LOCAL SITE RESPONSE IN SAN SALVADOR, EL SALVADOR: Comparison between the synthetics and the observed ground motion of the October 10, 1986 earthquake

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RESUMEN

El área de San Salvador está ubicada a lo largo del actual eje de la cadena volcánica centroamericana, que es producto de la subducción de la placa Cocos bajo la placa del Caribe con dirección noreste. Los terremotos destructivos ocurridos en El Salvador durante las últimas décadas han sido sismos someros y de tamaño moderado con epicentros ubicados en la cadena volcánica. El más reciente de éstos, el del 10 de octubre de 1986 (Ms = 5.4) ha causado un daño considerable a la ciudad de San Salvador con más de 1500 muertos y alrededor de 10000 lesionados. Las pérdidas materiales alcanzaron los 1.5 billones de dólares americanos. El presente estudio pretende demostrar los efectos de la geología en los movimientos fuertes y comparar los resultados de los registros sintéticos con los reales, para proveer una base a los esfuerzos que se están haciendo en preparar el nuevo código de diseño sísmico para El Salvador.

Los registros de movimiento fuerte del sismo del 10 de octubre de 1986 son usados para investigar la respuesta local del sitio en San Salvador. Los cocientes espectrales de las componentes horizontales de cuatro sitios sedimentarios con respecto a un sitio de referencia, indican amplificaciones máximas por un factor de 8 a 22. Las amplificaciones varían en diferentes sitios, dependiendo mayormente de las frecuencias. Generalmente existe una buena correlación entre el tipo de sedimento y las amplificaciones. Sin embargo, el espesor de los sedimentos no consolidados parece jugar un papel más crítico que el tipo de formación. Los registros sintéticos son generados, usando los programas de computadora SHAKE y AMPLE, y comparados con los reales obtenidos en la superficie para cada sitio, con el objetivo de evaluar su factibilidad. Nuestros resultados dan alguna evidencia de correlaciones positivas entre los dos set de datos. Sin embargo, los registros sintéticos fallan en estimar las amplificaciones dle sitio para frecuencias más bajas y las estimaciones en el rango de frecuencias de 1 a 5 Hz puede ser usado solamente como una aproximación muy gruesa. El uso de registros sintéticos en la estimación de la respuesta local del sitio, puede ser solamente aplicable cuando ellos son calibrados con datos reales. En otras palabras, las estimaciones de los sintéticos son grandemente dependientes del registro de movimiento introducido. Los resultados obtenidos de cocientes espectrales de registros reales, son por lo tanto más aplicables al área de San Salvador.

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ABSTRACT

The San Salvador area lies along the present axis of the Central American volcanic chain, which is the product of the northeast-directed subduction of the Cocos plate beneath the Caribbean plate. The destructive earthquakes occurred in El Salvador during the last few decades, originate basically from shallow, moderate sized earthquakes with epicenters falling into the volcanic zone. The most recent one of these, the Oct.10, 1986 earthquake (M_S=5.4) caused a considerable damage to the city of San Salvador with more than 1500 casualties and about 10,000 injured. The material losses reached up to USD 1,5 billion. Present study intends to demonstrate the effects of local geology on strong ground motion and to compare the results from the synthetic records with the observed data, in order to provide a basis for the ungoing efforts in preparing the new seismic design code for El Salvador.

Strong motion records from the Oct.10, 1986 earthquake are used to investigate the local site response in San Salvador. Spectral ratios of the horizontal components from four sedimentary sites with respect to a reference site, indicate maximum amplifications by a factor of 8-22. The amplifications vary at different sites, largely depending on the frequencies. There is generally a good correlation between the type of the sediment and the amplifications. However, the thickness of the unconsolidated sediments seems to play a more critical role than the type of formation. Synthetic records are generated, using the computer programs SHAKE and AMPLE, and compared with the observed data, with the objective of testing their feasibility. Our results give some evidence for positive correlations between the two data sets. However, the synthetic records fail to estimate the site amplifications at lower frequencies and the estimates in the frequency range 1-5 Hz can only be used as a very rough approximation. Using synthetic records in estimating the local site response, may only be applicable when they are calibrated with observed data. Otherwise, the estimates from the synthetics are largely dependent on the input control motion. The results from the spectral ratios of the observed records, are therefore more applicable to the San Salvador area.

INTRODUCTION:

Any reliable estimation of seismic hazard, is largely dependent on the detailed information of the local site response. This phenomenon has been recognized for some time *(e.g. Milne, 1898)*. In order to determine the site response, several methods are used, that can be categorized into two major groups, the theoretical (analytical) and the empirical methods. The theoretical calculation of the site response, mainly based on the inversion techniques, basically require a very good knowledge of the geotechnical parameters to constrain the results. Depending on the type of inversion used, several assumptions have to be made regarding the shape of the source spectrum or the site response at the selected stations. Empirical methods are somehow more effective in the sense that they are based on calculating the frequency spectrum directly from the recorded ground motion. Among the empirical methods, the spectral ratio of a sedimentary site with respect to a bedrock reference site is becoming widely used in recent years *(e.g. Borcherdt, 1970; Borcherdt and Gibbs, 1976; Rogers et al., 1984)*. Effective use of this technique is demonstrated at different sites and geological conditions following the large destructive earthquakes during the last decade *(e.g. Singh et al., 1988; Lermo et al., 1988; Borcherdt et al., 1989; Hough et al., 1990)*. Some review papers, discuss the effectiveness of the different methods used in the site response estimate *(e.g. Aki, 1988; Hartzell, 1992; Aki, 1993)*. Some new methods were also introduced recently, based on using only one-station recordings (horizontal vs. vertical components) *(Nakamura, 1989; Lermo and Chávez-García, in press)*, and on the cross-spectrum estimate *(Şafak, 1991; Field et al., 1992)*.

The destructive earthquakes experienced in El Salvador during the last few decades, originate basically from the shallow, moderate sized earthquakes with epicenters falling in to the volcanic zone. The most recent one of these, the Oct.10, 1986 earthquake (M_S=5.4) has caused a considerable damage to the city of San Salvador with more than 1500 casualties and about 10,000 injured *(Olson, 1987)*. The material losses reached up to USD 1,5 billion. An improved seismic design code, is urgently needed, especially taking into account the crucial factors such as the local site response. Present study intends to demonstrate this effect to provide a basis for the ungoing efforts in preparing the new seismic design code for El Salvador.

In this study, we have used the strong motion records of the Oct.10, 1986 earthquake from the five accelerograph stations located within the metropolitan area of San Salvador, El Salvador *(Figure 1)*. One of the stations (SHE) is located close to the San Salvador volcano, and is used as a bedrock reference site. Spectral ratio method is used to obtain the amplifications at five different sites, related to the different unconsolidated sediments covering most of the metropolitan area. Results are compared with the site responses obtained from the synthetic records, using the computer programs SHAKE *(Selnes, 1987)* and AMPLE *(Nadim, 1991)*, with the objective of testing the feasibility of the results in estimating the site response in San Salvador area.

GEOLOGICAL SETTING:

The San Salvador area lies along the present axis of the Central American volcanic chain, which is the product of the northeast-directed subduction of the Cocos plate beneath the Caribbean plate with an absolute plate motion of 8.0 cm/year *(Rymer, 1987; Weinberg, 1992)*. The plate-tectonic framework of the Central America and the Caribbean is previously reviewed by several authors *(e.g. Molnar and Sykes, 1969; Malfait and Dinkelmann, 1972; Burke et al., 1984; Mann and Burke, 1984; Dengo, 1985)*. The generalized geological overview of El Salvador was discussed by Wiesemann *(1975)*, and later the geological map was published by Weber et al. *(1978)*.

The metropolitan area of San Salvador is underlain by middle and upper Cenozoic volcanic and volcanoclastic deposits of different origin, mainly derived from the adjacent volcanoes *(Weber et al., 1978)*. The area lies on the gentle eastern slope of the San Salvador volcano dissected by deeply incised streams and rivers *(Figure 2a)*, and is surrounded by four major volcanic features. These are; the San Salvador volcano, with a minor cinder cone in its center to the west-northwest; the Cerros de Mariona to the north; a collapsed caldera, lake Ilopango to the east; and an inactive volcanic dome with a minor parasitic cone, Cerro San Jacinto to the south-southeast *(Figure 4)*.

Relevant to the local site response, there are two major deposits forming part of the San Salvador Formation that cover the metropolitan area. These are the youngest unit, Holocene volcanic ashes, locally named as tierra blanca because of its light colour, and the underlying Pleiostecene aged, browned coloured tuffs *(Schmidt-Thomé, 1975)*. The latter unit is as thick as 25 m and is derived from the San Salvador volcano, whereas the younger unit, is approximately 25 m thick immediately underneath the city and may reach up to 50 m towards the lake Ilopango *(Rymer, 1987)*. This younger unit represents multiple eruptions from the former Ilopango volcano. The characteristics of the uppermost 10 to 30 m of these sediments, are revealed in either geotechnical investigations or in cross sections outcropping along the river banks. The clast compositions and the grain sizes vary considerably within short distances as well as the thicknesses. The degree of consolidation is another characteristic feature varying considerably as indicated by the penetration tests *(Figure 2b)*.

There are three major fault trends in the area, in NNE-SSW/N-S, NE-SW and NW-SE *(Durr et al., 1960)*. In addition, the fourth and the oldest trend can be inferred from the general strike direction of the volcanic chain in the WNW-ESE/E-W direction *(Rymer, 1987)*. Among the other three, the north-south trending faults are less distinct and occur only locally *(Rymer, 1987)*. The youngest faults are the dominant trend in the NE-SW and the conjugate set in the NW-SE directions. All faults seem to have steep dip angles generally larger than 65° and appear active *(Schmidt-Thomé, 1975)*. Although the individual fault trends may have developed at different times, they have been repeatedly reactivated. The reactivation of the NNE-SSW trending fault during the October 10, 1986 earthquake is the most recent example.

SEISMICITY:

In El Salvador, as well as in most Central American countries, the main cause of seismic activity is the subduction of the Cocos plate under the Caribbean plate with an average velocity of 8 cm/yr *(Weinberg, 1992)*. Around 80% of the seismic activity in El Salvador has its origin in the subduction zone. The other 20% is generated either by local fault movements or volcanic activity.

The city of San Salvador has experienced several destructive earthquakes within this century. The most damaging were; on June 8, 1917, where two almost consecutive events with magnitudes 6.4 and 6.3 (M_S) occurred respectively, followed by an eruption half an hour later; on April 27, 1919 (M_S=6.0); and on May 3, 1965 (M_S=6.0), where it was preceeded by an unusual number of shocks (more than 8000) *(White et al., 1987)*. Although the epicenter of the latter is close to the October 10, 1986 earthquake, the casualties were much lower due to the high number of foreshocks which alerted the population. Even though the earthquakes ocurring in the subduction zone have larger magnitudes than the ones occurring inland they are less destructive. This is mainly due to the relative larger epicentral distances and deeper focal depths. As in the case of El Salvador, the most destructive earthquakes in Central America have been inland earthquakes related to the volcanic zone. Among them, December 23, 1972 earthquake in Nicaragua (M_S=6.2; NEIS), April 14, 1973 in Costa Rica (M_S=6.5; NEIS), February 4,1976 in Guatemala (M_S=7.5; NEIS) and October 10, 1986 in El Salvador (M_S=5.4; NEIC) have caused considerable damage and a high number of casualties.

The earthquake of Oct.10, 1986:

The main shock occurred at 17:49 (UT) with an epicenter close to the southern end of the city of San Salvador (Latitude 13° 40' N; Longitude 89° 11.4' W; Depth=7.3km) *(White et al., 1987)*. Despite its relatively moderate magnitude (M_S=5.4; mb=5.1; M_W=5.6), this earthquake caused more than 1500 casualties and left more than USD 1.5 billion in material losses.

Practically no earthquakes preceded the October 10, 1986 earthquake, only one event (M_C=3.8), on July 18 and three aftershocks were located near the epicenter of the main shock. However, this type of seismicity is commonly recorded along the volcanic chain in El Salvador.

The two largest aftershocks occurred in the northern and western part of the city, the first, 14 minutes after the main shock on October 10 (M_C=4.8), and the second on October 13, at 22:24 (M_C=4.6), respectively *(Figure 4)*. Within the next 24 hours following the mainshock, a total of 790 events were recorded *(Alvarez, 1987)*. The activity lasted until May

1987, decreasing sharply after the first three months. The distribution of the majority of the aftershock epicenters until October 13, indicates a clear trend propagating in the NNE direction. This zone was expanded during the period from October 18, to October 25, with still the majority of the aftershocks occurring in the NNE direction. The depth distribution indicates a range from the surface to 15 km, with a concentration around 5-11 km *(White et al., 1987)*. The fault plane solution of the main shock, based on the first motions and on the aftershock distribution, indicates a left-lateral strike slip displacement along a plane striking N32°E dipping nearly vertical *(Figure 4) (White et al., 1987)*.

The main shock of the October 10, 1986 earthquake reached intensities as high as IX on the Modified Mercalli intensity scale mainly in the area along the fault plane striking NNE-SSW *(Alvarez, 1987) (Figure 3)*. The highest intensities also correspond to the central and densely populated part of the city. *Figure 3* shows the distribution of damage with increasing degree of intensity, as well as the macroseismic intensity contours. The shallow depth of the mainshock has resulted in high damage concentrated in a relatively narrow zone. This, combined with the fact that most of the damage to buildings was the result of poor construction practices, have lead to a large number of casualties reaching up to 1500 with more than 10,000 wounded *(Olson, 1987)*.

When the October 10, 1986 earthquake occurred, 11 high-gain telemetered seismograph stations and 4 low-gain stations were operating. There was also a strong motion network composed of 10 three component accelerographs located in and around the city of San Salvador. The five accelerograph stations, Centro de Investigaciones Geotécnicas (CIG), Instituto Geográfico Nacional (IGN), Universidad Centro Americana (UCA), Hotel Camino Real (HCR) and Hotel Sheraton (SHE), used in this study are shown in *Figure 1*.

COMPARISON OF THE SPECTRA AND THE SPECTRAL RATIOS:

Sediment vs. bedrock on the observed data:

The spectral ratios of the four sedimentary sites CIG, IGN, UCA and HCR are computed with respect to the bedrock reference site SHE. The S-wave window, including the S-wave coda (believed to give similar amplifications *e.g. Gutierrez and Singh, in press)*, recorded on N-S and E-W components, are selected to study the spectral amplification. The signals were cosine-tapered and Fourier transformed. The spectral amplitudes were then smoothed with one-third octave band filter.

The SHE station is underlain by Pleistocene basaltic and andesitic lavas originating from the San Salvador volcano *(Figure 2a)*. The sedimentary cover, the browned coloured tuff, is less than 6 m thick *(Italtekna-Italconsult, 1987)*. This geological information, together with the low maximum observed absolute accelerations at SHE with respect to other sites, *(Table I, see also Figure 1)*, have allowed us to assume reasonably that SHE can be used as a bedrock reference site. The amplification related to the SHE site, which is by a factor of 2, is later taken into consideration within the relevant frequency range, when comparing the site amplifications from the different sites *(Atakan and Torres, 1993)*. Regarding the location of the earthquake source, we assume that the path effects due to the differences in the geographical locations of the sites, are minimal *(Atakan and Torres, 1993)*.

Several general observations are made on the spectras and the spectral ratios of the N-S components *(Figure 5)*. Generally all sedimentary sites have higher spectral amplitudes than the reference site within the frequency range 0.1 to 3.5. The situation is reversed at higher frequencies giving negative amplifications at the sedimentary sites. The site amplifications vary from a factor of 8 to 22 *(Figure 11; see also Table I)*. The highest site amplification is observed at IGN by a factor of 22. There are at least five critical frequencies on which the peak amplifications occur on the spectral ratios from all four sites. These are, at 0.4, 0.7, 1.3, 2.0, and 3.0 Hz. The amount of amplifications are largely frequency dependent and vary at different sites. However, in general the most prominent peaks are observed at either 0.7 or 1.3 Hz *(Figure 5; see also Table I)*.

The E-W components give also similar results, although there are some differences in the frequency ranges on which the amplifications occur *(Figure 6; see also Table I)*. There seems to be little amplifications at HCR with respect to SHE. At CIG the positive amplifications continue also at higher frequencies up to 10 Hz. IGN and UCA, on the other hand, have similar frequency ranges with slightly lower limits. In general the amplifications on the E-W components are lower than the N-S components and range from a factor of 2 to 8. The highest amplification among the four sites is observed at IGN *(Figure 11; see also Table I)*. Similar to N-S components, the amplifications are largely dependent on the frequencies *(Figure 6; see also Table I)*. Same five critical frequencies are also observed on the E-W components *(Figure 6)*.

Sediment vs bedrock on the synthetic data:

The synthetic traces are obtained using the two computer programs SHAKE *(Selnes, 1987)*, and AMPLE *(Nadim, 1991)*. The results presented in *Figures 7-10*, are from the trials that fit best to the observed data. The corresponding geotechnical parameters in the different input files for the SHAKE and the AMPLE programs are given in the Appendices. The original geotechnical data used in the initial trials, were modified in order to create the best fit to the observed data. These are given in *Tables II-V*. The synthetic data for the E-W components of the records from the two of the sites IGN and UCA, were previously been obtained in a separate study *(Figueroa, 1993)*. The same input geotechnical parameters are also used for the N-S components.

The two computer programs used in this study have different approaches in creating the synthetics. Both programs use an input ground motion (assumed to represent the bedrock ground motion), and create the corresponding response at a chosen level in the sedimentary profile assuming one-dimensional, horizontally layered medium. SHAKE *(Selnes, 1987)*, solves the one-dimensional wave propagation problem through a horizontally layered visco-elastic medium in the frequency domain. The conversion of time histories to frequency domain and vice versa is done by Fast Fourier Transformation (FFT). The non-linear behaviour of the sedimentary deposits is approximated by an itirative, quasi-linear procedure. The input earthquake motion can be specified at any point within the sedimentary profile, including the surface bedrock or at the any outcropping level. AMPLE *(Nadim, 1991)* on the

other hand, models the horizontally layered sedimentary profile as a non-linear shear beam. The resulting non-linear wave propagation equations are solved in the time domain by the explicit central difference method. Several constitutive laws, such as linear elastic , failure-seeking with hyperbolic initial curve, and plastic with nested yield surfaces, are available. In this study, failure-seeking model is used, which is one of the simplest non-linear models. The non-linear behaviour of the sedimentary deposits is defined by only two geotechnical parameters, the initial shear modulus (G_0) and shear strength (S_U). The input ground motion can only be specified at the bedrock within the sedimentary profile or at the bedrock outcrop.

The input earthquake motion for both programs is the bedrock simulation of the observed record at SHE. This is done by deconvolving both N-S and E-W components of the accelerograms recorded at the surface, by using the SHAKE program. The geotechnical parameters used in this deconvolution process are explained in a separate report by Figueroa *(1993)*. The earthquake motion at the surface for the four sedimentary sites (CIG, IGN, HCR and UCA) were then obtained for both N-S and E-W components and with the two programs SHAKE and AMPLE, by using the corresponding geotechnical parameters as input. Several trials were made altering the initial parameter settings given in the *Tables II-V*. The results are compared with the observed traces and the best fitting data were chosen for each site for the two horizontal components. The spectral plots of the chosen synthetic traces were later used as a basis for the spectral ratios of the four sedimentary sites with respect to the bedrock reference site SHE. The results for the N-S components by using SHAKE are given in *Figure 7*. Here, the spectral ratios indicate amplification at the sedimentary sites ranging from a factor of 3-6 *(Figure 11c; Table I)*. The frequencies on which the amplifications occur are within the range 2-5 Hz. The maximum amplifications for CIG is at 5.0 Hz, for IGN at 2.0, for UCA at 2.2 Hz, and for HCR at 3.2 Hz. The spectral ratios obtained using AMPLE for the N-S components *(Figure 8)*, indicate amplifications in the range 5-11 *(Figure 11c; Table I)*, which are higher than the results obtained by using SHAKE. The frequencies on which the highest amplifications occur are for CIG at 4.0 Hz, for IGN at 8.0 Hz, for HCR at 2.2 Hz, and for UCA at 6.0 Hz. The results for the E-W components are given in *Figures 9 and 10*, for SHAKE and AMPLE respectively. The amplifiation factors for SHAKE vary from 3-10, and for AMPLE from 3-11 *(Figure 11d; Table I)*. The frequencies on which the

maximum amplifications occur vary for each site and are different from the observed data *(Table I)*.

The amplification factors obtained for the N-S components using AMPLE gave better estimates than the values obtained using SHAKE, although they are still lower than the observed values (approximately 1/2 of the observed). For the E-W components the amplification factors obtained by both programs are somehow closer to the observed data, however, the differences are within the range $\pm$ 3. The reversing of the amplification at higher frequencies, which is the characteristic of all the observed data, is only seen on the E-W component of the IGN synthetics from SHAKE *(Figure 9)*. Otherwise the synthetic traces from SHAKE tend to show little or no amplifications at higher frequencies *(Figures 7 and 9)*. On the other hand, the results from AMPLE almost always indicate higher amplifications at high frequencies *(Figures 8 and 10)*.

DISCUSSION:

Several observations related to the comparison of the spectral amplifications at different sites are open to discussion. To provide a basis for these comparisons, some 3-D diagrams are prepared showing the differences between the four sedimentary sites, and are presented in *Figure 11*. These are prepared for the results from the observed (REAL), and from the synthetics by using SHAKE and AMLPLE.

Regarding the comparison between the maximum and the average (being the average of all amplifications at equal intervals within the frequency range where spectral amplifications occur) spectral amplifications on the observed data, the N-S components give larger amplifications at all sites *(Atakan and Torres, 1993)*. The site IGN, gives the highest amplification factor (x22), whereas the two sites CIG and HCR have also relatively high amplifications, 15 and 17, respectively *(Table I)*. The UCA site, gives the lowest amplification close to a factor of 8. The average values between 3 and 6, give similar relative comparison between the sites. The same is also true for the E-W components, except HCR, where the average value is much lower than expected *(Atakan and Torres, 1993)*. It is

important to note here, that there is no good correlation between the highest absolute accelerations and the maximum amplification factors *(Figure 11)*. The highest absolute acceleration for the N-S components is observed at HCR, whereas the highest amplification factor is at IGN. The comparisons shown in *Figures 5 and 6*, clearly demonstrate the frequency dependency of the spectral amplifications. In general 0.7 and 1.3 Hz seem to give the highest amplifications at most of the sites. There is also a tendency of decreasing amplifications with increasing frequencies *(Figures 5 and 6)*.

In general there is a good correlation between the synthetic and the observed traces, regarding the maximum accelerations (A_{max}), which is obtained basically by calibrating the synthetic traces with the observed data. The differences in A_{max} between the synthetics using SHAKE and the observed data varies from ± 0.093 **g** for the N-S, to ± 0.070 **g** for the E-W components *(Figure 11a and 11b; Table I)*. The differences in using AMPLE, on the other hand, changes from ± 0.093 **g** for the N-S, to ± 0.090 **g** for the E-W component *(Figure 11a and 11b; Table I)*. The best correlations, as expressed by the least differences in A_{max} values, is obtained by using SHAKE, for IGN (E-W) (0.01 g), and for HCR (N-S) (0.01 g). The results from AMPLE is best for UCA on both components (0.02 g for N-S and 0.01 g for E-W). The largest difference (i.e. the poorest correlation) is for CIG (E-W) by using AMPLE (0.25 g). The correlation in the frequency content of the traces, on the other hand, is generally poor. This is probably due to the failure of one-dimensional approximation in simulating the effects of the long period surface waves, especially related to the basin geometry *(e.g. Graves, 1993)*. The spectral plots prepared for the synthetic traces *(Figures 7-10)*, when compared to the observed *(Figures 5 and 6)*, clearly demonstrates that the frequency range of the spectral amplification on the synthetic data is different than the frequency range on the observed data. The five common frequencies on which spectral amplifications occur are not observed on the synthetic traces. As a consequence, the spectral ratios obtained from the synthetics show poor correlation with the observed data.

Based on the above considerations, we have tried to do some correlations with the spectral amplifications and the local geology. In general, the thickness of the sedimentary cover seems to be a more crucial factor than the type of formation. The example to be given here are from the sites which have similar compositions but different thicknesses. In this

respect IGN and UCA, having the same composition, which is Pleistocene aged, browned colored tuff, usually stratified with volcanic ash, can be compared *(Figure 2a)*. The geographical locations suggest that the IGN station has a larger thickness and thereby gives larger site amplifications. Regarding the spectral shapes and the dominant peaks in the spectral ratios, both sites give similar results *(Figure 5)*. The site CIG, has a similar formation as the HCR (Holocene volcanic ash) *(Figure 2a)*. The topographical levels are different suggesting that CIG has a lower topographical level, which is expected to contain thicker sedimentary cover. But, since it is close to the San Jacinto hill, this assumption may not be totally true. Here, the site amplification is slightly lower than the IGN station, but the spectral shapes are very similar *(Figure 5)*.

In the above discussion about the correlation between the sedimentary thicknesses and the spectral amplifications, the degree of consolidation of the sediments (i.e. cementation and compaction), a rather critical factor, must be taken into consideration. There is unfortunately no detailed information available to do a thorough analyses of this problem. However, based on the geotechnical data available at few of the sites, the degree of consolidation seems to play an important role in the spectral amplifications. An example can be given, comparing the two sites UCA and HCR. HCR gives higher spectral amplifications than UCA, although the thickness of the total sedimentary cover at UCA is higher than HCR (i.e. approximately 33 m at UCA and 21 m at HCR; *Italtekna/Italconsult, 1987*). The thickness of the unconsolidated parts of the sedimentary cover, on the other hand, is opposite being thicker at HCR than UCA, which seems to support the assumption that the degree of consolidation is an important parameter. This problem is generally quite difficult to adress, unless there is a detailed information about the local variations of this parameter. The two cross-sections shown in *Figure 2b* (see variation in the penetration test results at short distances, given at each location), clearly illustrates this problem.

Several recent observations about the weak motion and the strong motion suggest that the non-linear amplification at sediment sites may be very common *(e.g. Singh et al., 1988; Aki, 1993)*. First, on the average, the amplification is always greater at the younger sedimentary sites for all frequencies up to 12 Hz, in the case of weak motion; while the relation is reversed for frequencies higher than 5 Hz, in the case of strong motion *(Aki,*

1993). Our observations also indicate a reversing of the same relation. However, the frequencies in which the reversing occur are slightly lower than the frequencies mentioned by Aki *(1993)*. At CIG the reversing occurs at 3.8 Hz, at UCA it is at 3.4 Hz, at IGN and HCR it is at 2.3 Hz. It has also been argued *(Aki, 1993)* that for the epicentral distances less than 50 km, peak ground velocity and displacement, as well as the Arias intensity, show higher amplifications for soil sites, while peak ground acceleration is roughly independent of the site classification. In our observations on the accelerograms, we observe the site dependent amplifications very clearly. This is in contrast with the previous observations done at other areas *(e.g. Boore et al., 1989)*.

The distribution of damage *(Figure 3)*, and the spectral amplifications at different sites are correlated *(Figures 5 and 6)*. There seems to be a positive correlation for the IGN and CIG sites, where clear site amplifications occur close to those parts that have experienced a high damage. The number of sites used in this study, however, are not sufficient to do any detailed comparison between the damage and site amplifications. This comparison becomes especially difficult, when factors such as the engineering properties for the collapsed structures, vary considerably.

The results from this study clearly demonstrate the site amplifications related to the sedimentary cover in the metropolitan area of San Salvador. It is strongly recommended that the local site response should be taken into consideration in any seismic hazard estimation. The October 10, 1986 earthquake data provides a unique data set to calibrate the site response estimates from any other study. Furthermore, our results from the synthetic data using computer programs SHAKE and AMPLE, only give a rough site response estimate, and fail to simulate the lower frequency content of the actual signal. More comprehensive testing at different site conditions is needed. Using only one dimensional synthetic modelling in estimating the site response, may only be applicable when they are calibrated with observed data. Otherwise, the estimates from the synthetics are largely dependent on the input control motion.

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FIGURE CAPTIONS:

Figure 1. The locations of the five accelerograph stations used in this study. At each site, the N-S component of the acceleration recordings from the October 10, 1986 earthquake are shown for comparison. Note the lower amplitudes at SHE. The major roads are shown for orientation.

Figure 2.a. Map showing the geology of the San Salvador area *(Simplified from the 1:15 000 geological map prepared by Centro de Investigaciones Geotécnicas, 1987).* Major fault trends, as well as the main roads are shown. **b.** The parallel N-S cross-sections, AA' AND BB', showing the lithology and thickness variations. The numbers at each site indicates the results from the penetrations tests.

Figure 3. The macroseismic intensity (Modified Mercalli) contour map *(from Alvarez, 1987).* The distribution of damage is also shown with darker patterns indicating higher damage *(modified from Centro de Investigaciones Geotécnicas, 1987).* The stars indicate the areas where total damage to buildings occurred. the epicenter of the October 10, 1986 earthquake is also shown by a larger star. Stippled line indicates the city limits. Note that the distribution is largely along a NNE-SSW trend.

Figure 4. The mainshock and the immediate aftershocks (within the first 24 hours) of the October 10, 1986 earthquake *(from White et al., 1987).* The first intermadiate aftershock (M_S=4.8) is shown on the northern part of the city. The focal mechanism of the main shock is shown on the lower left corner. The cross-section AA' clearly shows the steeply dipping fault plane.

Figure 5. The spectral plots and the spectral ratios of N-S components of the observed records from four sedimentary sites with respect to the bedrock reference site SHE. The solid lines are the spectras corresponding to the sedimentary sites, whereas the dashed lines indicate the spectra of the bedrock reference site. The acceleration traces for each site are also shown. All amplitudes are in **g**. The accelerogram from SHE is shown on the right for comparison.

Figure 6. The spectral plots and the spectral ratios of E-W components of the observed records from four sedimentary sites with respect to the bedrock reference site SHE. Notations are as in Figure 5.

Figure 7. The spectral plots and the spectral ratios of N-S components of the synthetic records for the four sedimentary sites, obtained using SHAKE. The accelerograms are also shown on the left of each spectral plot. Notations are as in Figure 5.

Figure 8. The spectral plots and the spectral ratios of N-S components of the synthetic records for the four sedimentary sites, obtained using AMPLE. The accelerograms are also shown on the left of each spectral plot. Notations are as in Figure 5.

Figure 9. The spectral plots and the spectral ratios of E-W components of the synthetic records for the four sedimentary sites, obtained using SHAKE. The accelerograms are also shown on the left of each spectral plot. Notations are as in Figure 5.

Figure 10. The spectral plots and the spectral ratios of E-W components of the synthetic records for the four sedimentary sites, obtained using AMPLE. The accelerograms are also shown on the left of each spectral plot. Notations are as in Figure 5.

Figure 11. The comparison of the maximum accelerations (Amax) in **g** and the maximum amplification factors on observed (REAL) and the synthetic (SHAKE and AMPLE) accelerograms for the four stations CIG, IGN, HCR and UCA. All traces are the N-S components. **a)** Maximum accelerations for the N-S components from observed and synthetics. **b)** Maximum accelerations for the E-W components from observed and synthetics. **c)** Maximum amplification factors for the N-S components from observed and synthetics. **d)** Maximum amplification factors for the E-W components from observed and synthetics.

TABLE I. The maximum accelerations (A max) in g and the maximum amplification factors for the N-S and E-W components of the observed (REAL) and the synthetic (SHAKE and AMPLE) records for the four sedimentary sites CIG,IGN, HCR and UCA. The amplification factors are measured within the frequency range 0.1-10.0 Hz. The values in paranthesis correspond to the frequencies in Hz, for each amplification factor.

STATION	A max (g)						AMPLIFICATION FACTOR					
	N - S			E - W			N - S			E - W		
	REAL	AMPLE	SHAKE	REAL	AMPLE	SHAKE	REAL	AMPLE	SHAKE	REAL	AMPLE	SHAKE
CIG	0.42	0.54	0.60	0.71	0.46	0.61	15.0 (1.3)	7.0 (4.0)	5.8 (5.0)	6.0 (0.7)	6.8 (4.0)	10.0 (10.0)
IGN	0.40	0.51	0.31	0.54	0.48	0.53	22.0 (0.7)	10.8 (8.0)	3.3 (2.0)	6.5 (1.3)	11.0 (7.0)	3.0 (1.8)
HCR	0.47	0.35	0.46	0.34	0.38	0.40	17.0 (0.7)	6.0 (2.2)	5.1 (3.2)	4.6 (2.0)	8.0 (7.0)	3.9 (3.0)
UCA	0.39	0.37	0.30	0.43	0.42	0.54	7.8 (2.0)	5.5 (6.0)	4.2 (2.2)	4.6 (0.7)	3.5 (2.2)	4.0 (1.8)

TABLE II. Initial geotechnical parameters used in the synthetic trials for the sedimentary site CIG with SHAKE and AMPLE computer programs. The same values are used in both N-S and E-W components. The values are from Italtekna-Italconsult *(1987)*.

CIG Shake **Damping = 2 %**

LAYER	THICKNESS (mts)	SUBLAYER	DENSITY (kg/m^3)	V_s (m/s)
1	1.50	1	1450	144.6
2	2.45	1	1500	185.6
3	2.55	1	1550	214.7
4	1.00	1	1600	275.6
5	0.90	1	1650	305.7
6	1.55	1	1700	331.2
7	BEDROCK		2200	2100

NOTE: V_s values are from Italtekna-Italconsult (1987)

CIG Ample **Damping = 1 %**

LAYER	THICKNESS (mts)	DENSITY (Kg/m^3)	V_s (m/s)	G_0 (MPa)
1	1.50	1450	144.6	30
2	2.45	1500	185.6	52
3	2.55	1550	214.7	71
4	1.00	1600	275.6	122
5	0.90	1650	305.7	154
6	1.55	1700	331.2	186
7	BEDROCK	2200	2100	

TABLE III. Initial geotechnical parameters used in the synthetic trials for the sedimentary site IGN with SHAKE and AMPLE computer programs. The same values are used in both N-S and E-W components. The values except V_S, are from the unpublished data by Soil Mechanics Dept., Centro de Investigaciones Geotécnicas, MOP.

IGN Shake — Damping = 1 %

LAYER	THICKNESS (mts)	DENSITY (Kg/m^3)	SUBLAYER	V_s (m/s)	V_s (m/s)
1	4.0	1550	1	178.7	179.32
			2	180	
2	0.5	1550	1	180	180
3	1.5	1650	1	190	190
4	2.5	1650	1	213	221.5
			2	230	
5	7.0	1650	1	235	236
			2	237	
6	4.0	1650	1	325	368
			2	410	
7	10.5	1700	1	431	431
			2	431	
8	BEDROCK	2200			2100

NOTE: Vs values are from Italtekna-Italconsult (1987)

IGN Ample — Damping = 2 %

LAYER	THICKNESS (mts)	DENSITY (Kg/m^3)	V_s (m/s)	G_0 (MPa)
1	2.00	1550	178.7	49.47
2	2.00		180	50.00
3	0.50		180	50.00
4	1.50	1650	190	59.60
5	1.25		213	74.90
6	1.25		230	87.30
7	3.50		235	91.00
8	3.50		237	92.70
9	2.00		325	174.00
10	2.00		410	277.00
11	5.25	1700	431	315.80
12	5.25		431	315.80
13	BEDROCK	2200	1000	

TABLE IV. Initial geotechnical parameters used in the synthetic trials for the sedimentary site HCR with SHAKE and AMPLE computer programs. The same values are used in both N-S and E-W components. The values are from Italtekna-Italconsult *(1987)*.

HCR Shake **Damping = 2 %**

LAYER	THICKNESS (mts)	SUBLAYER	DENSITY (Kg/m^3)	Vs (m/s)
1	1.50	1	1600	155
2	1.50	1	1600	155
3	2.30	1	1600	220
4	2.30	1	1600	220
5	3.80	1	1700	170
		2		
6	3.80	1	1700	170
		2		
7	6.00	1	1700	220
		2		
		3		
8	BEDROCK		2200	2100

NOTE: V_s values are from Italtekna-Italconsult (1987)

HCR Ample **Damping = 1 %**

LAYER	THICKNESS (mts)	DENSITY (Kg/m^3)	V_s (m/s)	G_0 (MPa)
1	1.5	1600	155	38
2	1.5	1600	155	38
3	2.3	1600	220	77
4	2.3	1600	220	77
5	1.9	1700	170	49
6	1.9	1700	170	49
7	1.9	1700	170	49
8	1.9	1700	170	49
9	2.0	1700	220	82
10	2.0	1700	220	82
11	2.0	1700	220	82
12	BEDROCK	2200	2100	

TABLE V. Initial geotechnical parameters used in the synthetic trials for the sedimentary site UCA with SHAKE and AMPLE computer programs. The same values are used in both N-S and E-W components. The values are from the unpublished data by Soil Mechanics Dept., Centro de Investigaciones Geotécnicas, MOP.

UCA Shake Average Density = 1650 Kg/m3 Damping = 2 %

LAYER	THICKNESS (mts)	SUBLAYER	N (SPT)	V_s (m/s)	V_s (m/s)
1	4.0	1	8	171	187
		2	13	203	
2	1.0	1	16	220	220
3	5.0	1	35	291	266.5
		2	21	242	
4	2.5	1	33	285	307.5
		2	50	330	
5	31.5	1			400
		2			
		3			
6	BEDROCK	DENSITY 2200 kg/m^3			2000

UCA Ample Average Density = 1650 Kg/m^3 Damping = 2 %

LAYER	THICKNESS (mts.)	V_s (m/s)	G_0 (MPa)
1	2.00	171	48
2	2.00	203	68
3	1.00	220	80
4	2.50	291	140
5	2.50	242	97
6	1.25	285	134
7	1.25	330	180
8	5.25	400	264
9	5.25	430	305
10	5.25	435	312
11	5.25	440	319
12	5.25	445	327
13	5.25	450	334
14	BEDROCK	1000	

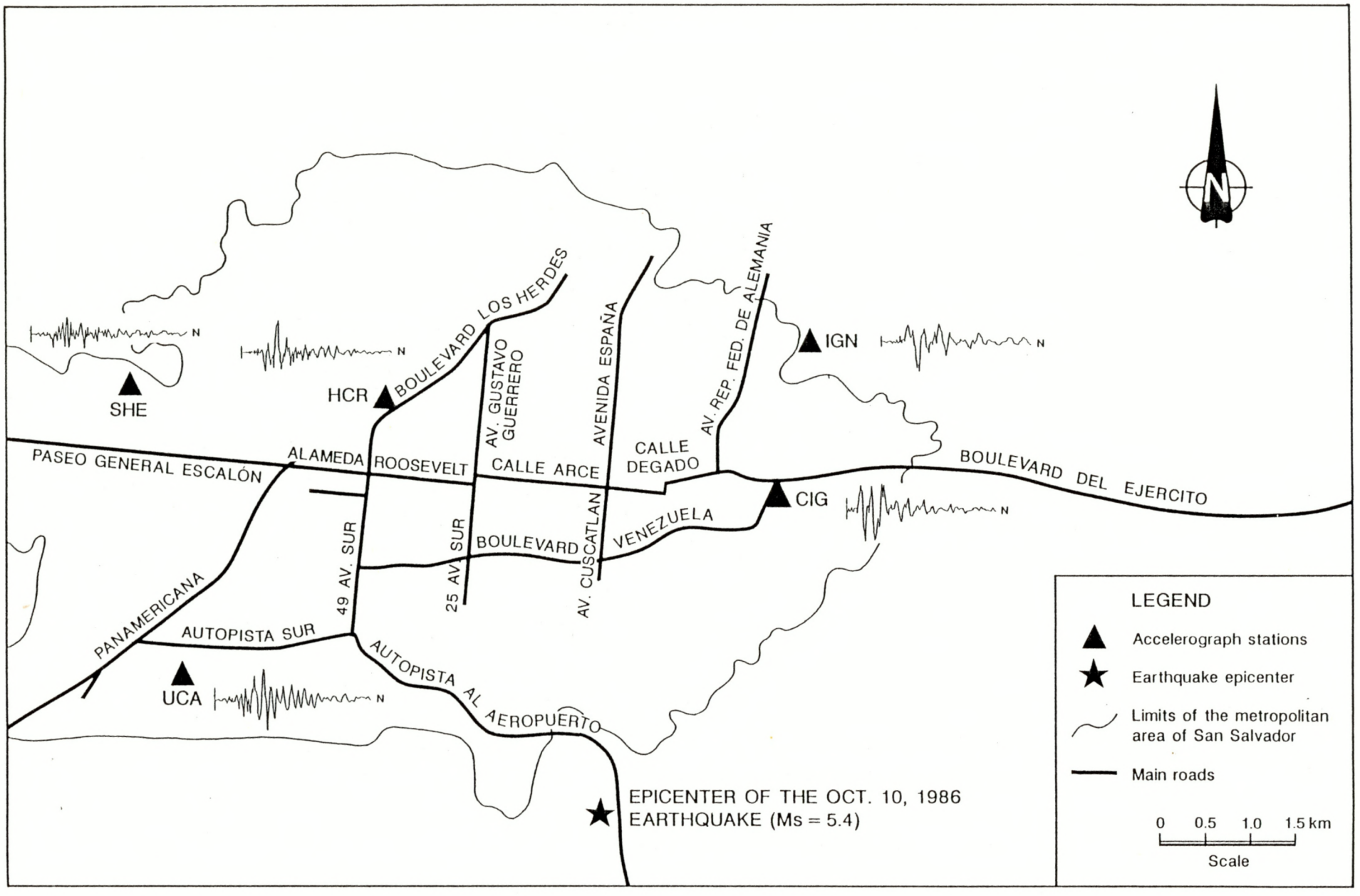
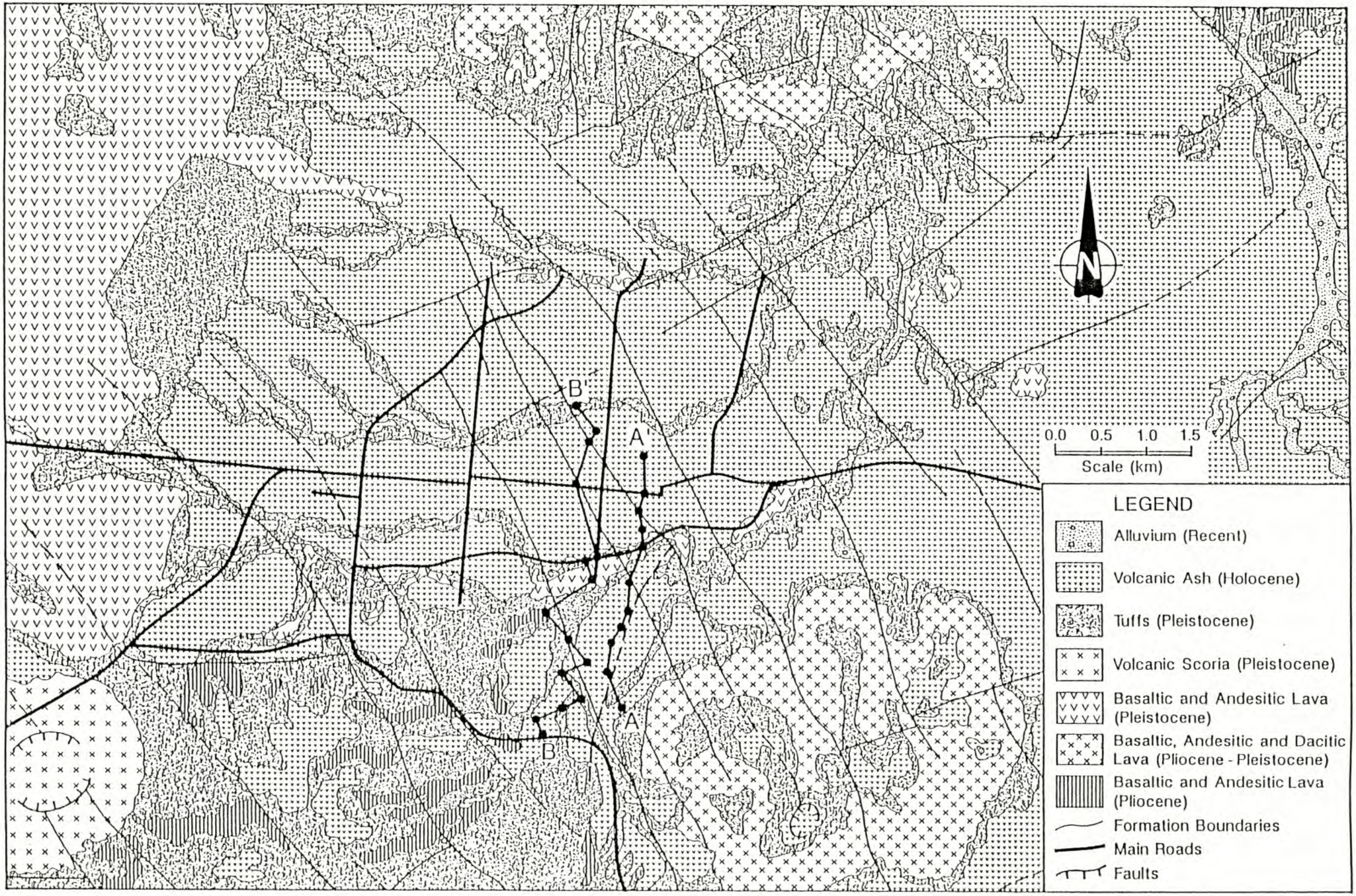
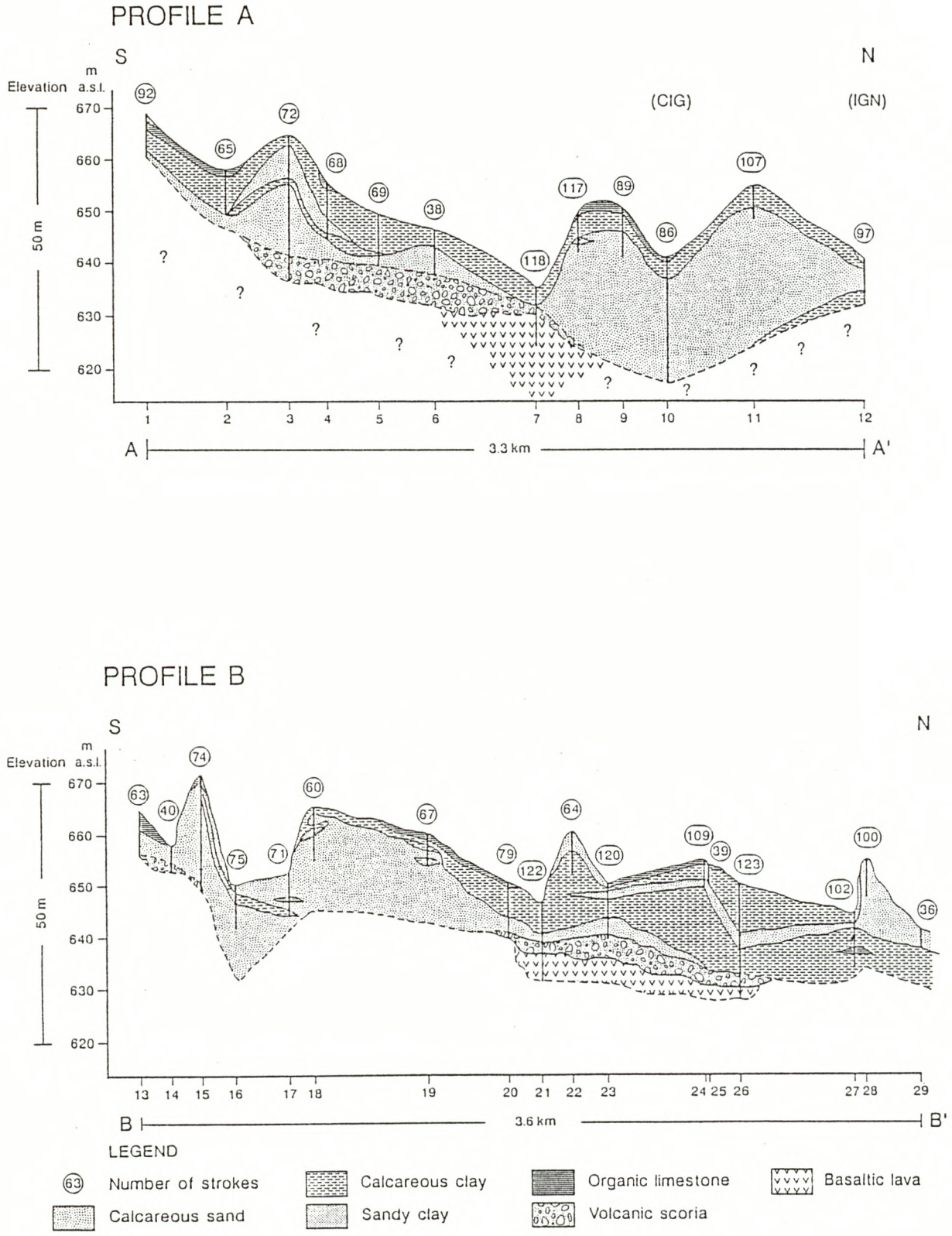

N
SHE
HCR
IGN
CIG
UCA
BOULEVARD LOS HEROES
AV. GUSTAVO GUERRERO
AVENIDA ESPAÑA
AV. REP. FED. DE ALEMANIA
PASEO GENERAL ESCALÓN
ALAMEDA ROOSEVELT
CALLE ARCE
CALLE DEGADO
BOULEVARD DEL EJERCITO
49 AV. SUR
25 AV. SUR
BOULEVARD VENEZUELA
AV. CUSCATLAN
PANAMERICANA
AUTOPISTA SUR
AUTOPISTA AL AEROPUERTO
EPICENTER OF THE OCT. 10, 1986 EARTHQUAKE (Ms = 5.4)
LEGEND
Accelerograph stations
Earthquake epicenter
Limits of the metropolitan area of San Salvador
Main roads
0 0.5 1.0 1.5 km
Scale

Figure 1.


N
B'
A'
A
B
0.0 0.5 1.0 1.5
Scale (km)
LEGEND
Alluvium (Recent)
Volcanic Ash (Holocene)
Tuffs (Pleistocene)
Volcanic Scoria (Pleistocene)
Basaltic and Andesitic Lava (Pleistocene)
Basaltic, Andesitic and Dacitic Lava (Pliocene - Pleistocene)
Basaltic and Andesitic Lava (Pliocene)
Formation Boundaries
Main Roads
Faults


PROFILE A
S
N
m
Elevation a.s.l.
(CIG)
(IGN)
670
660
650
640
630
620
50 m
92
72
65
68
69
38
118
117
89
86
107
97
1
2
3
4
5
6
7
8
9
10
11
12
A
3.3 km
A'
PROFILE B
S
N
m
Elevation a.s.l.
74
63
40
60
67
64
75
71
79
122
120
109
39
123
100
102
36
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
B
3.6 km
B'
LEGEND
Number of strokes
Calcareous sand
Calcareous clay
Sandy clay
Organic limestone
Volcanic scoria
Basaltic lava

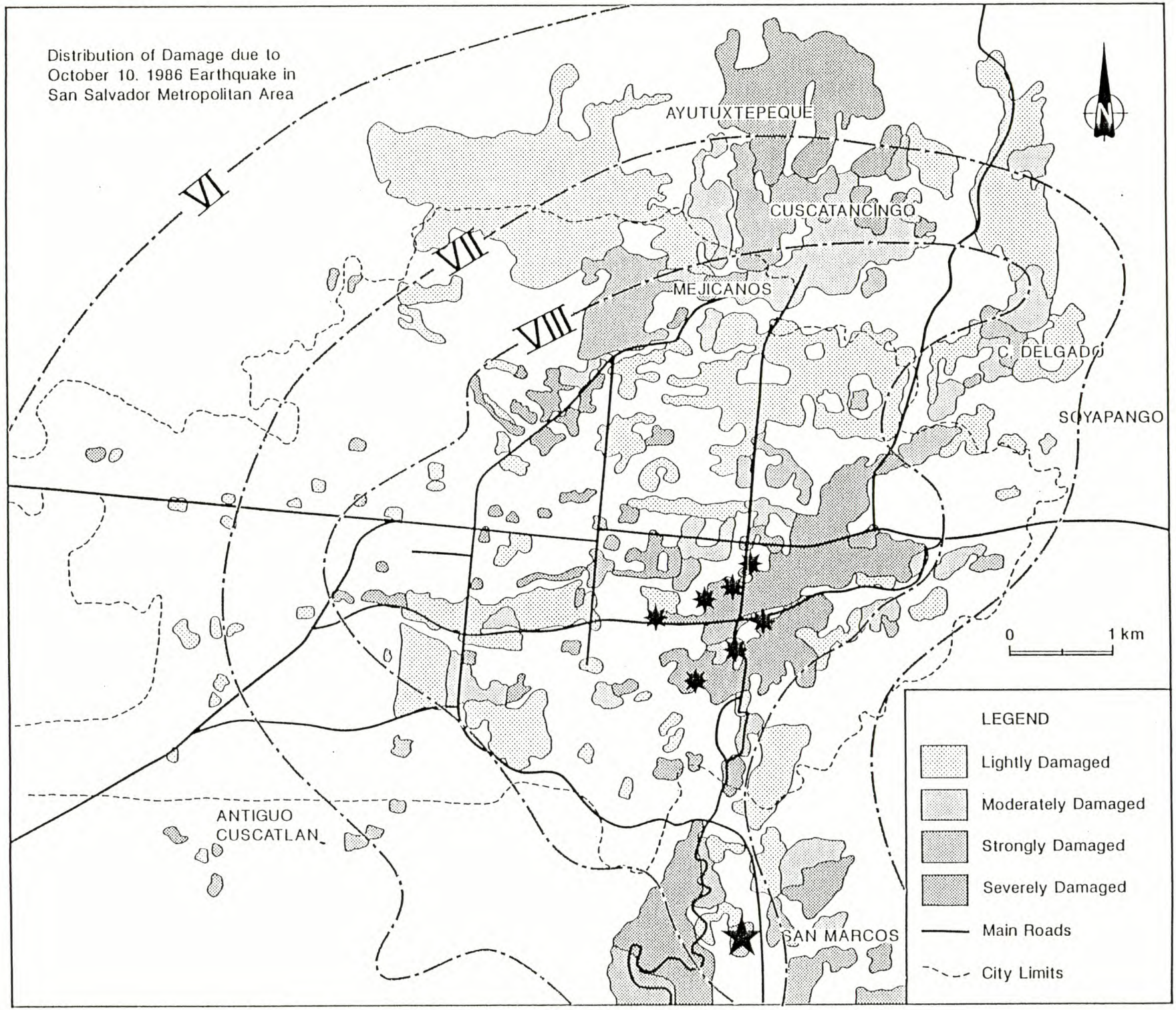
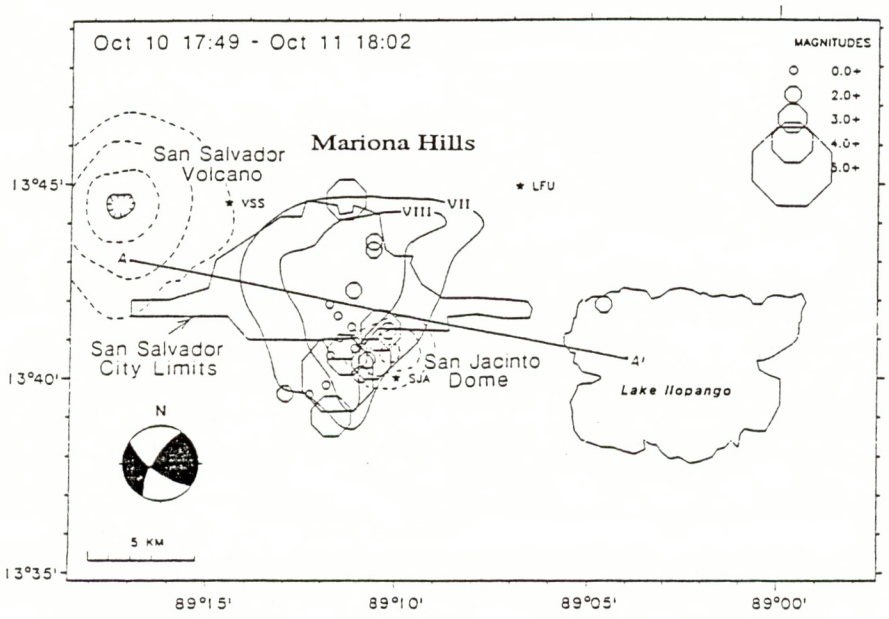

Distribution of Damage due to
October 10. 1986 Earthquake in
San Salvador Metropolitan Area
VI
VII
VIII
AYUTUXTEPEQUE
CUSCATANCINGO
MEJICANOS
C. DELGADO
SOYAPANGO
ANTIGUO
CUSCATLAN
SAN MARCOS
N
0
1 km
LEGEND
Lightly Damaged
Moderately Damaged
Strongly Damaged
Severely Damaged
Main Roads
City Limits

Figure 3.

Figure 4.


Oct 10 17:49 - Oct 11 18:02
MAGNITUDES
0.0+
2.0+
3.0+
4.0+
5.0+
Mariona Hills
San Salvador Volcano
VSS
LFU
VIII
VII
A
A'
San Salvador City Limits
San Jacinto Dome
SJA
Lake Ilopango
N
5 KM
13°45'
13°40'
13°35'
89°15'
89°10'
89°05'
89°00'

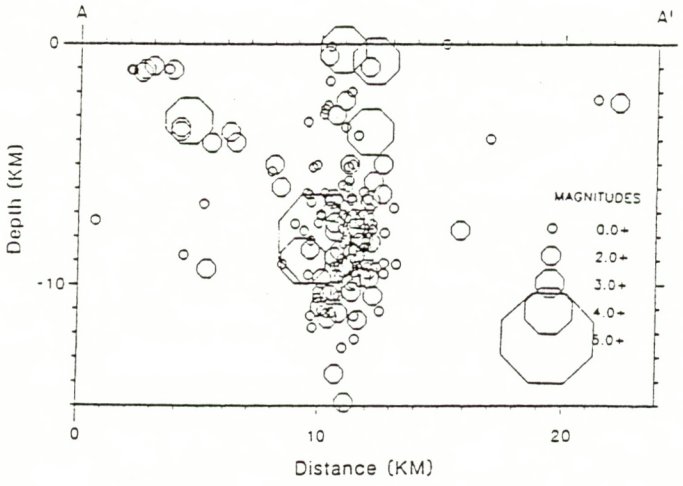

A
A'
0
-10
Depth (KM)
MAGNITUDES
0.0+
2.0+
3.0+
4.0+
5.0+
0
10
20
Distance (KM)

Figure 5.

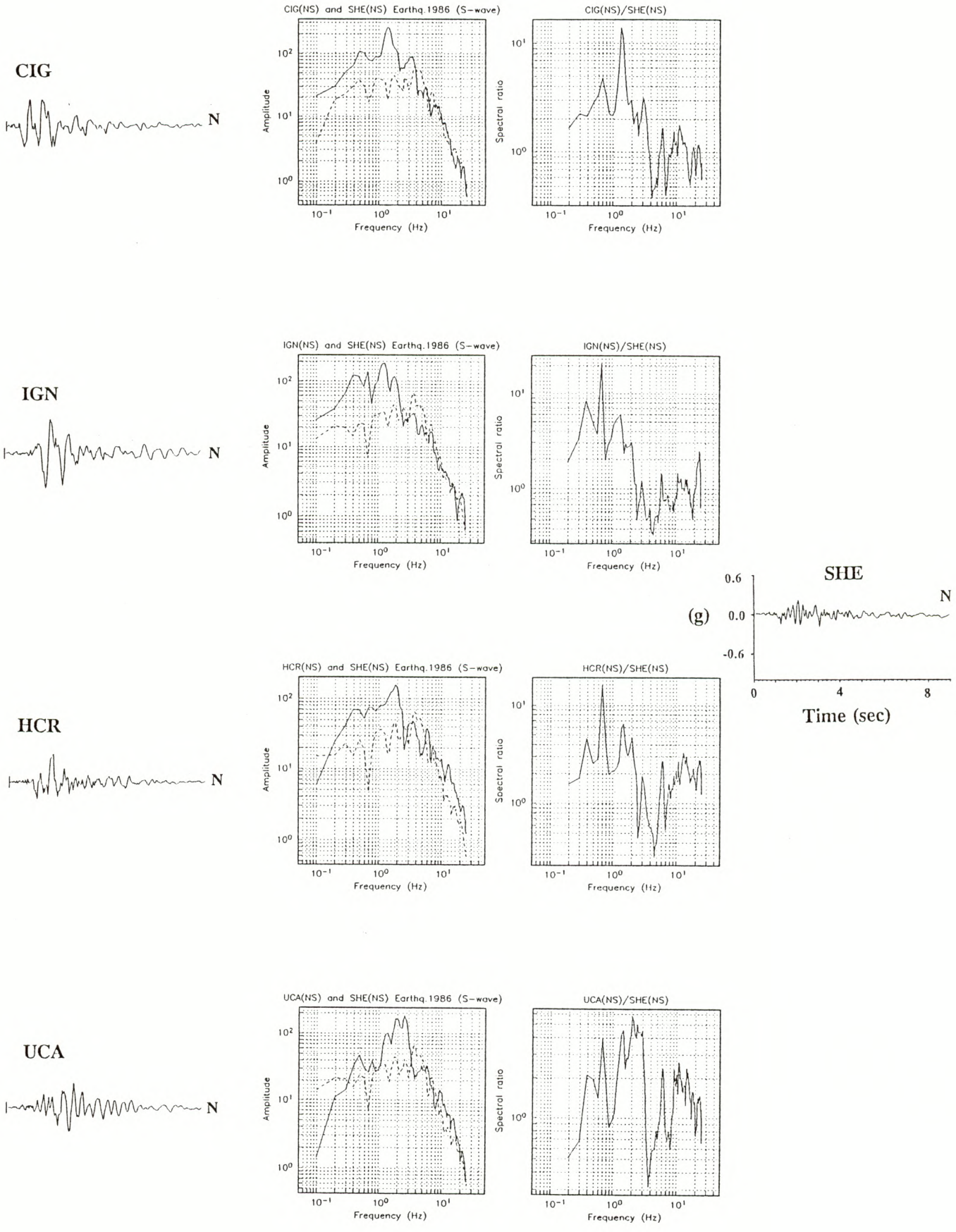

CIG
N
CIG(NS) and SHE(NS) Earthq.1986 (S-wave)
CIG(NS)/SHE(NS)
IGN
N
IGN(NS) and SHE(NS) Earthq.1986 (S-wave)
IGN(NS)/SHE(NS)
SHE
N
(g)
0.6
0.0
-0.6
0
4
8
Time (sec)
HCR
N
HCR(NS) and SHE(NS) Earthq.1986 (S-wave)
HCR(NS)/SHE(NS)
UCA
N
UCA(NS) and SHE(NS) Earthq.1986 (S-wave)
UCA(NS)/SHE(NS)
Amplitude
Spectral ratio
Frequency (Hz)

Figure 6.

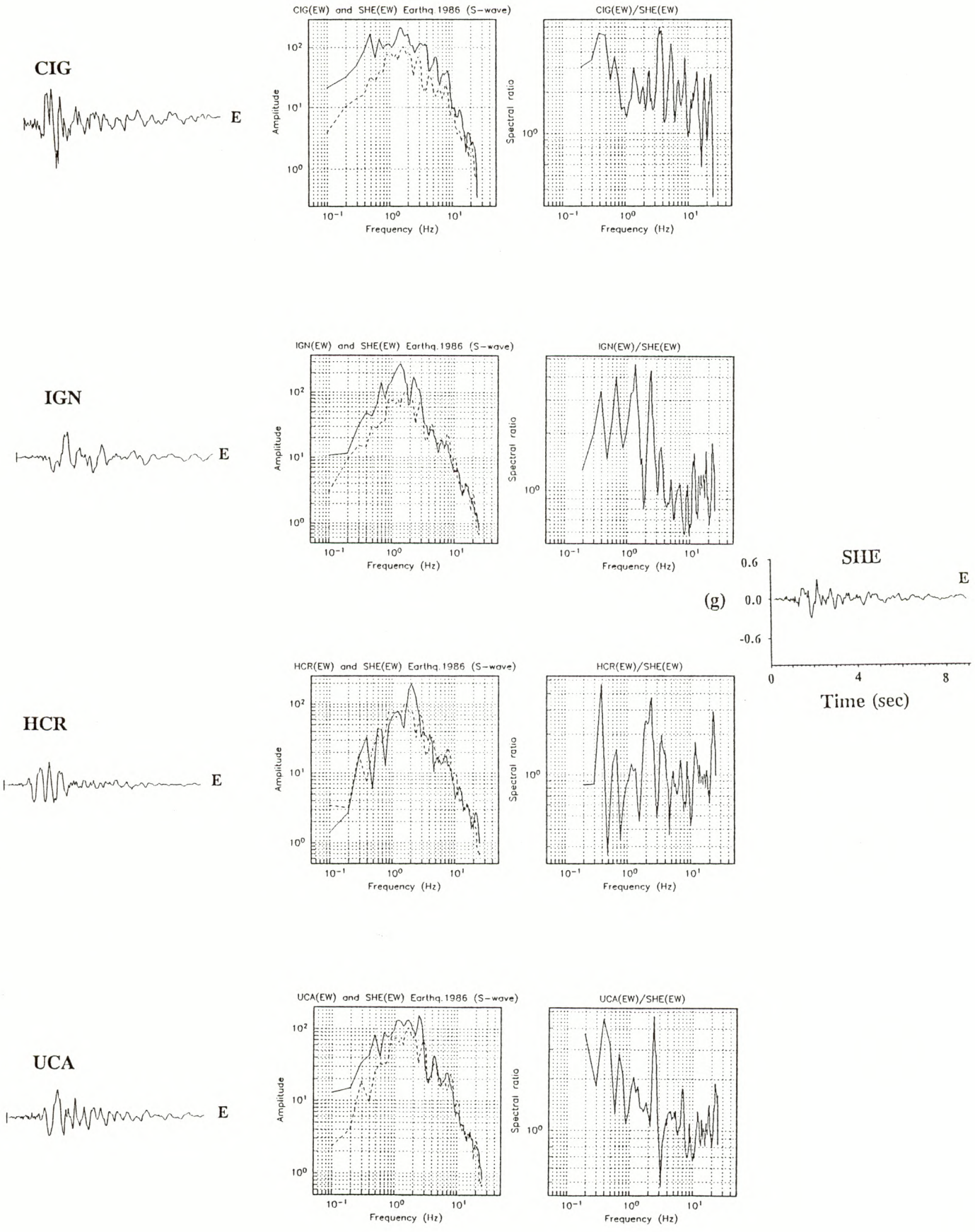

CIG
E
CIG(EW) and SHE(EW) Earthq.1986 (S-wave)
CIG(EW)/SHE(EW)
Amplitude
Spectral ratio
Frequency (Hz)
IGN
E
IGN(EW) and SHE(EW) Earthq.1986 (S-wave)
IGN(EW)/SHE(EW)
(g)
SHE
E
0.6
0.0
-0.6
0
4
8
Time (sec)
HCR
E
HCR(EW) and SHE(EW) Earthq.1986 (S-wave)
HCR(EW)/SHE(EW)
UCA
E
UCA(EW) and SHE(EW) Earthq.1986 (S-wave)
UCA(EW)/SHE(EW)

Figure 7.

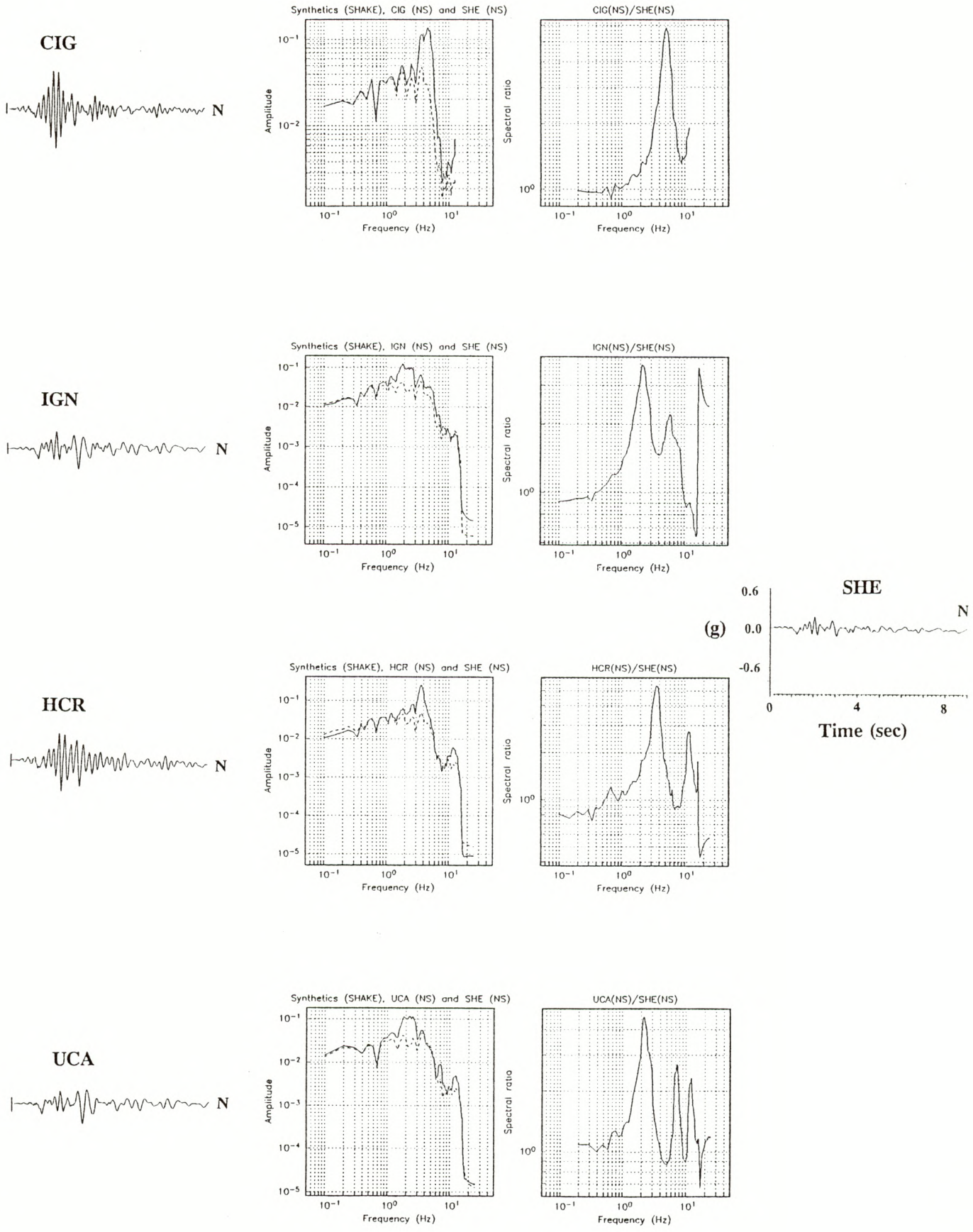

CIG
N
Synthetics (SHAKE), CIG (NS) and SHE (NS)
CIG(NS)/SHE(NS)
IGN
N
Synthetics (SHAKE), IGN (NS) and SHE (NS)
IGN(NS)/SHE(NS)
HCR
N
Synthetics (SHAKE), HCR (NS) and SHE (NS)
HCR(NS)/SHE(NS)
UCA
N
Synthetics (SHAKE), UCA (NS) and SHE (NS)
UCA(NS)/SHE(NS)
Amplitude
Spectral ratio
Frequency (Hz)
(g)
SHE
N
0.6
0.0
-0.6
0
4
8
Time (sec)

Figure 8.

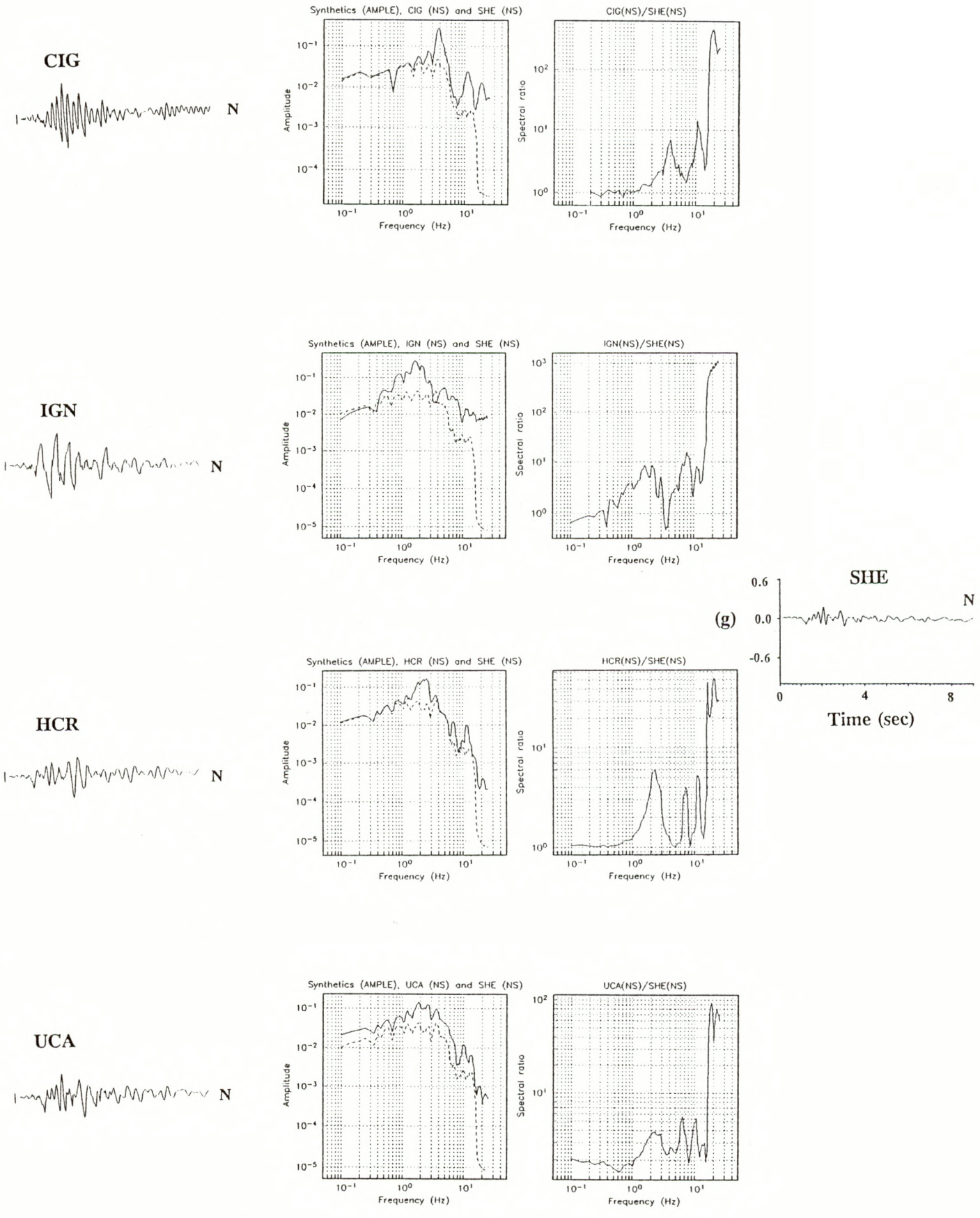

CIG
N
Synthetics (AMPLE), CIG (NS) and SHE (NS)
CIG(NS)/SHE(NS)
IGN
N
Synthetics (AMPLE), IGN (NS) and SHE (NS)
IGN(NS)/SHE(NS)
SHE
N
(g)
0.6
0.0
-0.6
0
4
8
Time (sec)
HCR
N
Synthetics (AMPLE), HCR (NS) and SHE (NS)
HCR(NS)/SHE(NS)
UCA
N
Synthetics (AMPLE), UCA (NS) and SHE (NS)
UCA(NS)/SHE(NS)
Amplitude
Spectral ratio
Frequency (Hz)

Figure 9.

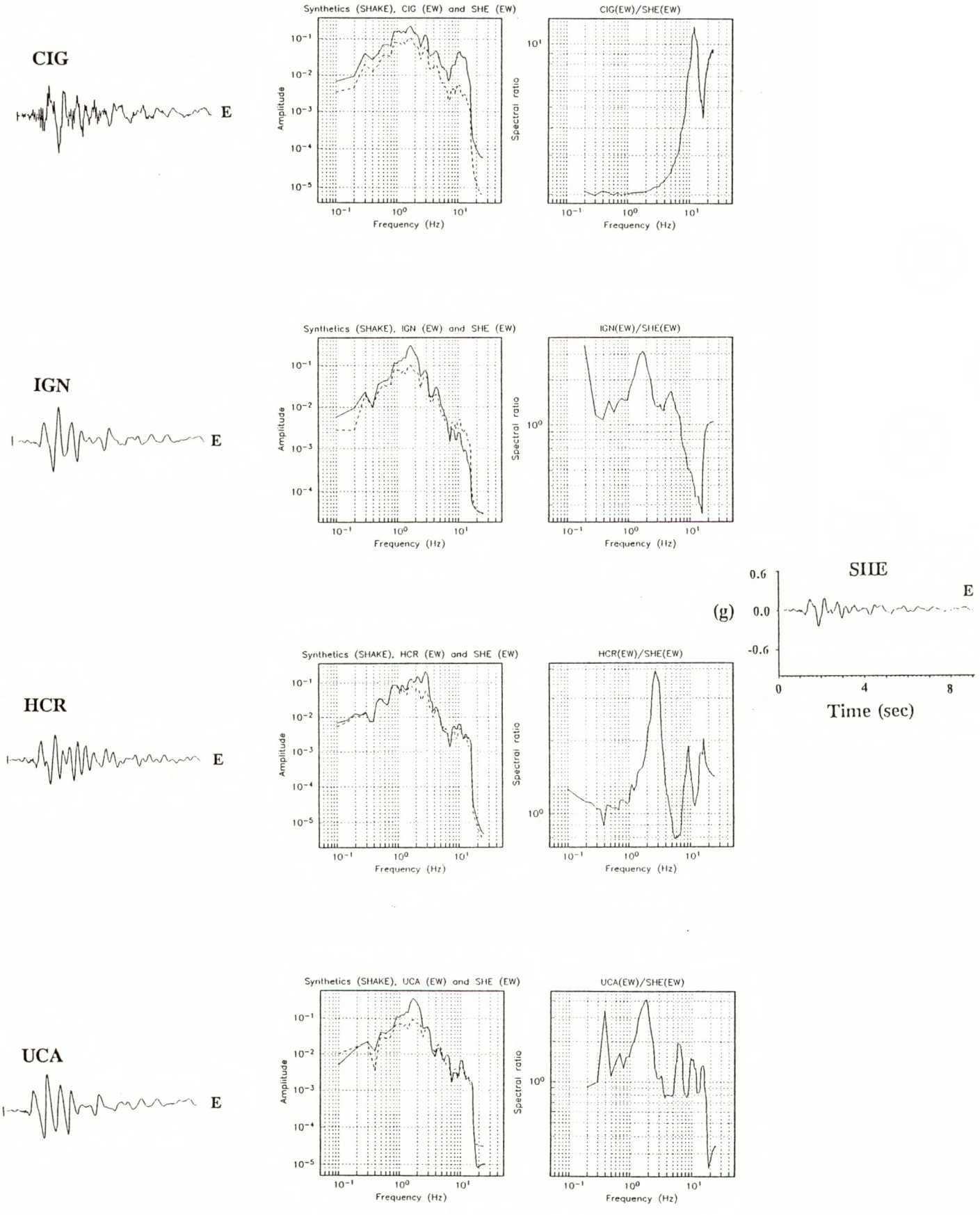

CIG
E
Synthetics (SHAKE), CIG (EW) and SHE (EW)
CIG(EW)/SHE(EW)
IGN
E
Synthetics (SHAKE), IGN (EW) and SHE (EW)
IGN(EW)/SHE(EW)
SHE
E
(g)
0.6
0.0
-0.6
0
4
8
Time (sec)
HCR
E
Synthetics (SHAKE), HCR (EW) and SHE (EW)
HCR(EW)/SHE(EW)
UCA
E
Synthetics (SHAKE), UCA (EW) and SHE (EW)
UCA(EW)/SHE(EW)
Amplitude
Spectral ratio
Frequency (Hz)

Figure 10.

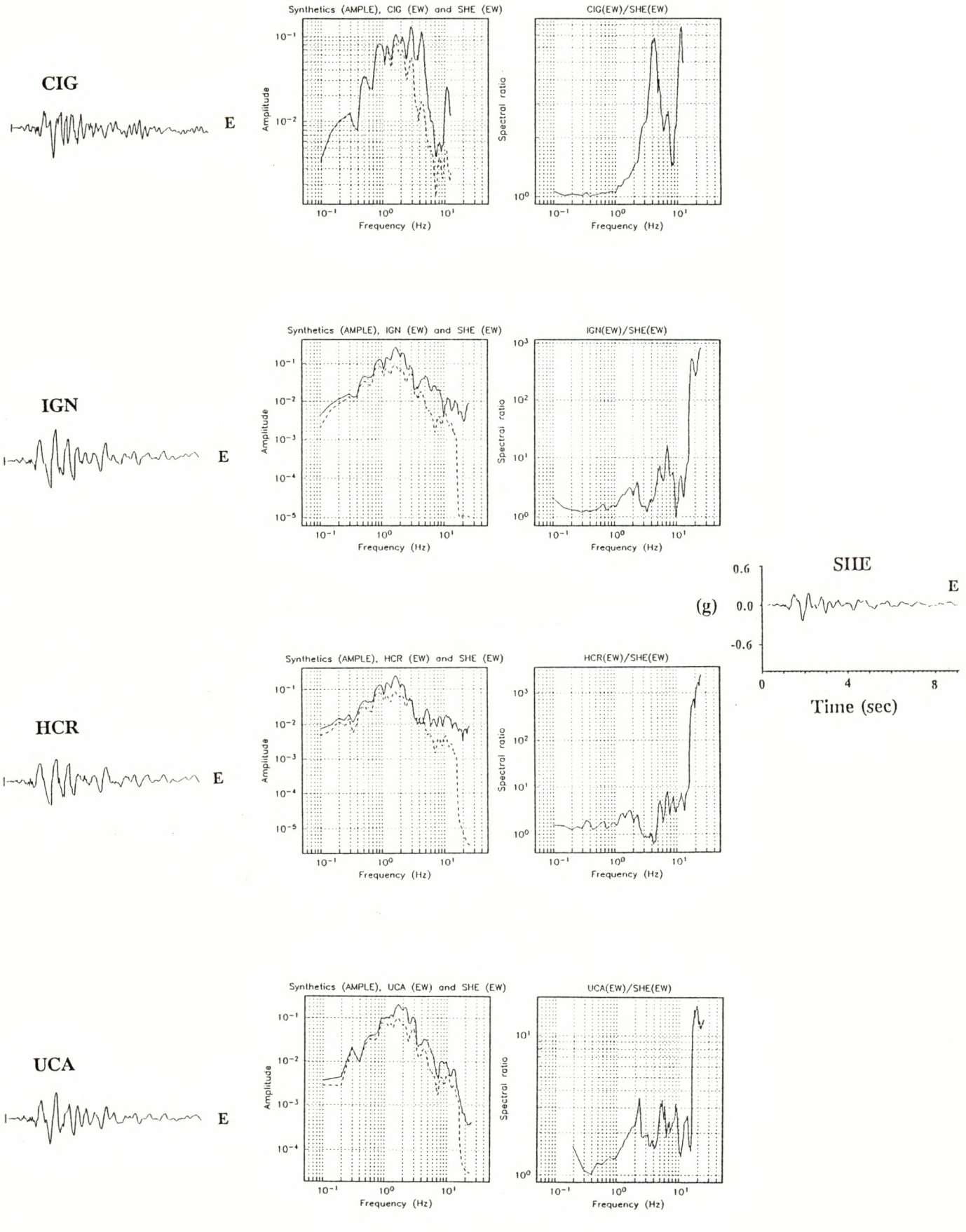
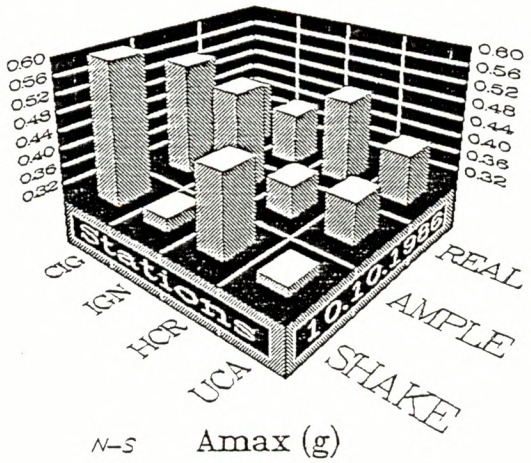

CIG
E
Synthetics (AMPLE), CIG (EW) and SHE (EW)
CIG(EW)/SHE(EW)
Amplitude
Spectral ratio
Frequency (Hz)
IGN
E
Synthetics (AMPLE), IGN (EW) and SHE (EW)
IGN(EW)/SHE(EW)
(g)
SHE
E
0.6
0.0
-0.6
0
4
8
Time (sec)
HCR
E
Synthetics (AMPLE), HCR (EW) and SHE (EW)
HCR(EW)/SHE(EW)
UCA
E
Synthetics (AMPLE), UCA (EW) and SHE (EW)
UCA(EW)/SHE(EW)

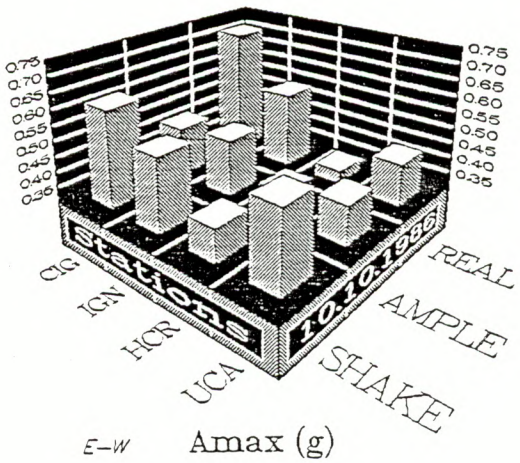
Figure 11.

a)



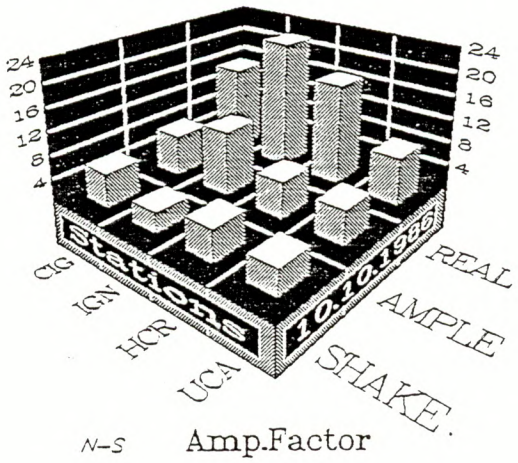
N–S Amax (g)

b)



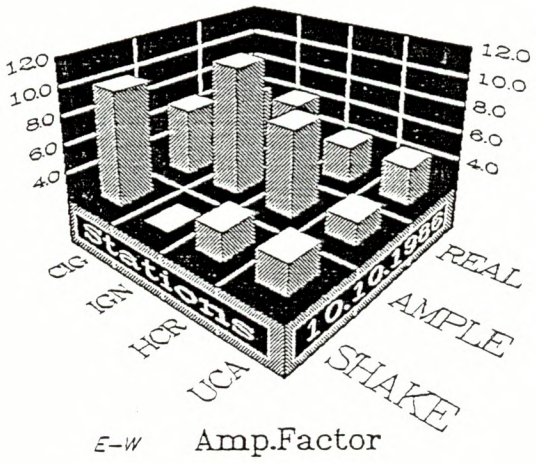
E–W Amax (g)

c)



N–S Amp.Factor

d)



E–W Amp.Factor

APPENDICES

Appendix 1.

```
11
'sherock.cns'
2048 0.02 2048 1  2048 1.0  0. 15.
30
7 0
20
7 7 'cig'
1 11 1 1.50 1.0 .02 1.20 144.60 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 2.45 1.0 .02 1.25 185.60 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 1 2.55 1.0 .02 1.30 214.70 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 1 1.00 1.0 .02 1.35 275.60 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 1 0.90 1.0 .02 1.40 305.70 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 11 1 1.55 1.0 .02 1.45 331.20 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
7 1  1 1.0  1.0 .00 2.20 2100   00. 00.
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
15 5. .65
50
1 2 3 4 5 6 7 0 0 0 0 0  0  0 0
1 1 1 1 1 1 0 0 0 0 0 0  0  0 0
1 0 0 0 0 0 0 0 0 0 0 0  0 0 0
0
```

```
11
'sherock.cns'
2048 0.02 2048 1 2048 1.0 0. 15.
30
13 0
20
8 8 'ign'
1 11 2 4.0 1.0 .02 1.55 179.32 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 0.5 1.0 .02 1.55 180.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 1 1.5 1.0 .02 1.65 190.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 2 2.5 1.0 .02 1.65 221.50 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 2 7.0 1.0 .02 1.65 236.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 11 2 4.0 1.0 .02 1.65 367.50 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
7 11 2 10.5 1.0 .02 1.70 431.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
8 1  1  1.0 1.0 0.00 2.2 1000.00 00. 0. 0
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 8 9 10 11 12 13 0 0
1 1 1 1 1 1 1 1 1  1  1  1  0 0 0
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0
```

Appendix 3.

```
11
'sherock.cns'
2048 0.02 2048 1  2048 1.5  0. 15.
30
12 0
20
8 12 'hcr'
1 11 1 1.50 1.0 .02 1.60 310.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 1.50 1.0 .02 1.60 310.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 1 2.30 1.0 .02 1.60 440.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 1 2.30 1.0 .02 1.60 440.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 2 3.80 1.0 .02 1.70 340.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 11 2 3.80 1.0 .02 1.70 340.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
7 11 3 6.00 1.0 .02 1.70 440.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
8 1  1 1.0  1.0  0  2.20 2100   0. 0.
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 8 9 10 11 12  0 0 0
1 1 1 1 1 1 1 1 1 1  1  0  0 0 0
1 0 0 0 0 0 0 0 0 0  0  0  0 0 0
0
```

Appendix 4.

```
11
'sherock.cns'
2048 0.02 2048 1  2048 1.0  0. 15.
30
11 0
20
6 6 'UCA'
1 11 2 4.0  1.0 .02 1.65 374.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 1.0  1.0 .02 1.65 440.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 2 5.0  1.0 .02 1.65 533.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 2 2.5  1.0 .02 1.65 615.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 3 31.5 1.0 .02 1.65 500.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 1 1 1.0 1.0 0.00  2.2 2000.00 00. 1.0
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 8 9 10 11  0  0 0 0
1 1 1 1 1 1 1 1 1 1 1   0  0  0 0 0
1 0 0 0 0 0 0 0 0 0 0   0  0  0 0 0
0
```

```
SYNTHETIC RECORD IN SURFACE FOR CIG (NS) WITH AMPLE
   6  6    1
   0.2500    5.0000
   1     1    1.5000   1200.00   0.01000
   2     2    2.4500   1250.00   0.01000
   3     3    2.5500   1300.00   0.01000
   4     4    1.0000   1350.00   0.01000
   5     5    0.9000   1400.00   0.01000
   6     6    1.5500   1450.00   0.01000
  2200.00   2100.00
   1     2
  12500.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   2     2
  21500.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   3     2
  30000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   4     2
  51500.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   5     2
  65500.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   6     2
  79500.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
EARTHQUAKE OF SAN SALVADOR IN OCT. 10th 1986.
 2048      0.020     0.1681
   1
   1
```

```
SYNTHETIC RECORD IN SURFACE FOR IGN (NS) WITH AMPLE
  12   12    1
  0.2500    5.0000
   1    1   2.0000   1550.00   0.01000
   2    2   2.0000   1550.00   0.01000
   3    3   0.5000   1550.00   0.01000
   4    4   1.5000   1650.00   0.01000
   5    5   1.2500   1650.00   0.01000
   6    6   1.2500   1650.00   0.01000
   7    7   3.5000   1650.00   0.01000
   8    8   3.5000   1650.00   0.01000
   9    9   2.0000   1650.00   0.01000
  10   10   2.0000   1650.00   0.01000
  11   11   5.2500   1700.00   0.01000
  12   12   5.2500   1700.00   0.01000
  2200.00   1000.00
   1    2
  33000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   2    2
  33000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   3    2
  33000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   4    2
  40000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   5    2
  50000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   6    2
  58000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   7    2
  61000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   8    2
  62000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
   9    2
 116000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
  10    2
 185000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
  11    2
 210000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
  12    2
 210000.0   400.00    0.000    0.00    0.000    0.00    0.000    0.00
EARTHQUAKE OF SAN SALVADOR IN OCT. 10th 1986.
 2048     0.020    0.1681
   1
   1
```

```
SYNTHETIC RECORD IN SURFACE FOR HCR WITH AMPLE PRO
   11   11     1
    0.2500     5.0000
    1    1     1.5000    1440.00    0.02000
    2    2     1.5000    1440.00    0.02000
    3    3     2.3000    1440.00    0.02000
    4    4     2.3000    1440.00    0.02000
    5    5     1.9000    1530.00    0.02000
    6    6     1.9000    1530.00    0.02000
    7    7     1.9000    1530.00    0.02000
    8    8     1.9000    1530.00    0.02000
    9    9     2.0000    1530.00    0.02000
   10   10     2.0000    1530.00    0.02000
   11   11     2.0000    1530.00    0.02000
   2200.00    2100.00
    1    2
   38000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    2    2
   38000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    3    2
   77000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    4    2
   77000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    5    2
   49000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    6    2
   49000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    7    2
   49000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    8    2
   49000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
    9    2
   82000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
   10    2
   82000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
   11    2
   82000.0      100.00      0.000       0.00      0.000       0.00
 0.000       0.00
EARTHQUAKE OF SAN SALVADOR OCT. 10th. 1986.
 2048      0.020     0.1681
    1
    1
```

```
SYNTHETIC RECORD IN SURFACE FOR UCA (NS) WITH AMPLE
   13   13    1
   0.2500    3.0000
    1    1   2.0000   1650.00   0.02000
    2    2   2.0000   1650.00   0.02000
    3    3   1.0000   1650.00   0.02000
    4    4   2.5000   1650.00   0.02000
    5    5   2.5000   1650.00   0.02000
    6    6   1.2500   1650.00   0.02000
    7    7   1.2500   1650.00   0.02000
    8    8   5.2500   1650.00   0.02000
    9    9   5.2500   1650.00   0.02000
   10   10   5.2500   1650.00   0.02000
   11   11   5.2500   1650.00   0.02000
   12   12   5.2500   1650.00   0.02000
   13   13   5.2500   1650.00   0.02000
  2200.00   1000.00
    1    2
  48000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    2    2
  68000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    3    2
  80000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    4    2
 140000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    5    2
  97000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    6    2
 134000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    7    2
 180000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    8    2
 264000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
    9    2
 305000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
   10    2
 312000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
   11    2
 319000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
   12    2
 327000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
   13    2
 334000.0    400.00     0.000     0.00     0.000     0.00     0.000     0.00
EARTHQUAKE OF SAN SALVADOR IN OCT. 10th 1986.
 2048     0.020     0.1681
    1
    1
```

```
11
'sherock.cew'
2048 0.02 2048 1 2048 2.0 0. 15.
30
7 0
20
7 7 'cig'
1 11 1 1.50 1.0 .02 1.45 289.2  00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 2.45 1.0 .02 1.50 371.2  00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 1 2.55 1.0 .02 1.55 429.4  00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 1 1.00 1.0 .02 1.60 551.2  00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 1 0.90 1.0 .02 1.65 611.4  00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 11 1 1.55 1.0 .02 1.70 662.4  00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
7 1  1 1.0  1.0 .00 2.20 2100   00. 00.
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 0 0 0 0 0 0 0 0
1 1 1 1 1 1 0 0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0
```

```
11
'sherock.cew'
2048 0.02 2048 1 2048 1.0 0. 15.
30
13 0
20
8 8 'ign'
1 11 2 4.0 1.0 .02 1.55 179.32 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 0.5 1.0 .02 1.55 180.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 1 1.5 1.0 .02 1.65 190.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 2 2.5 1.0 .02 1.65 221.50 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 2 7.0 1.0 .02 1.65 236.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 11 2 4.0 1.0 .02 1.65 367.50 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
7 11 2 10.5 1.0 .02 1.70 431.00 00. 2.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
8 1  1  1.0 1.0 0.00 2.2 1000.00 00. 0. 0
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 8 9 10 11 12 13 0 0
1 1 1 1 1 1 1 1 1  1  1  1  0 0 0
1 0 0 0 0 0 0 0 0  0  0  0  0 0 0
0
```

```
11
'sherock.cew'
2048 0.02 2048 1  2048 1.0  0. 15.
30
12 0
20
8 12 'HCR'
1 11 1 1.50 1.0 .02 1.60 263.50 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 1.50 1.0 .02 1.60 263.50 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 1 2.30 1.0 .02 1.60 374.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 1 2.30 1.0 .02 1.60 374.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 2 3.80 1.0 .02 1.70 289.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 11 2 3.80 1.0 .02 1.70 289.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
7 11 3 6.00 1.0 .02 1.70 374.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
8 1  1 1.0  1.0  0  2.20 1000   0. 0.
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 8 9 10 11 12  0 0 0
1 1 1 1 1 1 1 1 1 1   1  0  0 0 0
1 0 0 0 0 0 0 0 0 0   0  0  0 0 0
0
```

```
11
'sherock.cew'
2048 0.02 2048 1  2048 1.0  0. 15.
30
11 0
20
6 6 'UCA'
1 11 2 4.0  1.0 .02 1.65 374.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
2 11 1 1.0  1.0 .02 1.65 440.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
3 11 2 5.0  1.0 .02 1.65 533.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
4 11 2 2.5  1.0 .02 1.65 615.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
5 11 3 31.5 1.0 .02 1.65 500.00 00. 1.0
  0 0. 0. 0.  0 0. 0. 0.  0. 0.  0.5
6 1 1 1.0 1.0 0.00  2.2 2000.00 00. 1.0
25
1
11 'SILT'
1.0 1.0 .98 .94 .83 .63 .37 .20 .10 .07 .05
1.5 1.5 1.5 1.8 2.4 4.0 7.0 11.6 14. 24. 30.
40
5 5. .65
50
1 2 3 4 5 6 7 8 9 10 11  0  0 0 0
1 1 1 1 1 1 1 1 1 1   0  0  0 0 0
1 0 0 0 0 0 0 0 0 0   0  0  0 0 0
0
```

```
SYNTHETIC RECORD IN SURFACE FOR CIG WITH AMPLE PRO
    6     6     1
    0.2500     5.0000
    1     1     1.5000    1200.00    0.01000
    2     2     2.4500    1250.00    0.01000
    3     3     2.5500    1300.00    0.01000
    4     4     1.0000    1350.00    0.01000
    5     5     0.9000    1400.00    0.01000
    6     6     1.5500    1450.00    0.01000
   2200.00    2100.00
    1     2
   12500.0     400.00      0.000       0.00      0.000       0.00
 0.000       0.00
    2     2
   21500.0     400.00      0.000       0.00      0.000       0.00
 0.000       0.00
    3     2
   30000.0     400.00      0.000       0.00      0.000       0.00
 0.000       0.00
    4     2
   51500.0     400.00      0.000       0.00      0.000       0.00
 0.000       0.00
    5     2
   65500.0     400.00      0.000       0.00      0.000       0.00
 0.000       0.00
    6     2
   79500.0     400.00      0.000       0.00      0.000       0.00
 0.000       0.00
EARTHQUAKE IN SAN SALVADOR, OCT. 10th. 1986.
 2048      0.020     0.2551
    1
    1
```

```
SYNTHETIC RECORD IN SURFACE FOR IGN (EW) WITH AMPLE
  12   12    1
  0.2500    5.0000
   1    1   2.0000   1550.00   0.01000
   2    2   2.0000   1550.00   0.01000
   3    3   0.5000   1550.00   0.01000
   4    4   1.5000   1650.00   0.01000
   5    5   1.2500   1650.00   0.01000
   6    6   1.2500   1650.00   0.01000
   7    7   3.5000   1650.00   0.01000
   8    8   3.5000   1650.00   0.01000
   9    9   2.0000   1650.00   0.01000
  10   10   2.0000   1650.00   0.01000
  11   11   5.2500   1700.00   0.01000
  12   12   5.2500   1700.00   0.01000
 2200.00   1000.00
   1    2
 33000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   2    2
 33000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   3    2
 33000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   4    2
 40000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   5    2
 50000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   6    2
 58000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   7    2
 61000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   8    2
 62000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   9    2
116000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  10    2
185000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  11    2
210000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  12    2
210000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
EARTHQUAKE OF SAN SALVADOR IN OCT. 10th 1986.
 2048     0.020     0.2550
   1
   1
```

```
SYNTHETIC RECORD IN SURFACE FOR HCR (EW) WITH AMPL
   11   11     1
    0.2500     5.0000
    1     1     1.5000    1650.00    0.01000
    2     2     1.5000    1650.00    0.01000
    3     3     2.3000    1650.00    0.01000
    4     4     2.3000    1650.00    0.01000
    5     5     1.9000    1650.00    0.01000
    6     6     1.9000    1650.00    0.01000
    7     7     1.9000    1650.00    0.01000
    8     8     1.9000    1650.00    0.01000
    9     9     2.0000    1650.00    0.01000
   10    10     2.0000    1650.00    0.01000
   11    11     2.0000    1650.00    0.01000
   2200.00    2100.00
    1     2
   40000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    2     2
   40000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    3     2
   80000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    4     2
   80000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    5     2
   48000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    6     2
   48000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    7     2
   48000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    8     2
   48000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
    9     2
   80000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
   10     2
   80000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
   11     2
   80000.0     400.00      0.000       0.00      0.000       0.00
 0.000      0.00
EARTHQUAKE IN SAN SALVADOR OCT. 10th 1986.
 2048      0.020     0.2551
    1
    1
```

```
SYNTHETIC RECORD IN SURFACE FOR UCA (EW) WITH AMPLE
  13   13    1
  0.2500    3.0000
   1    1   2.0000   1650.00   0.02000
   2    2   2.0000   1650.00   0.02000
   3    3   1.0000   1650.00   0.02000
   4    4   2.5000   1650.00   0.02000
   5    5   2.5000   1650.00   0.02000
   6    6   1.2500   1650.00   0.02000
   7    7   1.2500   1650.00   0.02000
   8    8   5.2500   1650.00   0.02000
   9    9   5.2500   1650.00   0.02000
  10   10   5.2500   1650.00   0.02000
  11   11   5.2500   1650.00   0.02000
  12   12   5.2500   1650.00   0.02000
  13   13   5.2500   1650.00   0.02000
  2200.00   1000.00
   1    2
 48000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   2    2
 68000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   3    2
 80000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   4    2
140000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   5    2
 97000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   6    2
134000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   7    2
180000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   8    2
264000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
   9    2
305000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  10    2
312000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  11    2
319000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  12    2
327000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
  13    2
334000.0    400.00     0.000      0.00     0.000      0.00     0.000     0.00
EARTHQUAKE OF SAN SALVADOR IN OCT. 10th 1986.
 2048      0.020     0.2550
   1
   1
```