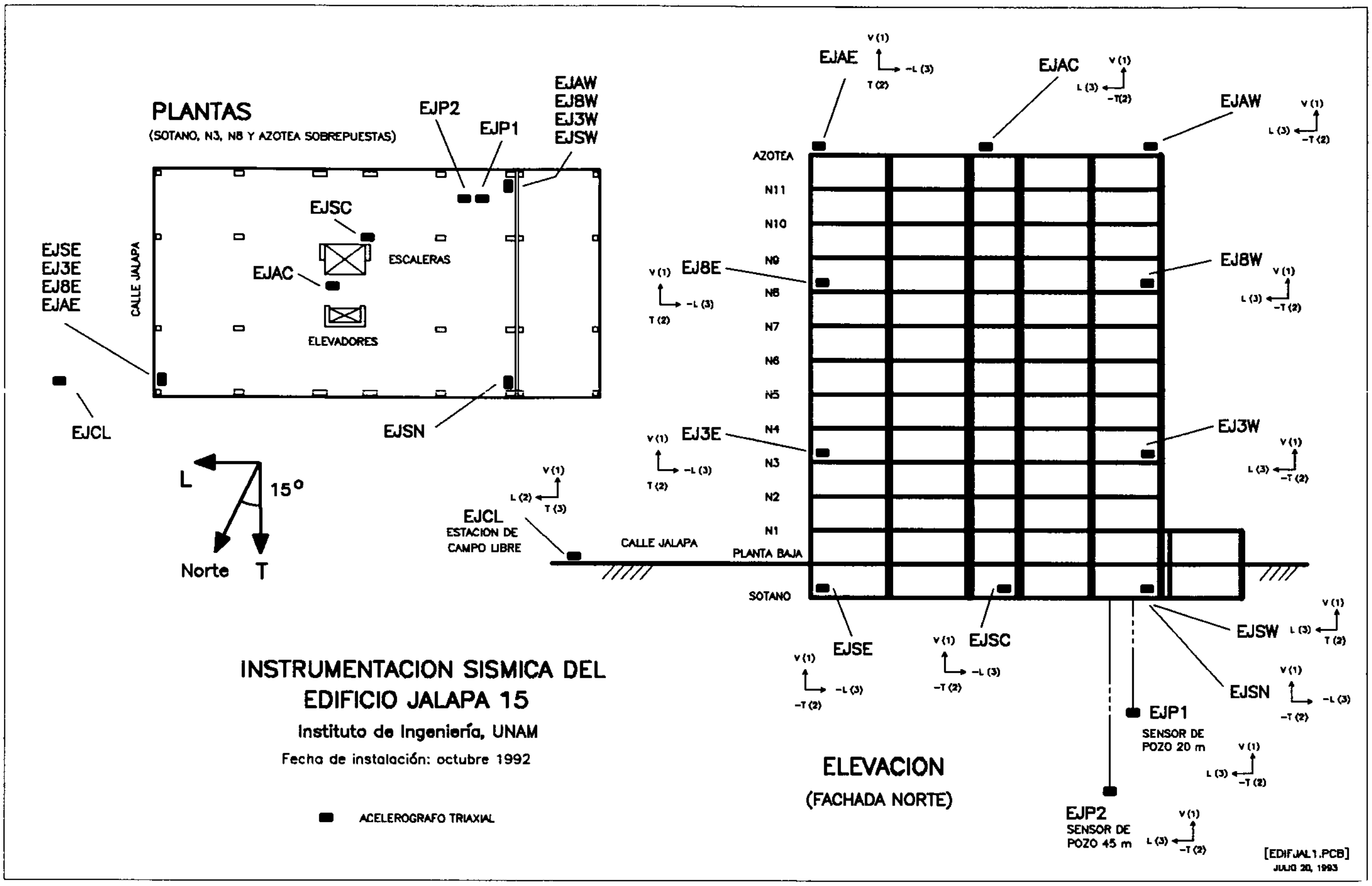
One feature of the CENAPRED network is that in Mexico City, most of its stations include a vertical array of sensors. Here we show in Figure 12 the seismograms from the station at Chapultepec, in the hill zone, and in Figure 13 the seismograms from Roma, in the lake bed. Chapultepec shows relatively little amplification, but Roma-C shows a factor of 4 to 6 amplification in the upper 100 m. Singh discussed the possibility that the long duration is due to extreme amplification of weak input signals. Figure 13 shows that the amplification in different parts of the record is variable. An evaluation of the frequency content through time, though, may confirm Singh's hypothesis.

Instituto de Ingenieria Networks

Some of the preliminary data recovered by the Instituto de Ingenieria are described in reports by Almora *et al.* (1995), Alcantara *et al.* (1995), and Quaas *et al.* (1995). The station distribution is described in Quaas *et al.* (1993). Figure 14 shows the station distribution in Acapulco. Figure 11 already



▲ **Figure 15** Accelerations recorded by the Instituto de Ingenieria station at Acapulco Centro Cultural (from Almora *et al.*, 1995).



▲ **Figure 16a** Drawing of the Jalapa building, showing locations of instruments operated there by the Instituto de Ingenieria (from Quaas *et al.*, 1995b).

shows an example of ground motions on rock in Acapulco. Figure 15 shows the ground motions at the station Acapulco Centro Cultural. This station shows a strong amplification and ringing, together with an increased duration. While it is perhaps less severe than the site effects in Mexico City, this record and others from within Acapulco demonstrate that there are significant site effects in that major city.

The Instituto de Ingenieria also maintains arrays that instrument several major buildings in Mexico City. An example of the response of a 12 story high building during the Copala earthquake (Quaas *et al.*, 1995b), instrumented with 14 accelerographs (Quaas and Almora, 1992), is shown in Figure 16a, b. The set of records correspond to a vertical line of instruments located on the southwest corner of the structure.

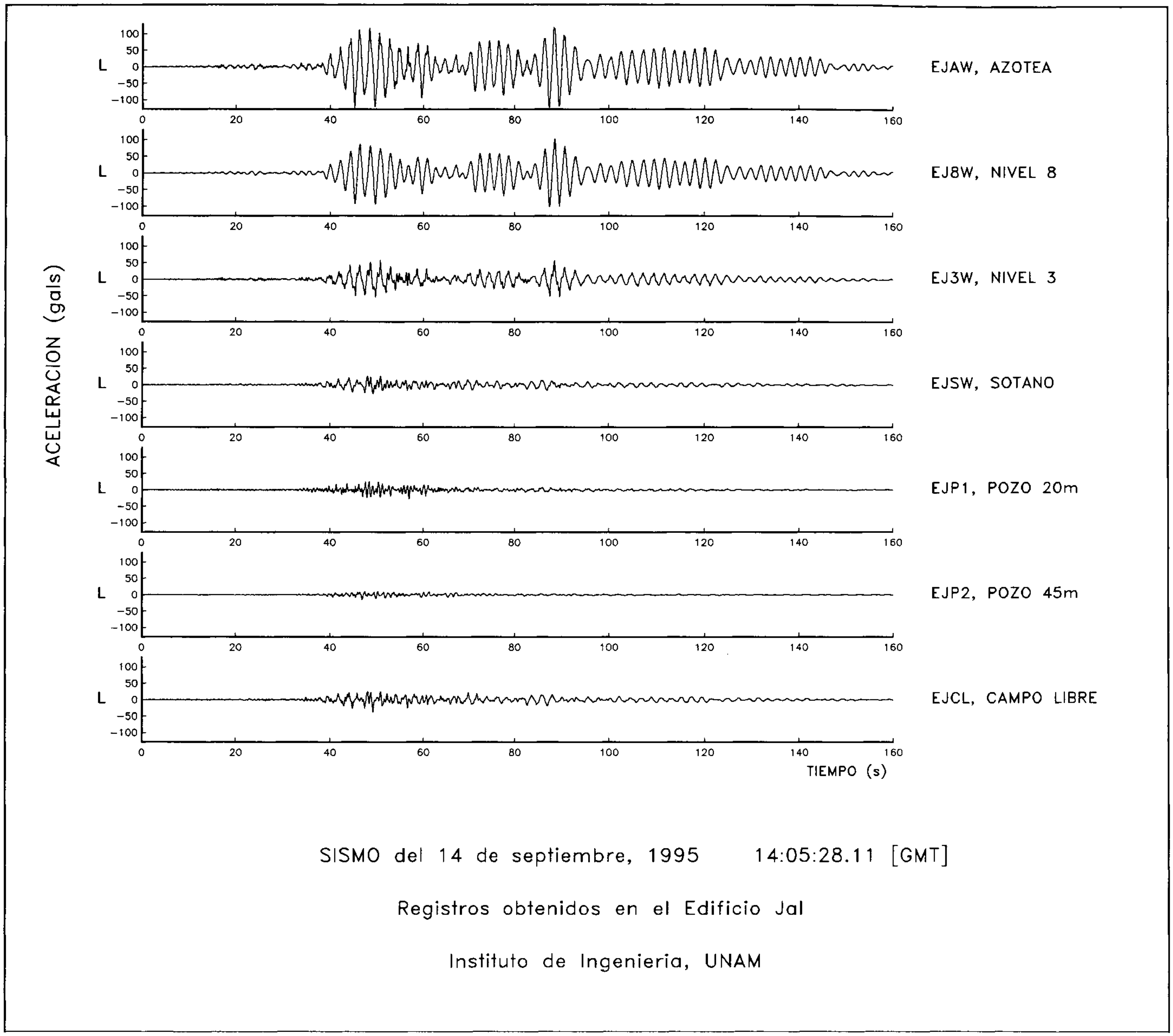
Fundacion Javier Barros Sierra Network in Mexico City

The Fundacion Javier Barros Sierra operates 86 stations in Mexico City. Preliminary data are illustrated by reports by Centro de Instrumentacion y Registro Sismico, A.C. (1995a,b). The stations are distributed widely throughout Mexico City, as seen in Figure 17.[10] With these data, it will be possible to study ground motions in Mexico City using array processing techniques. Seismograms are not shown here, as Figures 12 and 13 are considered representative of the quality and character of the data in Mexico City.

Comision Federal de Electricidad Network

The Comision Federal de Electricidad (CFE) operates 67 accelerograph stations at its most important hydroelectric power facilities. The only one that recorded the Copala earthquake was the network of stations at the El Caracol dam, about 145 km from the epicenter (Javier and Andrade, 1995). The next nearest stations are at the dams at La Villita and Infiernillo, near the western limit of the Guerrero network (Figure 4).

The El Caracol dam is an earth-filled dam, 126 meters high and 350 meters across. Figure 18 shows a map view of the geometry of the Balsas River and the El Caracol dam, and a cross-sectional view of the dam. The generators are installed underground on the right margin. On the dam CFE has installed six digital accelerographs, as shown on Figure 18. Accelerograms from the transverse component of motion are shown in Figure 19. Stations on firm rock recorded about 10 to 15 cm/sec^2 peak acceleration. The maximum acceleration at the crest, 44.5 cm/sec^2, is about four times that



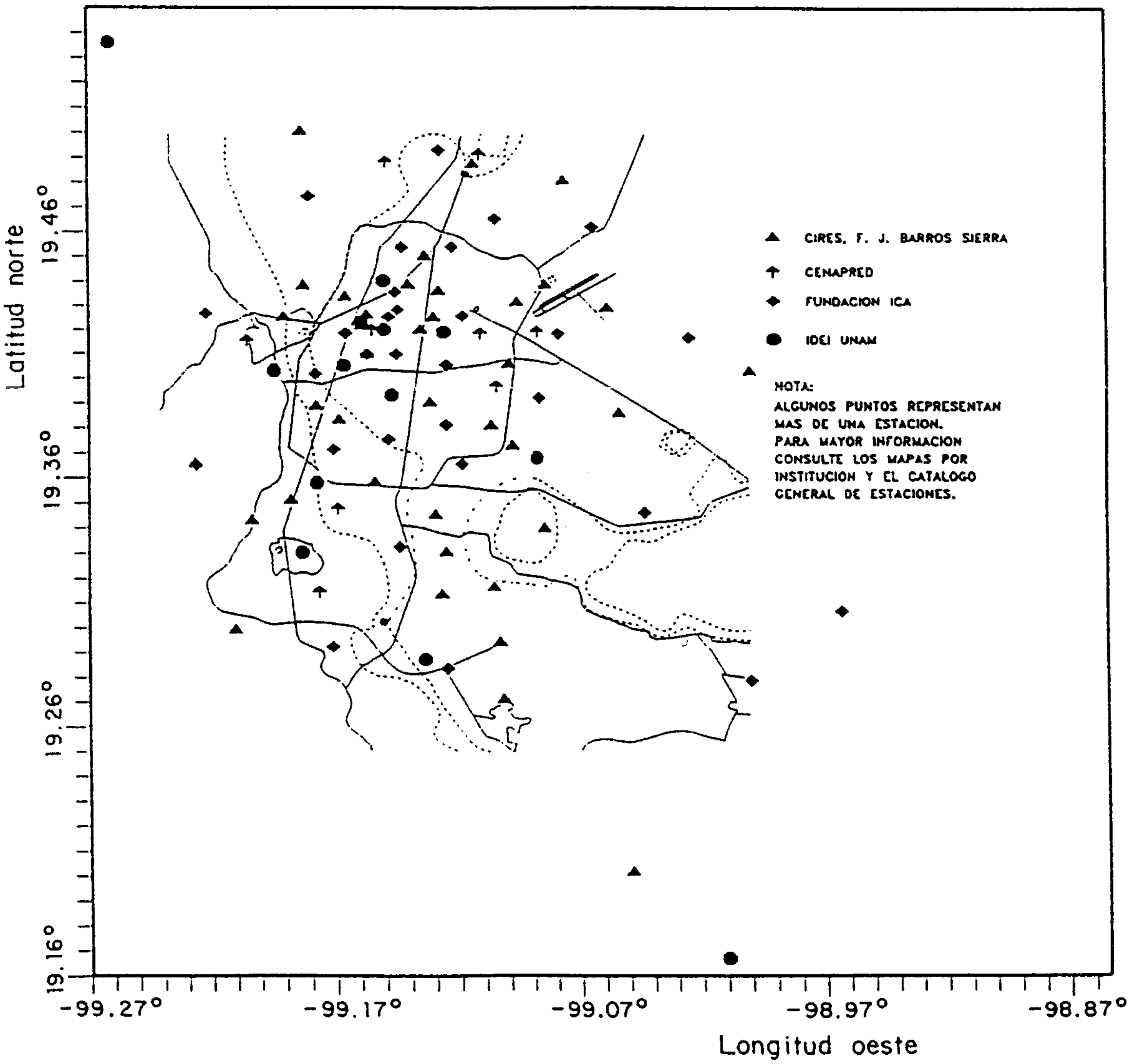
▲ **Figure 16b** Selection of accelerations recorded by the Instituto de Ingenieria in the Jalapa building (data described in Quaas *et al.*, 1995b).

obtained on the margins of the dam or in the substation on firm rock, illustrating structural amplification. The levels of acceleration at all locations were small and did not produce damage to any of the structures.

PRELIMINARY INTERPRETATIONS OF STRONG MOTIONS

To place data from the various networks into perspective, we begin by showing a plot of peak acceleration, as a function of distance, in Figure 20. The values are compared with the regression of Anderson and Lei (1994). Anderson and Lei (1994) used only data from the Guerrero network to develop a non-parametric attenuation relationship. In their model, accelerations are determined at points on a grid of magnitude and distance. Accelerations at other values are obtained using the interpolation function described in their paper. There is no assumption about shape of the regression, but there is a moderate smoothness constraint.

Most of the peak accelerations in Figure 20 from Guerrero network stations are lower than expected, based on the nonparametric regression of Anderson and Lei (1994). The cluster of points beyond 300 km represents the wide variety of site conditions in the Mexico City area. The open circles at shorter distances are generally from the attenuation array of CENAPRED (Guevara *et al.*, 1995; Gonzalez *et al.*,

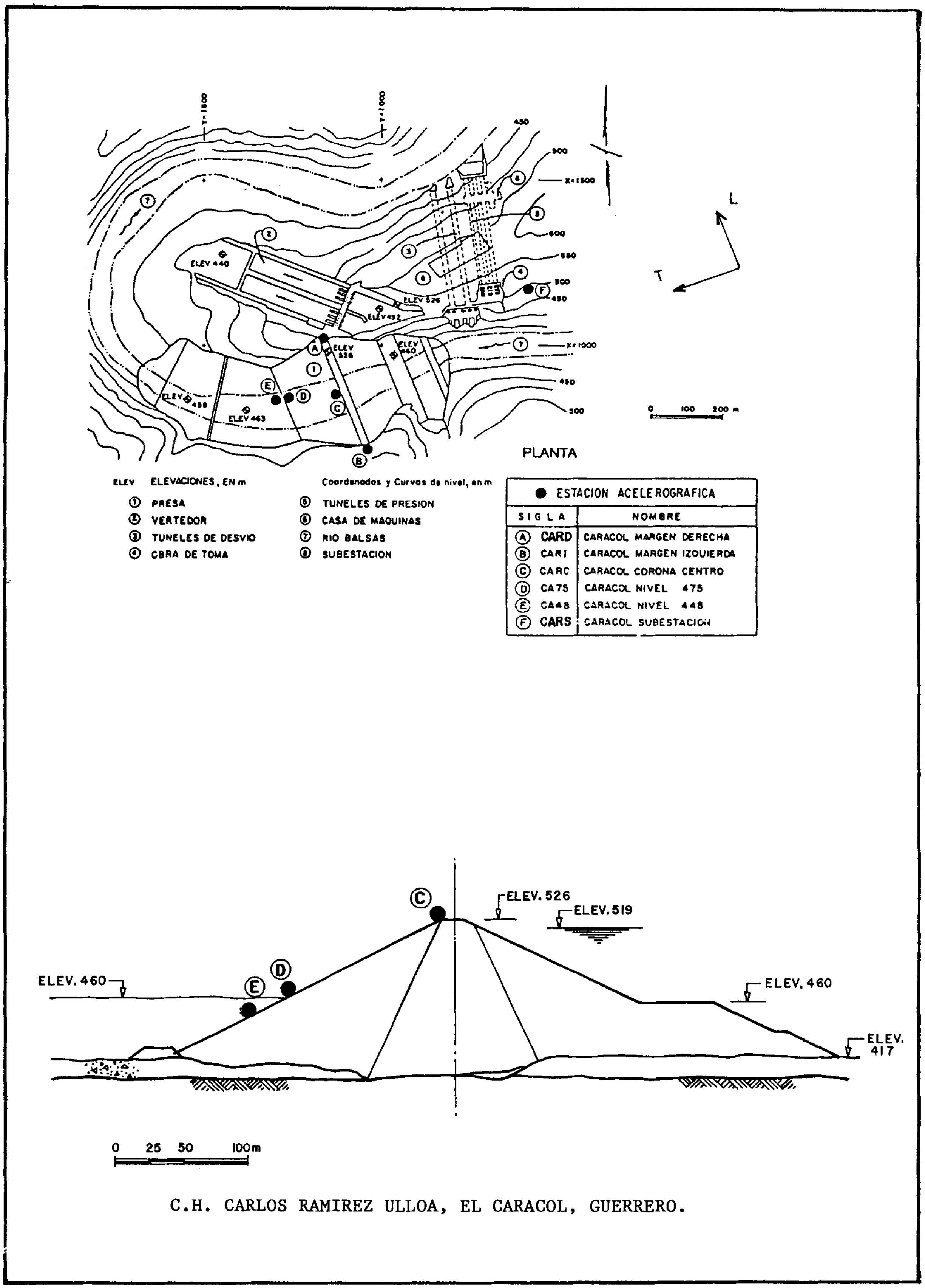


▲ **Figure 17** Map of accelerograph stations in the Valley of Mexico (from Quaas *et al.*, 1993).

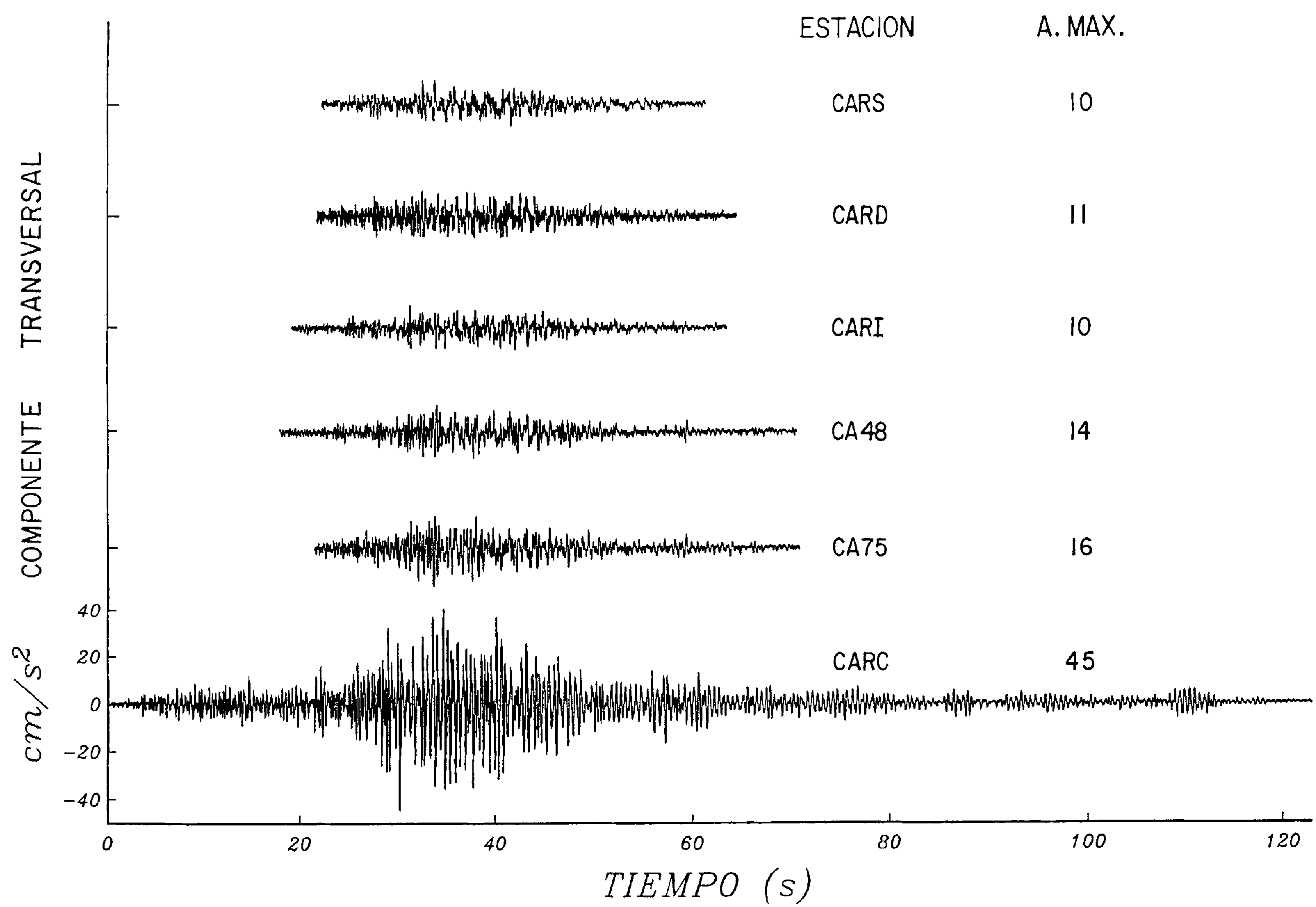
1995; Almora *et al.*, 1995), which is sited on rock. The low peak accelerations at the station at Copala, about 0.07 g, are a surprise. In 1985, at an equivalent distance to the hypocenter of the Michoacan earthquake ($M_S = 8.1$), peak accelerations were about 0.15 g (Anderson *et al.*, 1986). In the earthquake near San Marcos, in 1989, the network recorded about 0.17 g at San Marcos and 0.35 g at Cerro de Piedra (Anderson *et al.*, 1989). Unfortunately we lack records from both of these stations for this event.[11]

After some effort, we found that it was not possible to obtain an integral of the Copala record that had a reasonable appearance without allowing for a static offset to occur. Allowing for a static offset, Figures 21 and 22 show our preliminary estimates for the velocity and displacement at Copala. Figure 21 shows that the peak velocities at Copala are comparable to those obtained in the 1989 earthquake. Initial attempts to define the acceleration baseline compensated for the static offset in Figure 22 by introducing a large acausal displacement before the S-wave. The integration shown here has about 12 cm of displacement to both the south and west. Thus, this preliminary interpretation suggests a total horizontal offset of about 17 cm. The direction, at least, is consistent with the focal mechanism. The vertical offset of about 2 cm is also consistent with the focal mechanism, but the amplitude is not significantly different from zero. The rise time of the offset, about 10 seconds, is similar to the rise time of the Michoacan earthquake (Anderson *et al.*, 1986) and would be consistent with this earthquake breaking one asperity, where the Michoacan event broke two or more.

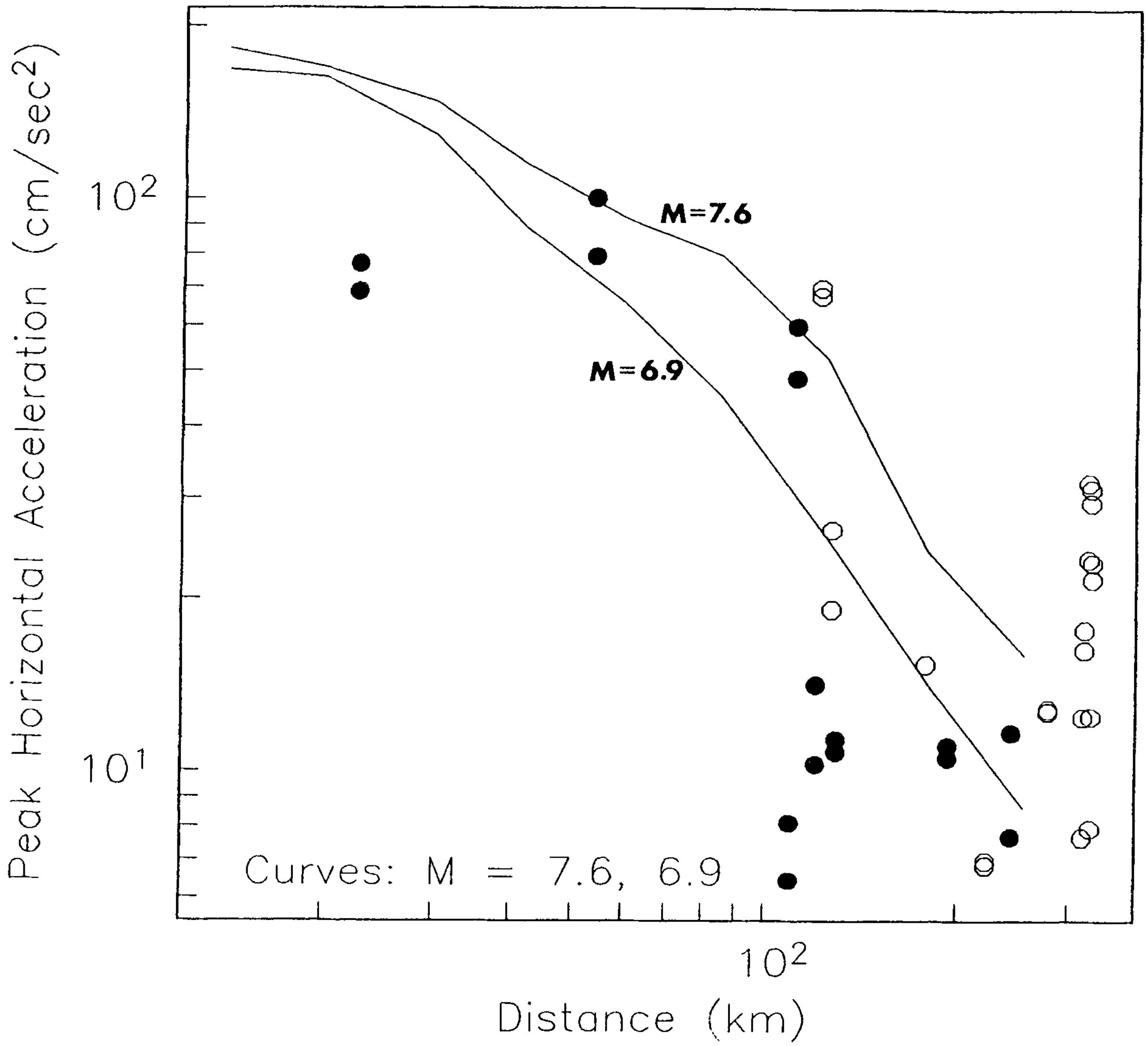
The plausibility of these static offsets is tested in Figure 23. This shows synthetic displacement for a geometry that could be a rough approximation of the actual fault geometry. Although no attempt has been made to fit the synthetics to



▲ **Figure 18** Map showing locations of accelerographs in the vicinity of the El Caracol dam (modified from Quaas *et al.*, 1993).



▲ **Figure 19** Transverse component of accelerations from stations in the vicinity of the El Caracol dam.

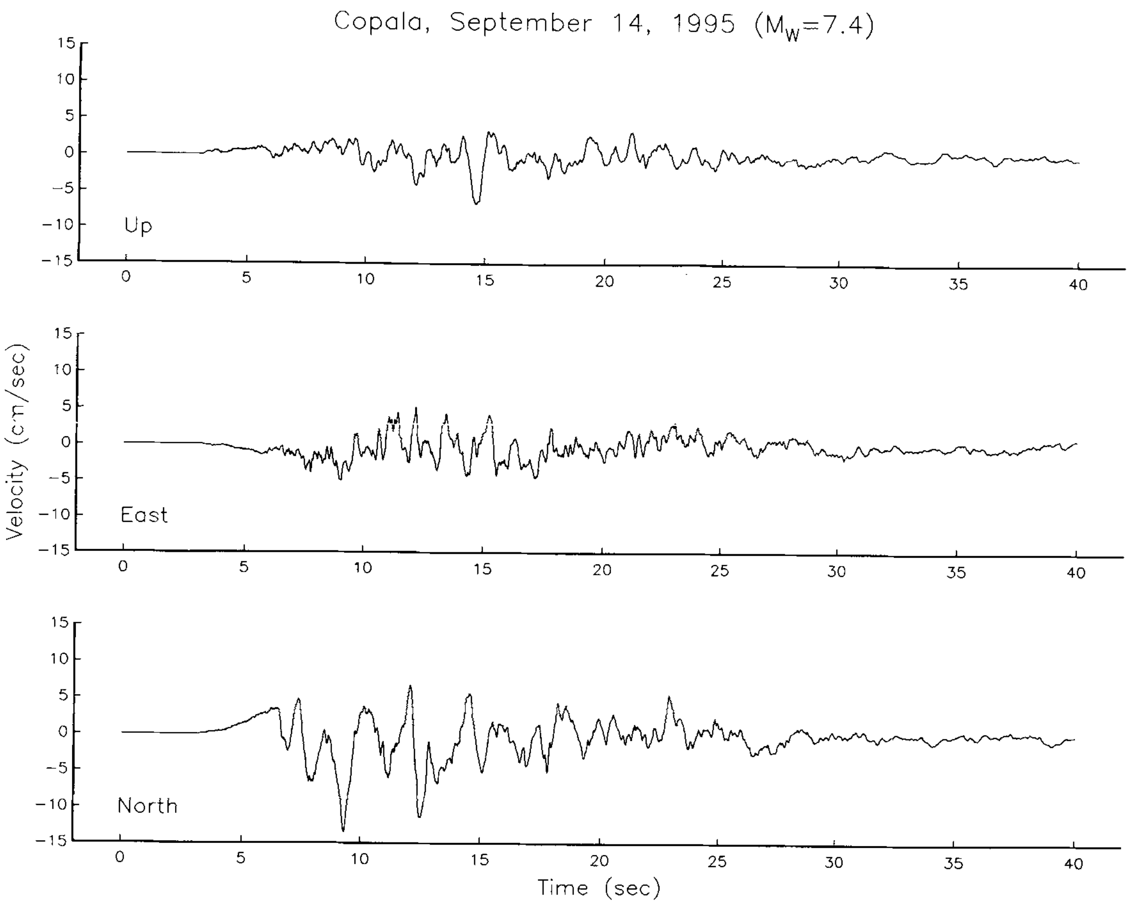


▲ **Figure 20** Peak acceleration as a function of distance from the epicenter (from Anderson *et al.*, 1995).

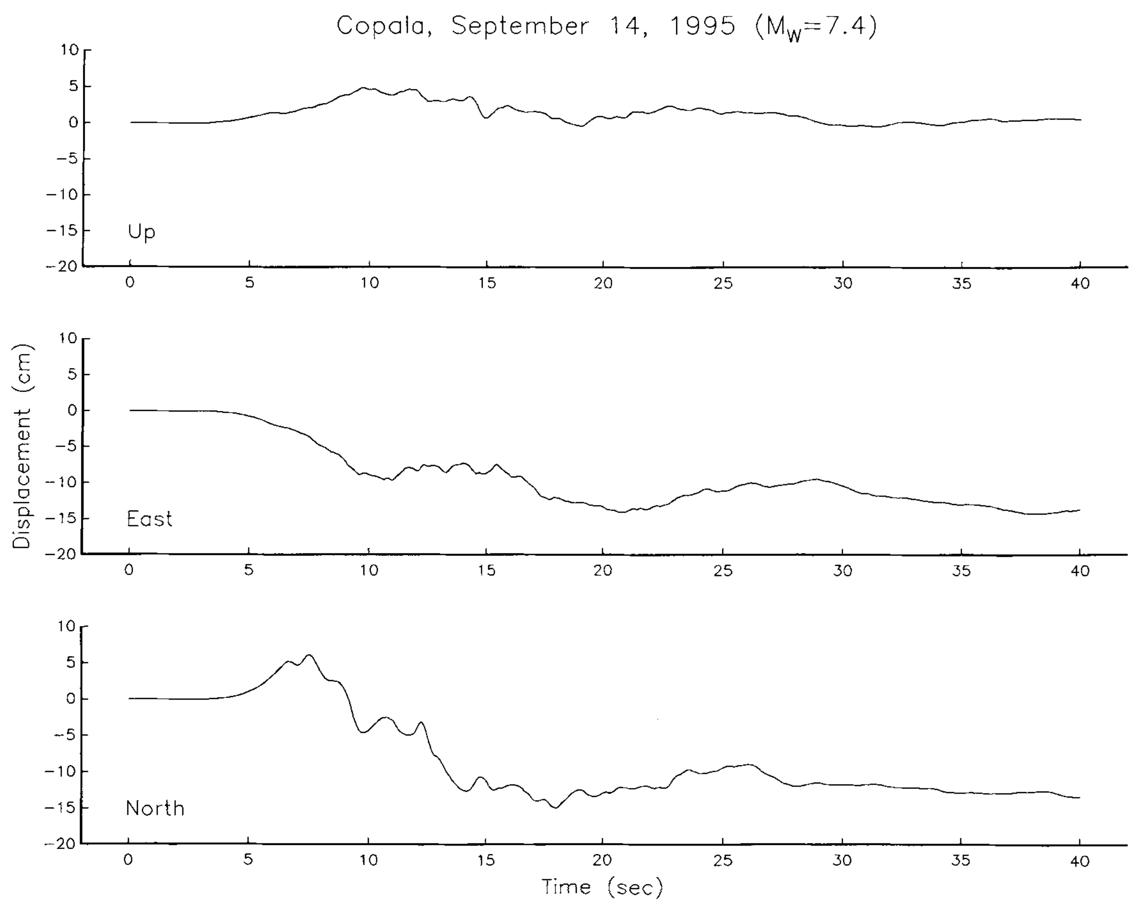
the actual displacements, on this plausibility test the static displacements in the north and east components are within a factor of two of those shown in Figure 22. Also, the initial character of the synthetics is consistent with the observations. The vertical components start with similar slopes, but the integrated accelerogram in Figure 22 has an insignificant static offset compared to this synthetic. Still, these synthetics demonstrate that some static offset at Copala is likely to have occurred, and that it would have had a direction and amplitude on the same order as the values derived in Figure 22.

The net duration of the strong shaking at Copala is about 20 seconds (e.g., Figures 8 and 21). This is a little longer than, but consistent with, prior observations of earthquakes of about this size in Guerrero (Anderson and Chen, 1995). The strongest motions are immediately after the arrival of the S wave. This suggests that the rupture propagated away from the Copala station, or towards the southeast. This would predict a short duration at Pinotepa Nacional, and indeed that is what is seen. The strong phase of motion there is only about 5 seconds long (Figure 9). Directivity of this type thus seems consistent with the teleseismic duration of about 12 seconds (Figure 24). A previous M = 7.5 aftershock in 1985 ruptured towards several of the Guerrero network stations and had a duration at those stations of about 10 seconds.

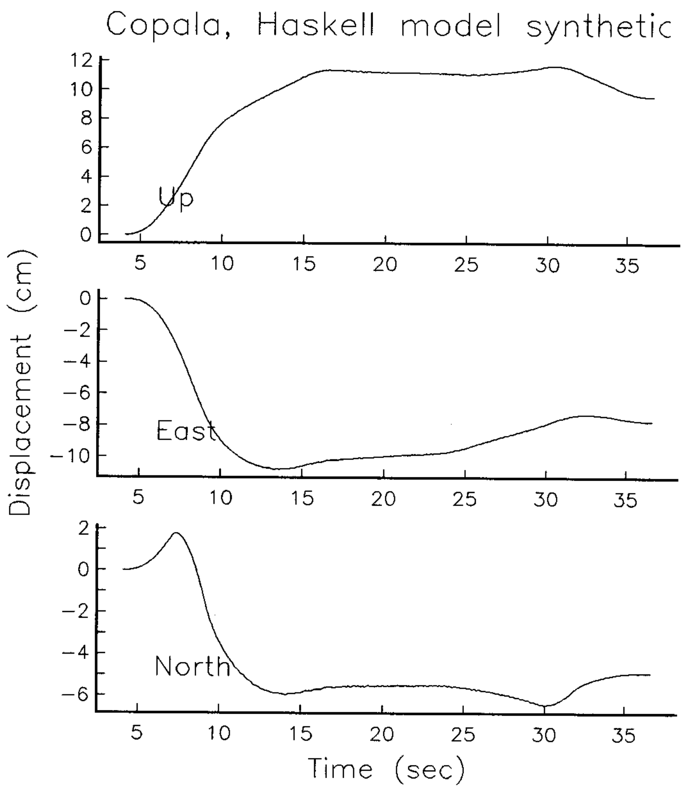
Fourier and response spectra at Copala are more or less consistent with past events. The record from Copala (Figure 25) peaks at about 0.7 Hz. For comparison, the spectrum from Las Vigas (Figure 26) peaks at about 7 Hz. The could be the result of differences in site response (see, for example, Humphrey and Anderson, 1992). It illustrates how a large earthquake with a very broad band acceleration signal can have substantially different spectral peaks depending on the site effect, and the difficulty of associating a predominant frequency with the magnitude of an earthquake.



▲ **Figure 21** Velocity derived from accelerograms recorded at Copala (from Anderson *et al.*, 1995).



▲ **Figure 22** Displacement derived from accelerograms recorded at Copala (from Anderson *et al.*, 1995).



▲ **Figure 23** Synthetic displacement from a Haskell dislocation model in an infinite medium. The geometry is chosen to approximate the northern half of the aftershock zone in Figure 4. The fault has a length along strike (109°) of 40 km, a width down dip (dip is 11°) of 45 km, with the southwest corner at the epicenter in Figure 1, at a depth of 20 km. The calculations use a rupture velocity of 3.0 km/sec, a rise time of 2.0 seconds, and a static offset of 300 cm.

CONCLUSIONS

Although there is still a large amount of strong motion data to be recovered from the various networks for this earthquake and its aftershocks, it is clear that the Copala earthquake is quite well documented. Data from the epicentral region will allow inversions for the source characteristics of the event. Data from Acapulco and Mexico City will be valuable for studies of site response.

In all of this, the various groups of data gatherers are setting high standards of cooperation. There is extensive, spontaneous sharing of data. On September 22, an ad-hoc seminar was organized to allow all of the groups to show some preliminary results. The quick distribution of data reports, following after the tradition established in 1985, continues.

NOTES

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4. Centro de Instrumentacion y Registro Sismico, A.C., Anaxagoras 814, Col. Narvarte, Benito Juarez, 03020 Mexico, D. F., Mexico. (525) 687-45-42; maranda@servidor.unam.mx; ajimenez@servidor.unam.mx
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7. Centro Nacional de Prevencion de Desastres, Av. Delfin Madrigal No 665, Pedregal de Sto. Domingo, Coyoacan 04360, Mexico, D.F.
8. Comision Federal de Electricidad, Gerencia de Ingenieria Experimental y Control, Augusta Rodin No. 265, Col. Nachebuena C. P. 03720, Mexico, D. F., Mexico.
9. Both of these reports are available from: Sociedad Mexicana de Ingenieria Sismica, AC, Camino a Santa Teresa 187, Villa Olimpica Miguel Hidalgo, 14020, Mexico, D.F. Mexico. Tel/fax: (52-5) 606-2323 ext. 49. The catalog of stations costs $18 U.S., and the data base of accelerograms costs $25 U. S., plus shipping.
10. Fundacion Javier Barros Sierra has assumed responsibility for stations associated with Fundacion ICA on this figure.
11. San Marcos, Las Vigas, Las Mesas, and Ocotillo were recording with the new K2 instruments, temporarily installed. Unfortunately, we have learned that these instruments use substantially more power than the 12 bit units described in our reports on instrumentation (e.g. Anderson *et al.*, 1994a, b). The earthquake occurred early in the morning and after a spell of bad weather. The net effect was that the batteries had been drained at San Marcos, Las Vigas, and Las Mesas, and no records were obtained, although some of the aftershocks might be recorded.

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950914_MEXICO
 LOCATION       16.700  LAT.      -98.500  LONG.
 ORIGIN TIME=   14 HOUR  4 MIN 31.8 SEC GMT
 Focal mechanism (MTRF inversion):
      strike  dip   rake
     115.5   77.4   87.1
 Depth  23. km (the best depth)
 Number of stations: 16
 The Maximum moment rate (10**20 Nm/s) =   0.128588
 One "space" represents    1.00000 sec
 Moment of the main pulse:  1.11  (10**20 Nm) at 15. sec

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0        10sec


 Numerical values of source time function
 Sampling dt:  1.0sec
 X10**18 Nm/sec
  0.00   3.73   6.79   9.81  11.53  12.75  12.86  12.57  11.78  10.16
  8.13   5.52   3.52   1.47   0.59   0.05
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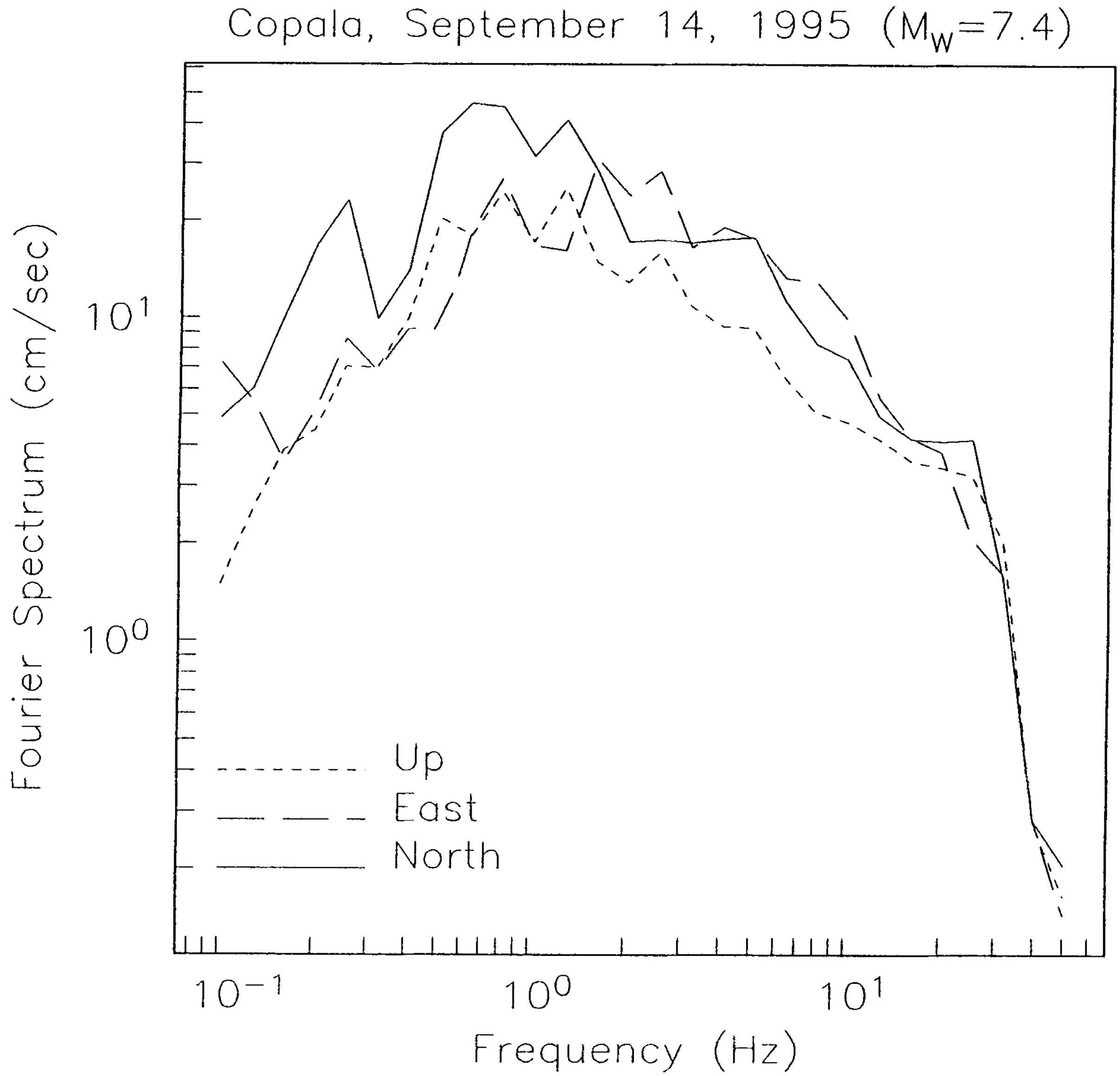
▲ **Figure 24** Source time function of the Copala earthquake (distributed over the internet by J. Johnson, Y. Tanioka and L. Ruff on Sept 15, 1995). Note that they derived this time function assuming that the fault plane is the conjugate plane to the one we prefer.



▲ **Figure 25** Fourier amplitude spectra of the entire accelerograms from the station at Copala (from Anderson *et al.*, 1995).

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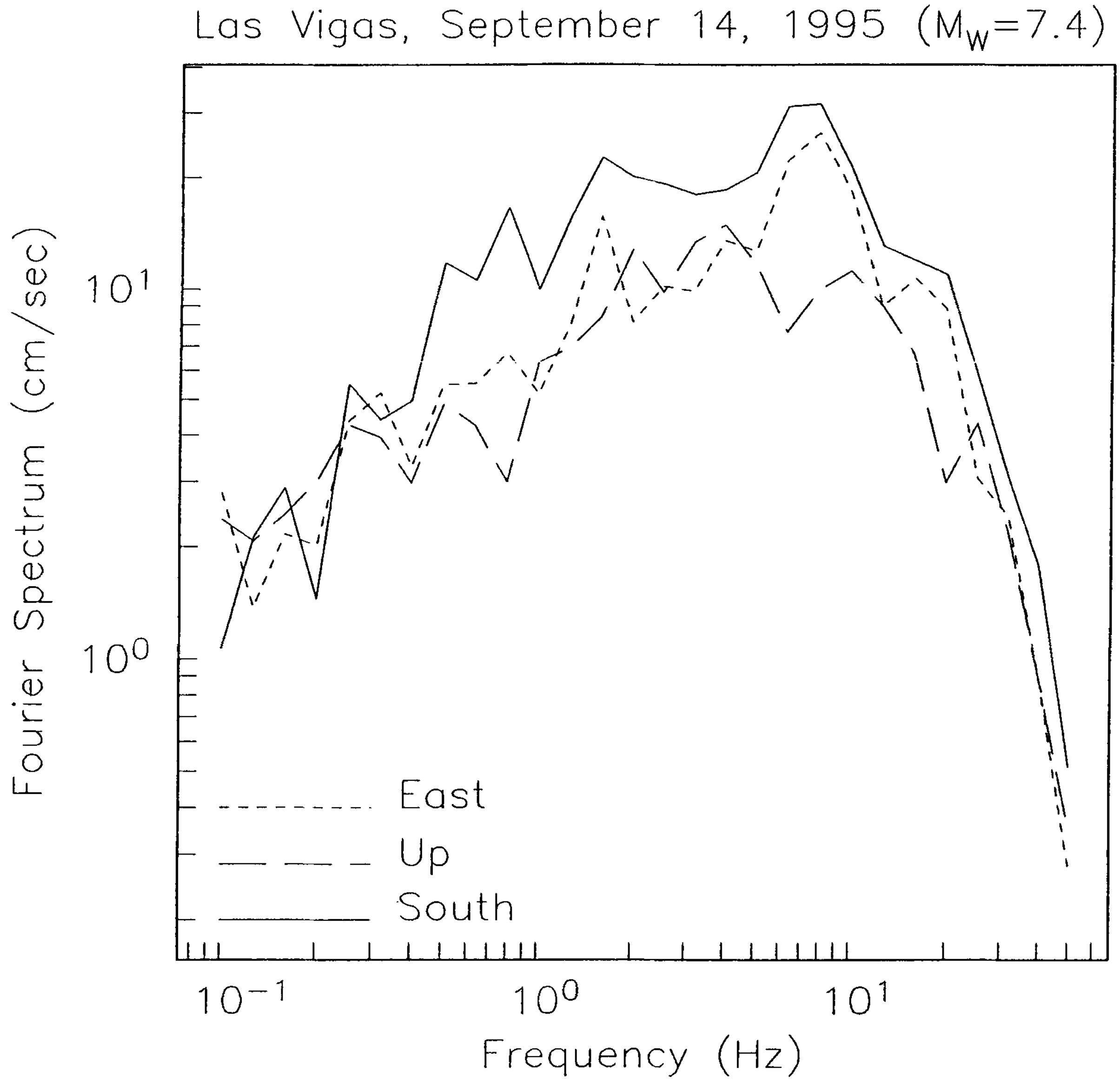

▲ **Figure 26** Fourier amplitude spectra of the entire accelerograms from the station at Las Vigas (from Anderson *et al.*, 1995).

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