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TOPOGRAPHICAL AND GEOLOGICAL AMPLIFICATIONS DETERMINED FROM STRONG-MOTION AND AFTERSHOCK RECORDS OF THE 3 MARCH 1985 CHILE EARTHQUAKE

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ABSTRACT

Site-response experiments were performed 5 months after the $M_S = 7.8$ central Chile earthquake of 3 March 1985 to identify amplification due to topography and geology.

Topographical amplification at Canal Beagle, a subdivision of Viña del Mar, was hypothesized immediately after the main event, when extensive damage was observed on the ridges of Canal Beagle. Using frequency-dependent spectral ratios of aftershock data obtained from a temporarily established dense array, it is shown that there is substantial amplification of motions at the ridges of Canal Beagle. The data set constitutes the first such set depicting topographical amplification at a heavily populated region and correlates well with the damage distribution observed during the main event.

Dense arrays established in Viña del Mar also yielded extensive data which are quantified to show that, in the range of frequencies of engineering interest, there was substantial amplification at different sites of different geological formations. To substantiate this, spectral ratios developed from the strong-motion records of the main event are used to show the extensive degree of amplification at an alluvial site as compared to a rock site. Similarly, spectral ratios developed from aftershocks recorded at comparable stations qualitatively confirm that the frequency ranges for which the amplification of motions occur are quite similar to those from strong-motion records. In case of weak motions, the denser arrays established temporarily as described herein can be used to identify the frequency ranges for which amplification occurs, to quantify the degree of frequency-dependent amplification and used in microzonation of closely spaced localities.

INTRODUCTION

The 3 March 1985 Central Chile earthquake ($M_S = 7.8$) caused a variety of damages to structures in the townships of San Antonio, Melipilla, Valparaiso, and Viña del Mar as well as the capital, Santiago. The general location of the epicenter of the main shock and some of the important aftershocks and heavily affected areas are depicted in Figure 1.

At the coastal town of Viña del Mar, some engineered structures with unique architectural features suffered extensive damage. And at Canal Beagle, a subdivision of Viña del Mar, the damages inflicted on the three distinctive types of buildings, situated on a hilltop crowned by ridges and canyons, indicated specific ridge effects as a result of the earthquake. While the four-story buildings in the canyon did not suffer any damage and only two of the many single- and two-story buildings on top of the hill suffered minor damage, on the ridges all of the four- and five-story buildings were extensively damaged, some beyond repair. In Figure 2, a general location map of Viña del Mar, Canal Beagle and surroundings, latitudes and longitudes, as well as general topography and geology are shown.

The purpose of this paper is to present results related to topographical and geological amplifications using selected sets of aftershock data obtained from dense arrays established temporarily at Viña del Mar and its subdivision, Canal Beagle,

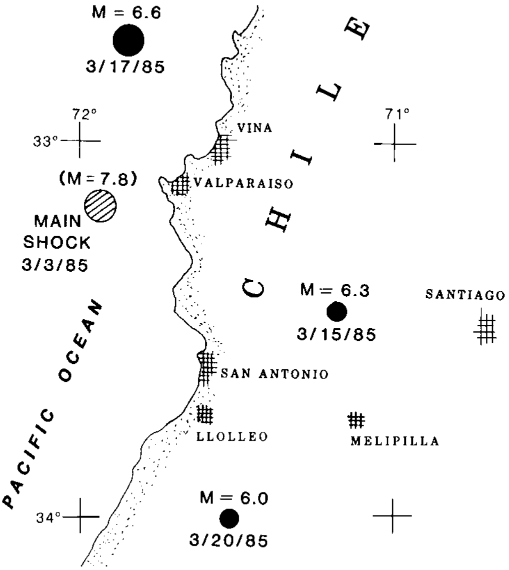

FIG. 1. Main population centers affected by the main shock and aftershock of the 3 March 1985 Chile earthquakes.

approximately 5 months after the main event. The data set from Canal Beagle represents the first such set of data depicting topographical amplification in a heavily populated area. The findings correlate well with the damage distribution observed after the main event. The scope of the paper includes description of the site-response experiments, the data obtained, and the identification of the topographical and geological amplifications as a function of frequency. The discussion of the geological amplification is further substantiated by using the spectra obtained from the strong-motion records of the Chilean strong-motion network (Saragoni *et al.*, 1985).

Previous theoretical and experimental studies on ridge effects were performed by a number of authors including Boore (1972, 1973), Davis and West (1983), and Bard and Tucker (1985). Shiga *et al.* (1979) have performed theoretical studies on effects of irregular geophysical features on seismic ground motions. The results of their study of the features, particularly of hills, display various degrees of freqency-dependent amplification of motion. Ridge effects have been observed in many hill towns of southern Italy during postearthquake studies of the Campania-Basilicata (Italy) earthquake of 1980 (Lagorio and Lager, 1981; Alexander, 1986). Steinbrugge, (1986, private communication) and Donovan (1986) have observed topographical effects in other parts of the world. The use of spectral ratios in describing amplification of ground motions at different sites is discussed by Gibbs and Borcherdt (1974) and Rogers *et al.* (1984).

Structural damage surveys related to the 3 March 1985 Chile earthquake is not intended herein. Detailed information on structural damage surveys have been documented by Çelebi (1985), Wyllie *et al.* (1986), and Monge *et al.* (1986). It is not intended to include extensive data sets related to the experiments either. These have been documented elsewhere (Çelebi, 1986).

In the site-response studies presented herein, the General Earthquake Observation System recorders and related peripherals were used. The General Earthquake Observation System is discussed in detail by Borcherdt *et al.* (1985). During the

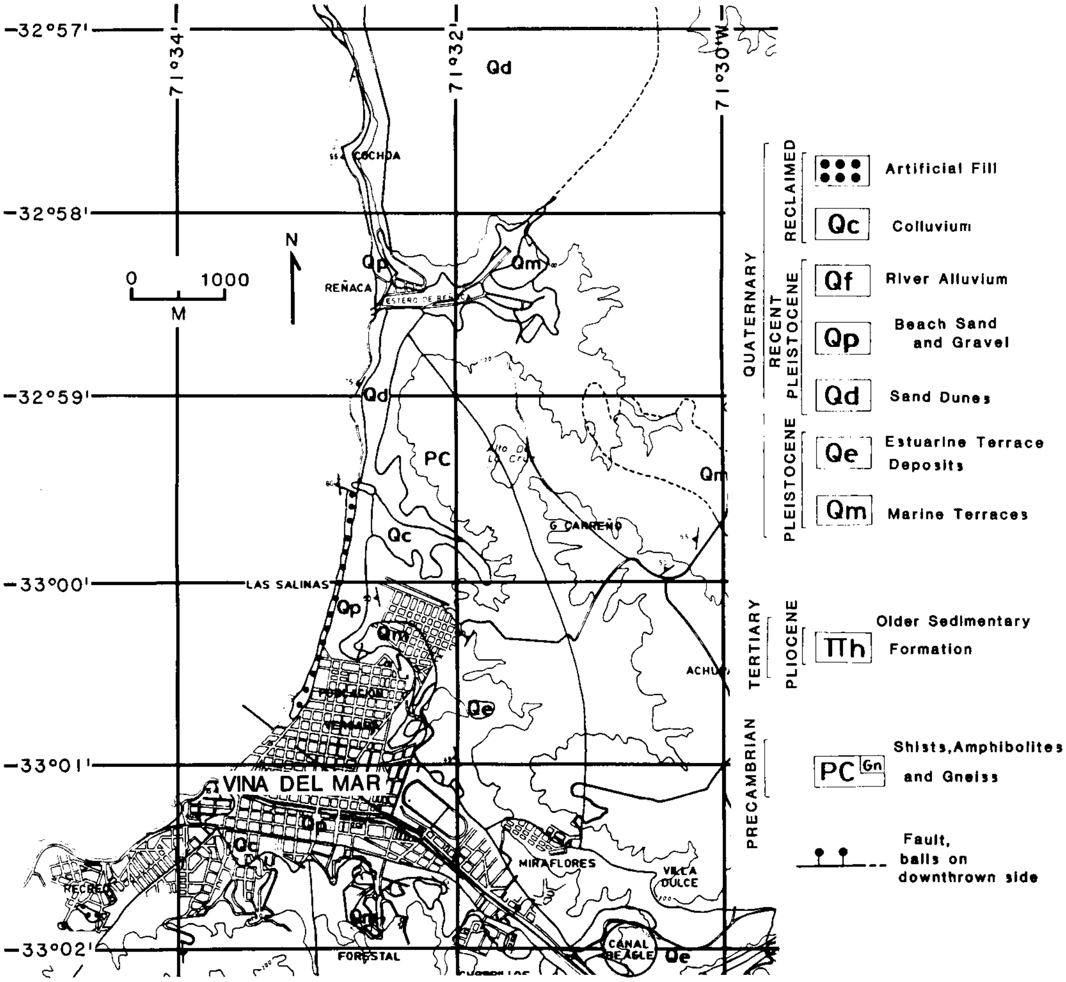

FIG. 2. General geology, topography, and coordinates of Viña del Mar, Canal Beagle, and Renecá on the central coast of Chile. Canal Beagle is circled.

course of these experiments, the three-component package Mark* Products L22–three-dimensional velocity transducers and the three-component package Kinemetrics* FBA–13 acceleration transducers were used.

ORGANIZATION OF THE PAPER

Since important results of two separate experiments are discussed in this paper, the manuscript will be divided into two parts: Part I will be devoted to topographical amplification at Canal Beagle, and Part II will be devoted to geological amplification at Viña del Mar.

PART I: TOPOGRAPHICAL AMPLIFICATION AT CANAL BEAGLE

Between 26 July and 10 August 1985, several aftershocks were recorded simultaneously in most of the stations established at Canal Beagle, as well as at two reference stations (MUN and VAL) in downtown Viña del Mar (an alluvial site)

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* These are commercial names of instruments used only and do not constitute endorsement of these products.

and at Valparaiso (an amphibolite gneiss rock site), respectively. Both reference stations were in the vicinity of the Chilean Strong-Motion Network stations. In Figure 3, the general layout of the Canal Beagle subdivision is shown; the three types of buildings and their locations are indicated. Also indicated in this figure are the ridges and the stations. In Figure 4, detailed topography and the locations of the stations (CBA-CBG) established at Canal Beagle are depicted. In Figure 5, location of reference station VAL is shown. The Canal Beagle subdivision stations (CBA-CBG) were all sited on alluvial deposits and decomposed granite (locally know at Maicillo). In selecting the particular sites of stations, care was taken to have representative ridge, canyon, and main hilltop locations in order to be able to distinguish the ridge effect. One of the ridges and the structures on it, as well as the geology, are depicted in Figure 6. A typical damaged structure and details of damage to structural components are shown in Figure 7. Typical profiles of the Canal Beagle area are shown in Figure 8. These profiles will be used in future work to perform theoretical studies of amplification of these ridges.

For the sake of brevity, only one typical set of velocity seismograms of one event at selected stations of Canal Beagle as well as the reference rock station, VAL, is provided in Figure 9. Referring even only to these seismograms whose components are plotted to the same scale, it is possible to distinguish that the ridges are subjected to amplified motions as compared to the canyon and reference rock station, VAL. Since the Canal Beagle stations are further away from the epicenter than the reference rock station, VAL, conservatively, the distance effect can be neglected; therefore, the spectral ratios of stations CBA/VAL provided in Figure 10 display the frequency-dependent geological amplification at Canal Beagle relative to the rock station in Valparaiso. On the other hand, since Canal Beagle stations are close to one another (see Figure 4 for scale) and all are sited on similar geology, the

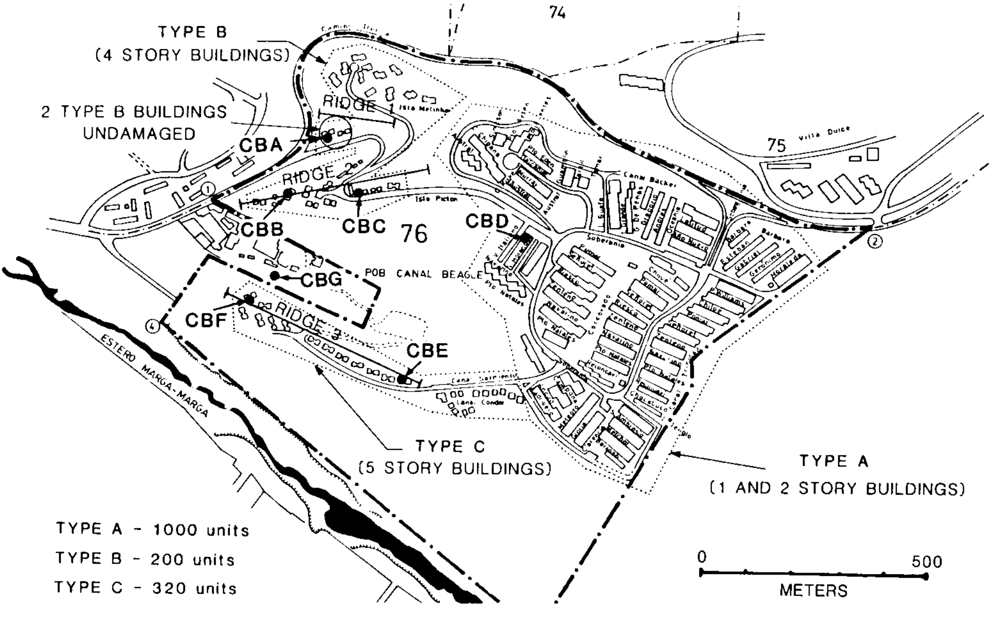

FIG. 3. General layout of the Canal Beagle subdivison. Types of buildings and their locations are indicated. Also, the locations of the temporary seismograph stations are shown.

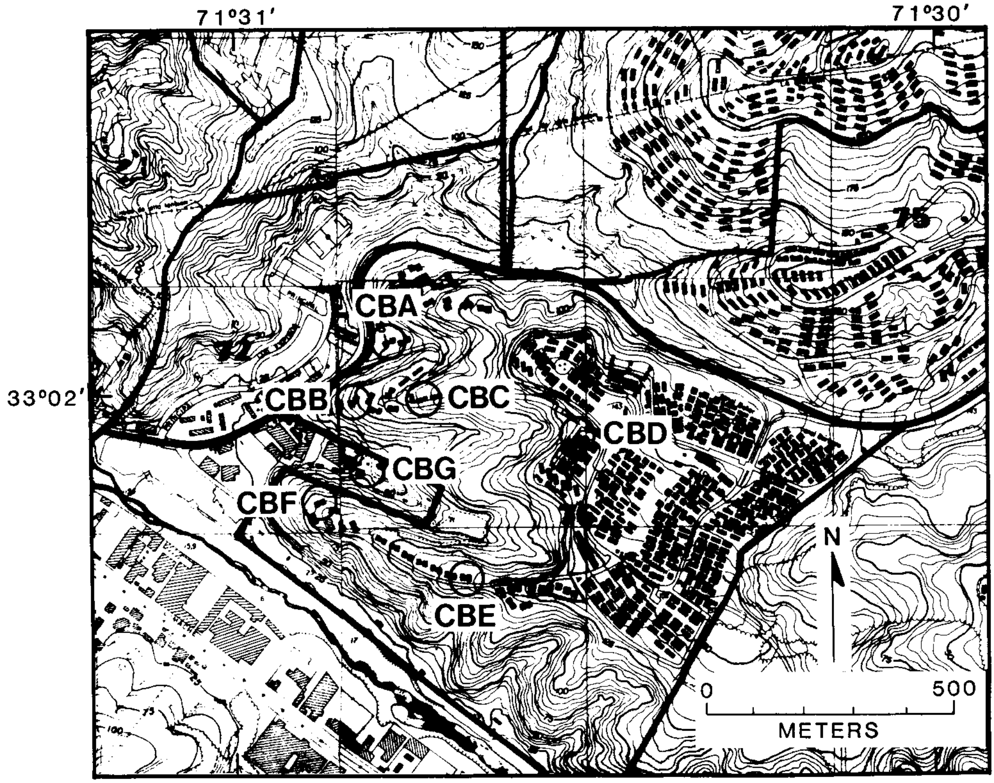

FIG. 4. Detailed topography of Canal Beagle. The ridge and the buildings on them as well as the stations established for aftershock studies are indicated. Details of contour lines are shown in Figure 8.

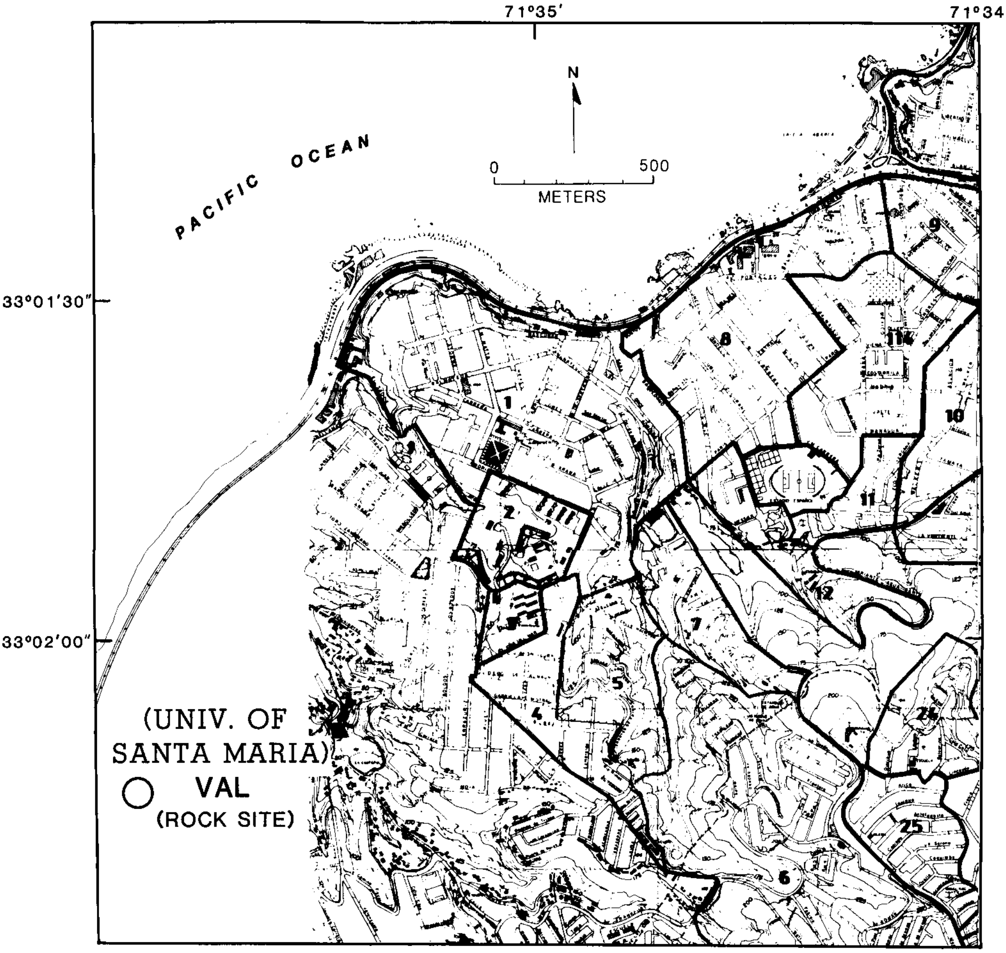

FIG. 5. Location of reference station VAL (same site of the accelerograph station of Chilean Strong-Motion Network).

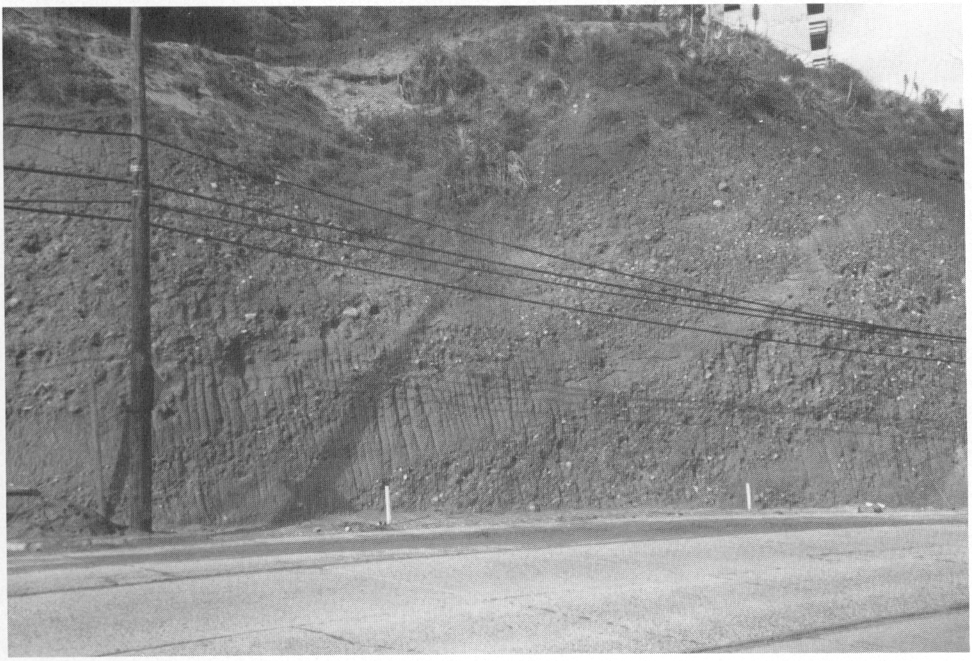

FIG. 6. One of the ridges of Canal Beagle and structures on it. The alluvial deposits of the ridge can be seen in this figure.

spectral ratio of motions at a ridge station with respect to the station CBA at the canyon represents the topographical amplification function, $T_t(\omega)$

$$T_t(\omega) = \frac{A_2(\omega)}{A_1(\omega)}$$

where $A_i(\omega)$ is the Fourier amplitude spectrum at station i. In Figure 11 (a to d), then, the frequency-dependent topographical amplification is clearly depicted in the spectral ratio plots (between 0 to 10 Hz) of stations on the ridges with respect to station CBA, which is in the canyon.

In general, the spectral ratios show that the frequency ranges for which horizontal amplification of motion occurs are 4 to 8 Hz for the canyon relative to the rock site (Figure 10) and 2 to 4 Hz as well as 8 Hz for the ridges of Canal Beagle relative to the canyon (Figure 11). The frequency range of 2 to 4 Hz is well within the fundamental frequencies of the four- and five-story buildings observed to be heavily damaged during the main event of 3 March 1985. On the other hand, the frequencies of the 2 four-story undamaged buildings in the canyon are outside the frequencies (4 to 8 Hz) for which amplification occurred in the canyon relative to the rock site. These spectral ratios (as well as others to follow) were smoothed with a triangular weighting function with width of 0.15 Hz. Other sets of velocity seismograms and spectral ratios related to topography of Canal Beagle are documented elsewhere (Çelebi, 1986). The spectral ratios of other events corresponding to each station indicate similarities and show repeatability of frequency-dependent amplification. This is clearly depicted in the superimposed spectral ratios from two or three events (as available) presented in Figure 12.

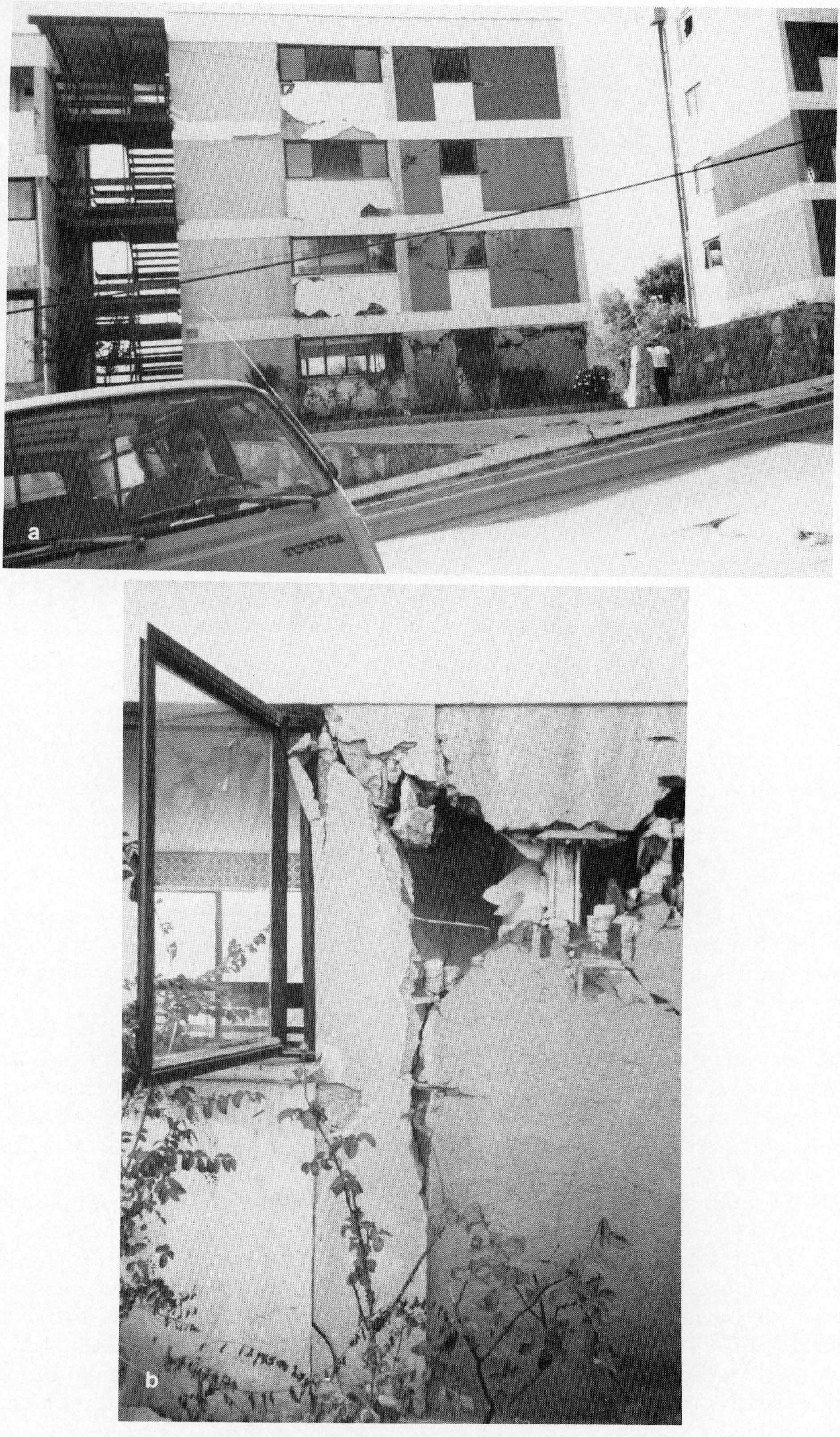

FIG. 7. (a) A typical damaged four-story building on a ridge and (b) close-up of damage to structural components.

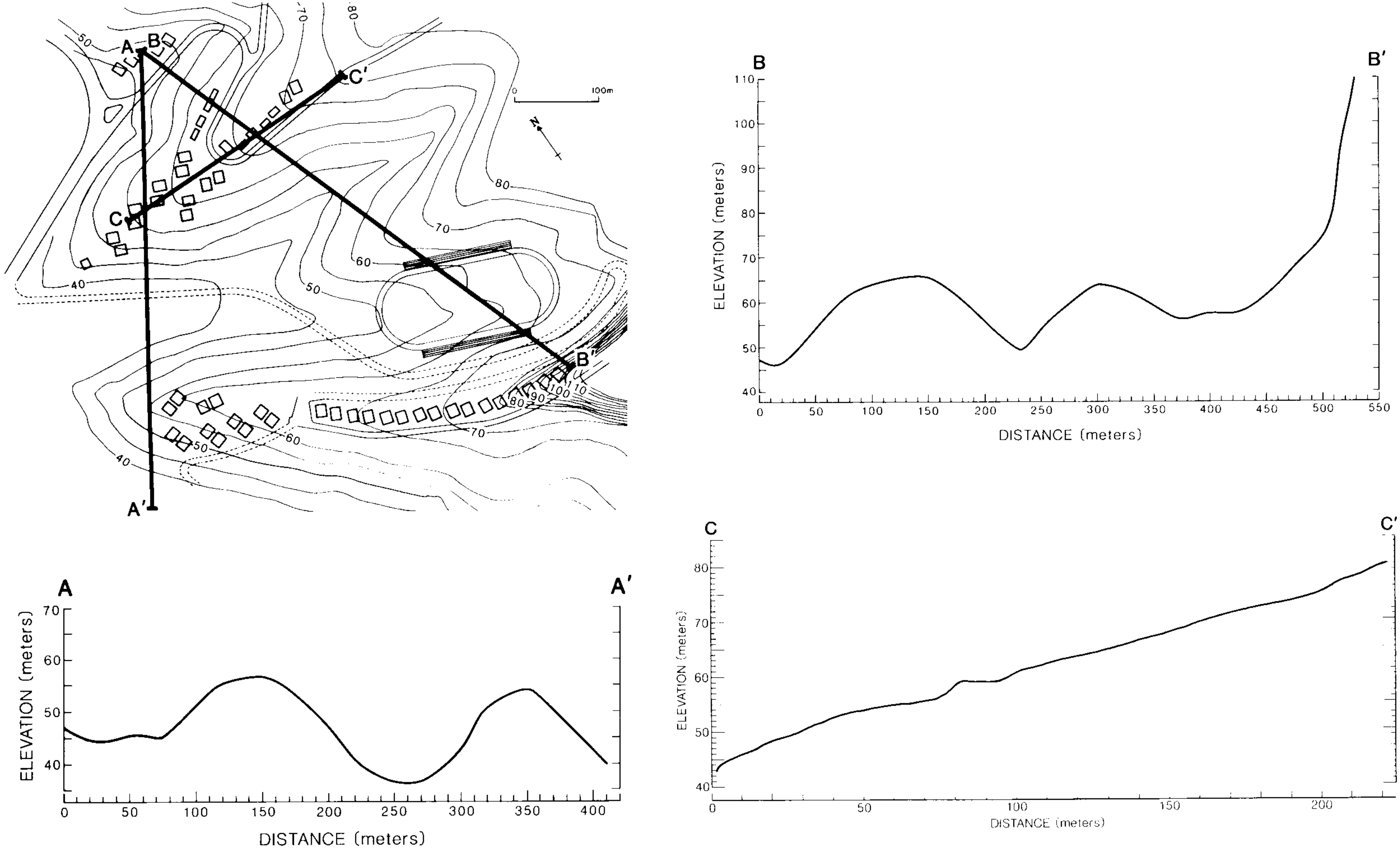

FIG. 8. Typical topography and profiles of Canal Beagle. Contour lines are provided in the general layout depicting the ridges and buildings.

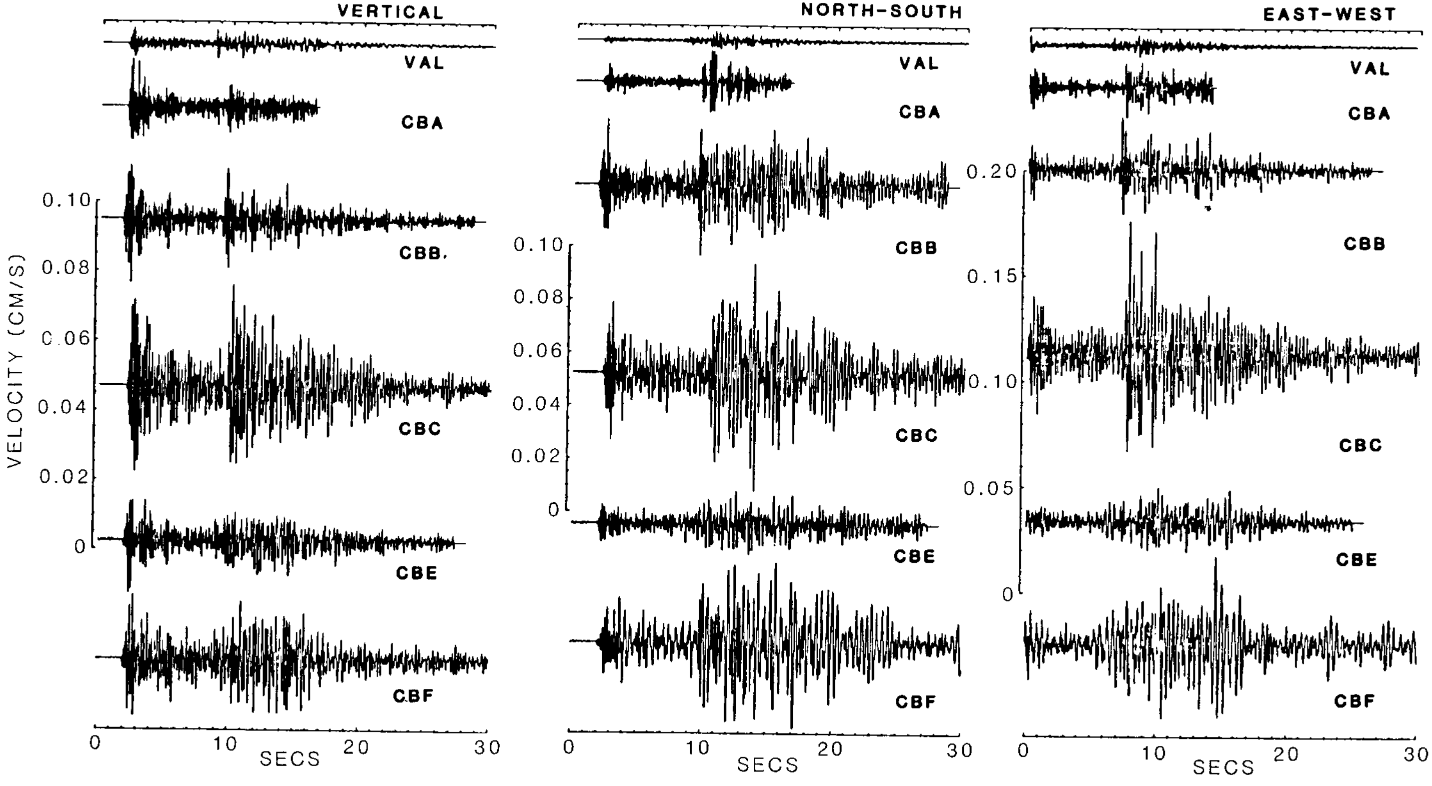

FIG. 9. A typical set of scaled velocity seismograms—event 2100652 corresponding to Julian 210 (29 July 1985) at 06:52 UTC—for the vertical and horizontal components, respectively, from the reference station VAL and Canal Beagle stations CBA, CBB, CBC, CBE, and CBF. Stations CBB, CBC, CBE, and CBF are on the ridges.

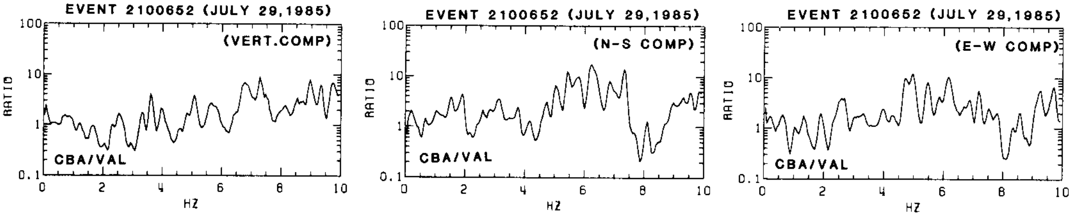

FIG. 10. Spectral ratios of event on 29 July 1985 (Julian 210) at 06:52 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations CBA/VAL.

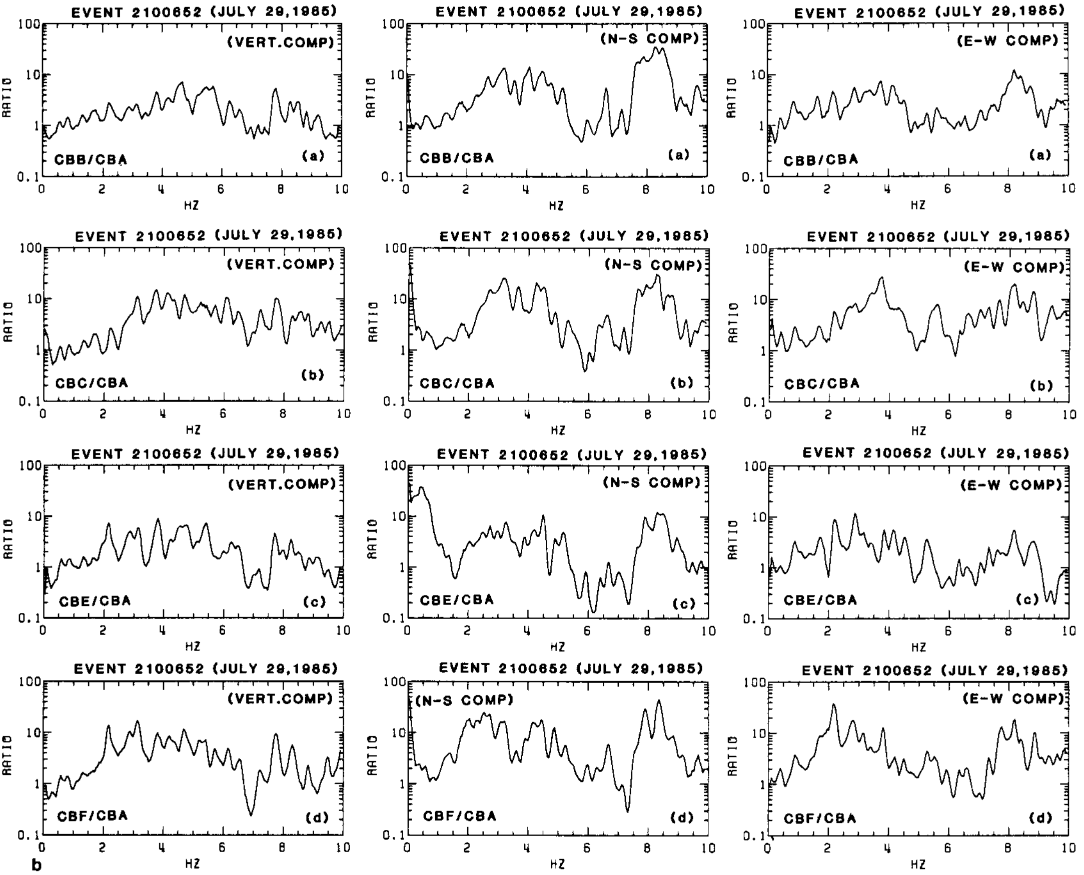

FIG. 11. (a) Spectral ratios of event on 29 July 1985 (Julian 210) at 06:52 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations CBB/CBA. Station CBB is on one of the ridges, and station CBA is in the canyon. Spectral ratios of event on 29 July 1985 (Julian 210) at 06:52 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations (b) CBC/CBA, (c) CBE/CBA, and (d) CFB/CBA. Stations CBC, CBE, and CBF are on the ridges.

Of particular interest are the spectral ratios in Figure 13 of the ridge stations relative to the rock site (VAL) station. These spectral ratios depict higher ordinates (amplification) due to the fact that they contain both topographical and geological effects while those spectral ratios in Figure 11 contain only topographical effects (ridge versus canyon). Qualitatively, the ridge versus rock station spectral ratios

(Figure 13) show peaks of horizontal amplification of motion around 3 Hz (as in Figure 11).

Ultimately, the spectral ratios can be used in microzonation of these sites or of similar sites with ridges. One such similar site in Viña del Mar is the subdivision of Gomez Carreño, which also suffered considerable damage during the 3 March 1985 event. Another site recently visited by the author is the La Foresta development in Santiago (approximately 120 km from the epicenter), where the homes on the ridges were damaged during the same event, while others on the flat areas were not.

PART II: GEOLOGICAL AND TOPOGRAPHICAL AMPLIFICATIONS IN VIÑA DEL MAR

Stations established in Viña del Mar are shown in Figures 14 and 15. The stations EAC, REN, and TRA were established at basements of three significant buildings (Edificio Acapulco, Edificio El Faro, and Edificio de Miramar), respectively, founded on sand (on the coast). Of these, Edificio Acapulco and Edificio El Faro were severely and extensively damaged during the main event. Edificio El Faro, built on sand dune hills of Renecá, had tilted due to crushing of first-floor shear walls and

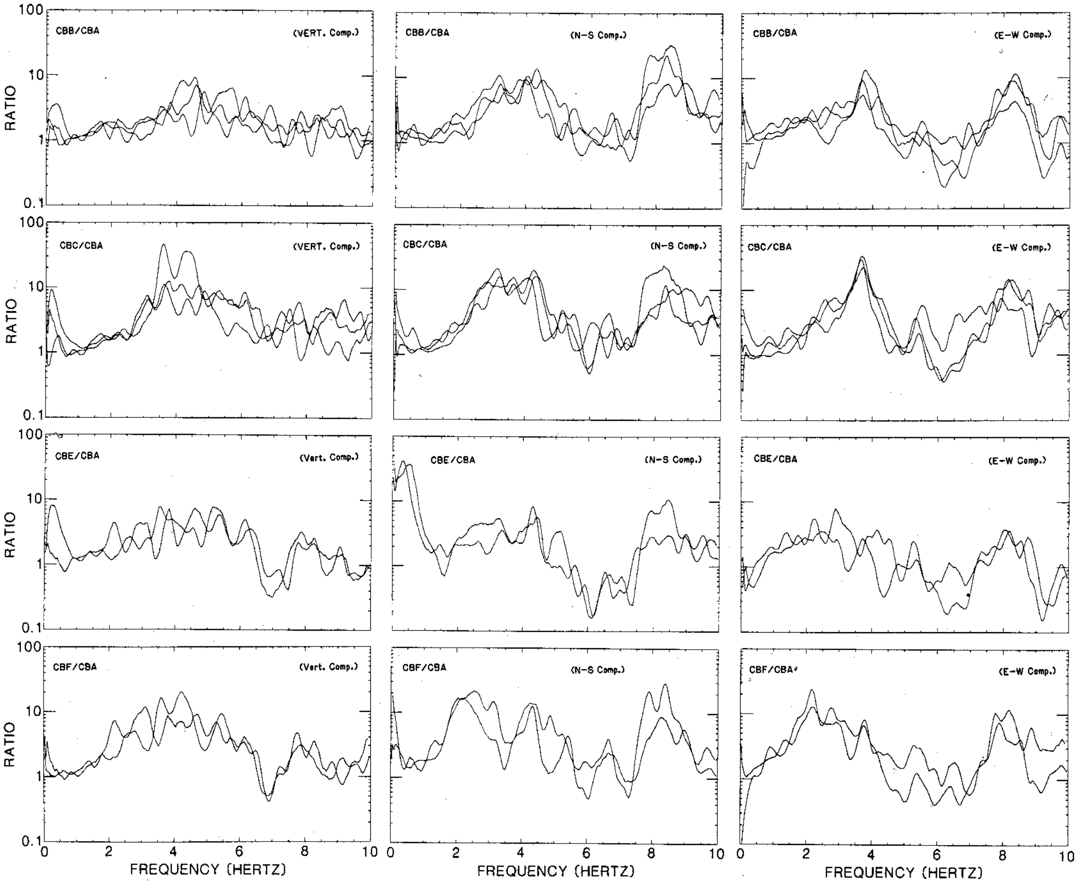

FIG. 12. Superimposed spectral ratios of two or three events (as available) at stations identified.

was later dynamited. Edificio de Miramar was not damaged. Alluvial-site station MUN (also a reference station) was located at the basement of the Municipality Building. Detailed pictures and descriptions of structural damages are documented elsewhere by Çelebi (1985, 1986), and Wyllie *et al.* (1986).

Figure 16 provides velocity seismograms (plotted to the same scale for each component) of a single event recorded at the stations mentioned above. These seismograms also show considerable amplification of motion at nonrock sites compared to the rock site (VAL). Figure 17 (a to d) show spectral ratio plots (between 0 to 10 Hz) of one event at each one of the stations listed above with respect to station VAL, respectively. Again, considerable frequency-dependent amplification of motions (particularly for frequencies of 1 to 4 Hz) at the sand and alluvial sites are displayed in these figures. Spectral ratios of stations REN/VAL reflect both geological and topographical effects and the others reflect only geological effects.

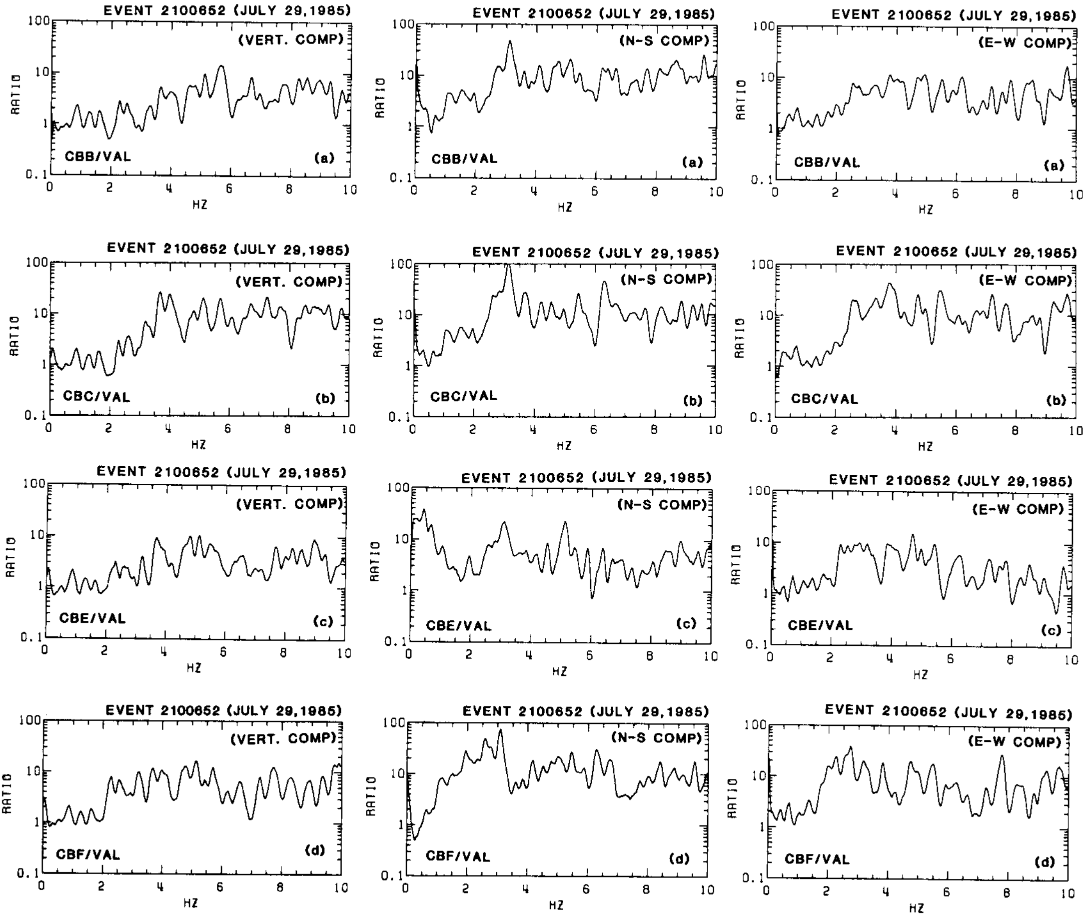

FIG. 13. Spectral ratios of events on 29 July 1985 (Julian 210) at 06:52 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations: (a) CBB/VAL, (b) CBC/VAL; (c) CBE/VAL; and (d) CBF/VAL.

AMPLIFICATION QUANTIFIED FROM THE STRONG-MOTION RECORDS OF 3 MARCH 1985

In Figure 18, the (vertical, N-S, and E-W components) spectral ratios developed from the main shock records of 3 March 1985 are shown for stations in Valparaiso (University of Santa Maria—a gneiss amphibolite rock site) and in Viña del Mar (an alluvial site). Only these two stations correspond to the dense array stations established temporarily for recording the aftershocks described earlier. The strong-motion data used to obtain the Fourier spectra and the spectral ratios have been obtained and digitized by the Chilean Strong-Motion Network operated by Saragoni *et al.* (1985). The seismogram and spectral ratio plots dramatically display the amplification of three-component motions at an alluvial site (near station MUN) with respect to a rock site (same as VAL) during the main strong-motion event and show peaks in the range of 0.5 to 1.5 sec. This same trend is exhibited in the weak-

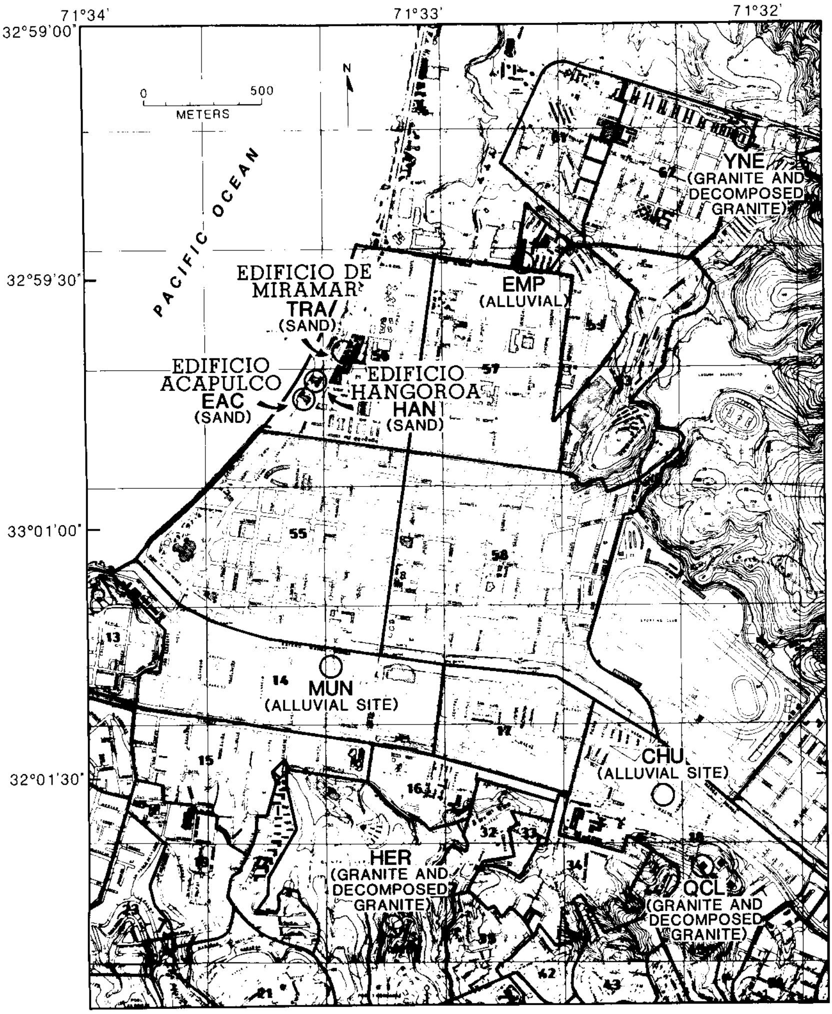

FIG. 14. Location of stations in Viña del Mar.

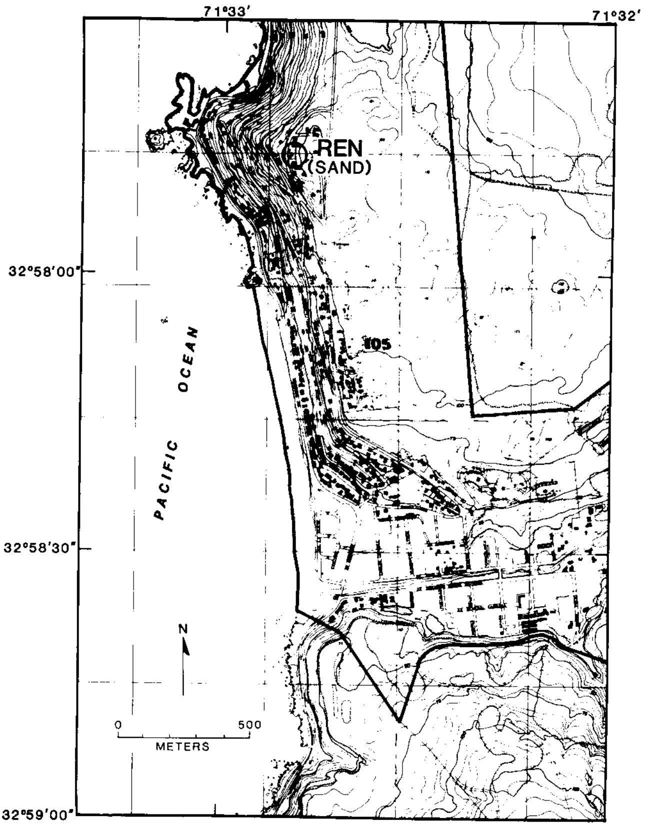

FIG. 15. Location of station REN in Renecá, a suburb of Viña del Mar.

motion spectral ratios corresponding to stations MUN/VAL presented in Figure 17d. Comparison of Figure 17d (weak-motion spectral ratios) and Figure 18 (strong-motion spectral ratios), at a minimum, qualitatively indicates that the weak-motion spectral ratios exhibit much greater amplification than the strong-motion spectral ratios. On the other hand, the frequency-dependent amplification of motions at Viña del Mar with respect to Valparaiso show amplification in similar frequency ranges for either strong or weak motions. However, any differences should be attributed to: (a) the Viña del Mar strong-motion data station is approximately 100 m from the weak-motion data station and therefore there is possibility of change of soil profile; (b) acceleration records of strong-motion data and velocity records of weak-motion data are used to obtain spectral ratios; (c) there was no time synchronization of the strong-motion data from Valparaiso and Viña del Mar and, therefore, the 77 sec of the strong-motion data used to obtain the spectral ratios provide only a qualitative spectral ratio and not an exact comparison; (d) the horizontal components of the strong-motion data have been rotated from their actual orientations to N-S and E-W directions to provide the comparison with the aftershock data; and (e) effect of possible nonlinear response of soil.

In addition, Figures 19 and 20 provide the relative velocity and absolute acceleration response spectra traced from plots of Saragoni *et al.* (1985) (only the 0 per cent damping spectra are traced for comparison purposes). Since the spectral ratios

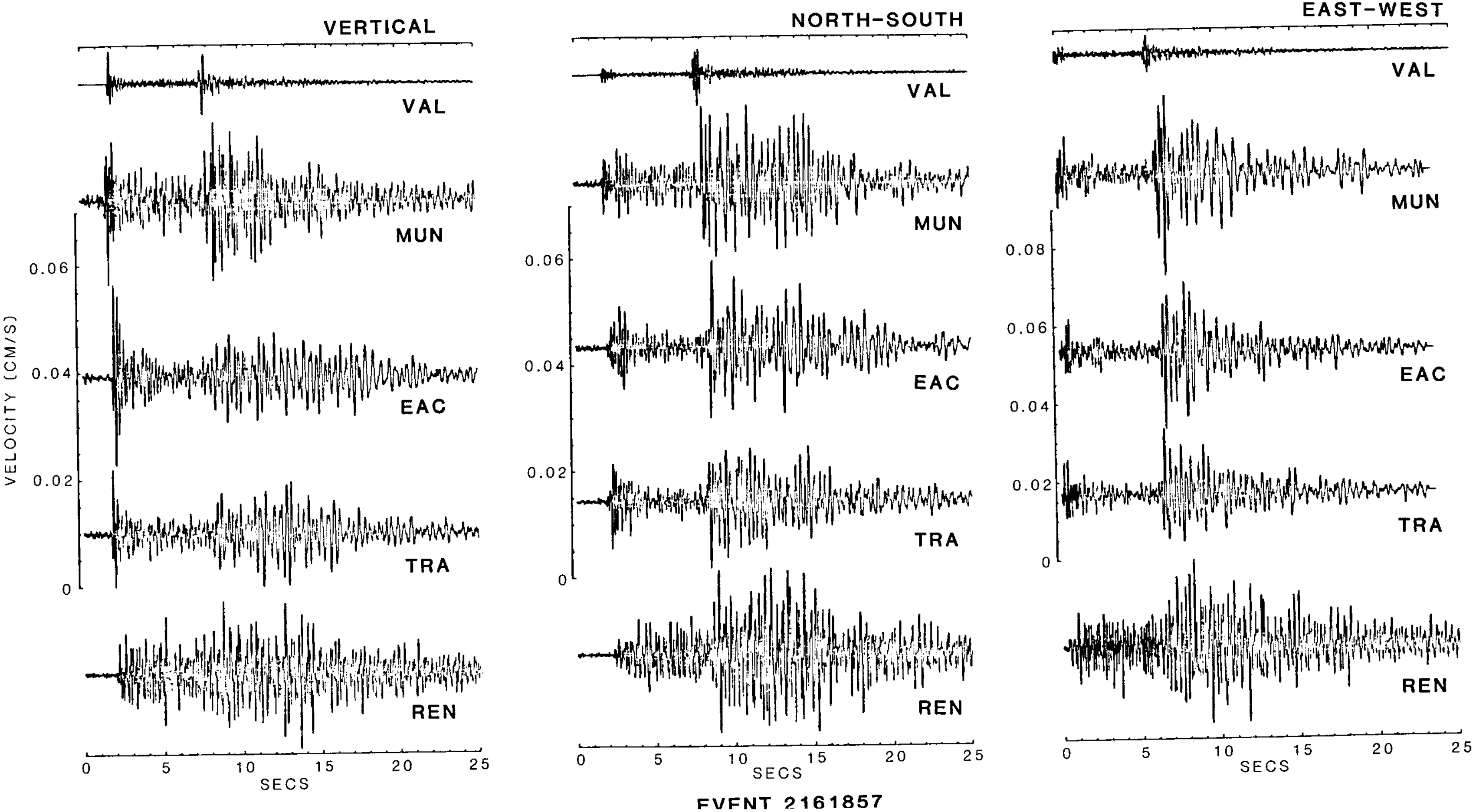

FIG. 16. A typical set of scaled velocity seismograms—event 2161857 corresponding to Julian 216 (4 August 1985) at 18:57 UTC—for the vertical and horizontal components, respectively, from reference stations VAL and MUN and stations EAC, TRA, and REN.

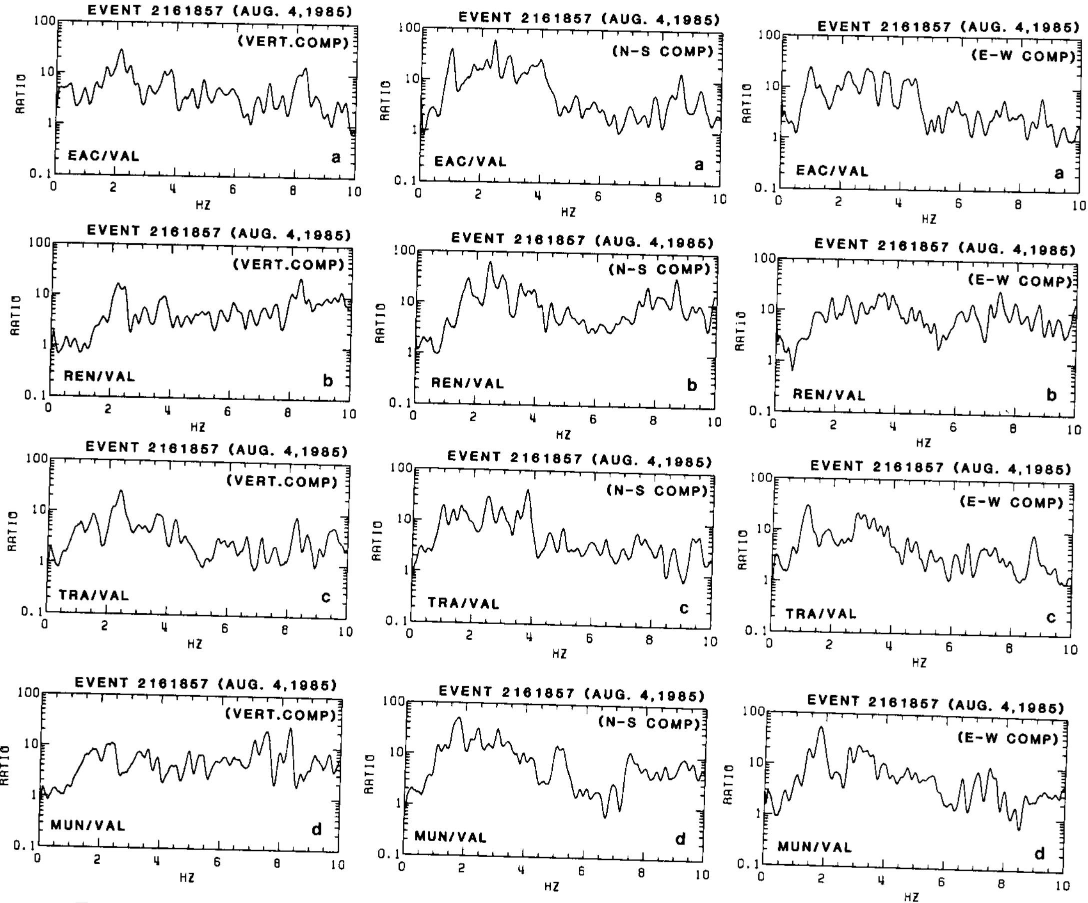

FIG. 17. (a) Spectral ratios of event on 4 August 1985 (Julian 216) at 18:57 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations EAC/VAL. (b) Spectral ratios of event on 4 August 1985 (Julian 216) at 18:57 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations REN/VAL. (c) Spectral ratios of event on 4 August 1985 (Julian 216) at 18:57 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations TRA/VAL. (d) Spectral ratios of event on 4 August 1985 (Julian 216) at 18:57 UTC for the vertical and horizontal components (N-S and E-W), respectively, of stations MUN/VAL.

from the weak-motion as well as the strong-motion data and the response spectra from the strong-motion data indicate the same trend of the frequency-dependent amplification at Viña del Mar with respect to Valparaiso, there is sufficient evidence to indicate that the spectral ratios from weak motions at other localities are valid just as well to identify those frequency ranges for which amplification of motions should be expected during strong-motion events. This point is further justified by the superimposed weak-motion spectral ratios of the ridges (Figure 12) which show good repeatability.

CONCLUSIONS

The objective of this paper is to demonstrate quantitatively and qualitatively the frequency-dependent amplification at sites with different geology and topography. By using the spectral ratios of motions obtained from aftershocks recorded at ridges and sites of differing geology, it can be asserted that amplification did take place

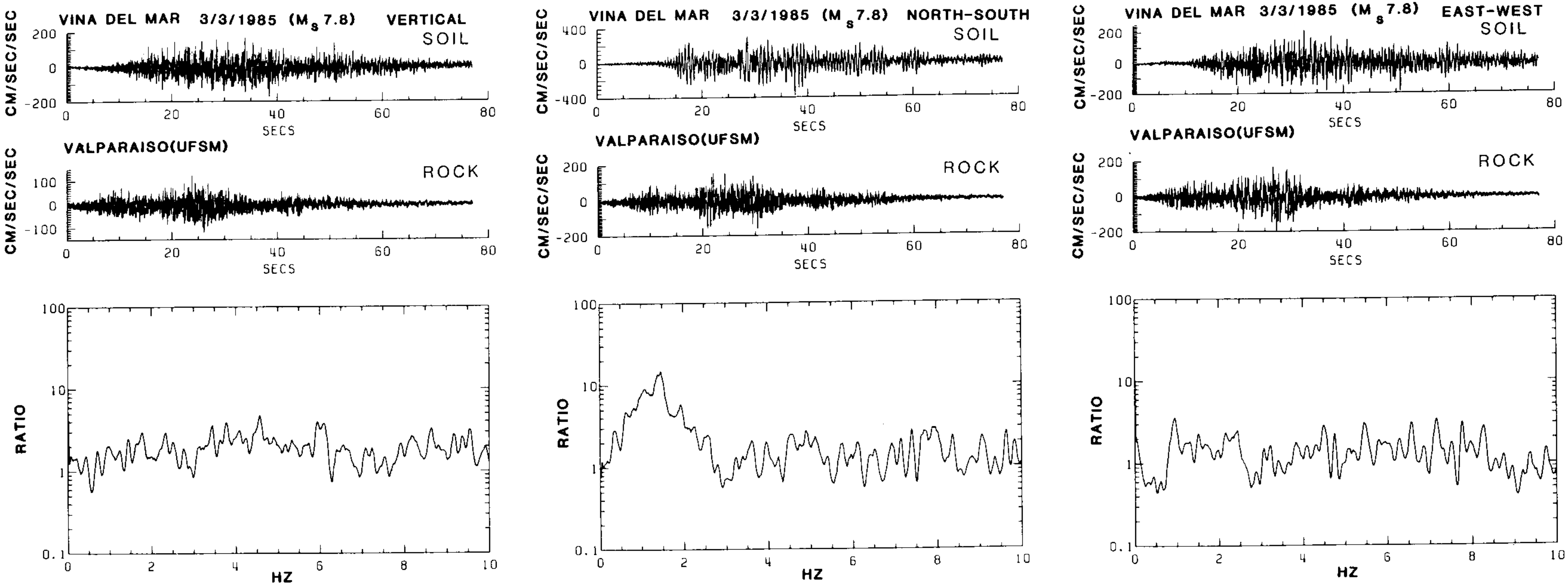

FIG. 18. Acceleration time histories (77-sec duration) and spectral ratios from records of the main event of 3 March 1985 ($M_S = 7.8$) for the vertical and horizontal (N-S and E-W) components, respectively, of stations Viña del Mar and Valparaiso (UFSM). The Valparaiso strong-motion station (rock site) is the same station as the temporary station established (VAL). The Viña del Mar strong-motion station is only one block (approximately 100 m) from the temporary station (MUN). Comparison of these spectral ratios with those of MUN/VAL (Figure 17d) qualitatively show amplification, particularly in low freqencies as determined from both strong-motion and weak-motion data.

during the occurrence of aftershocks as well as during the main shock. It must be remembered that observations of distribution of damage to structures on the ridges and at soft soil sites during the main event were the primary reason to look into the problems of amplification of motions in central Chile. This has been accomplished by recording the aftershocks and obtaining the spectral ratios. It is believed

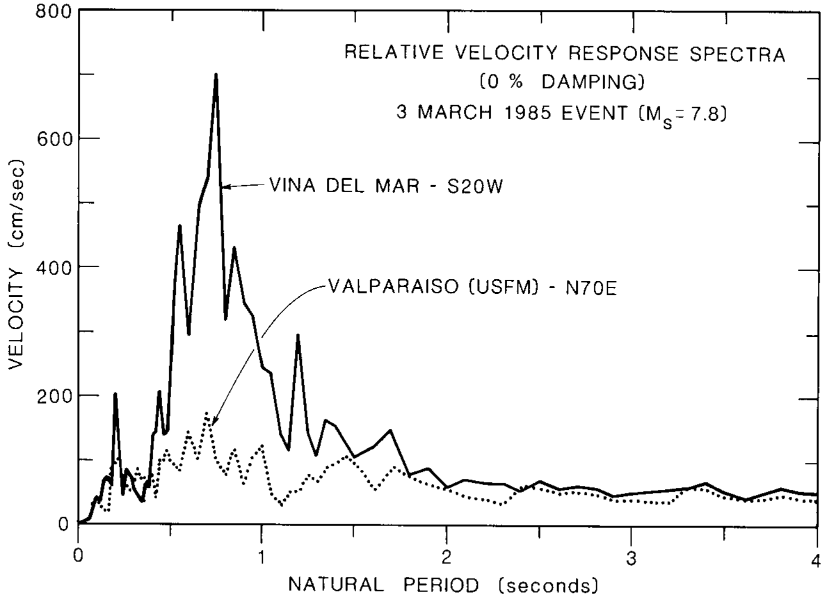

FIG. 19. Relative velocity (horizontal) response spectra (0 per cent damping) of records obtained at Valparaiso (rock site) and Vinña del Mar (alluvial site) during the main event of 3 March 1985 (M_S = 7.8) (from Saragoni *et al.*, 1985).

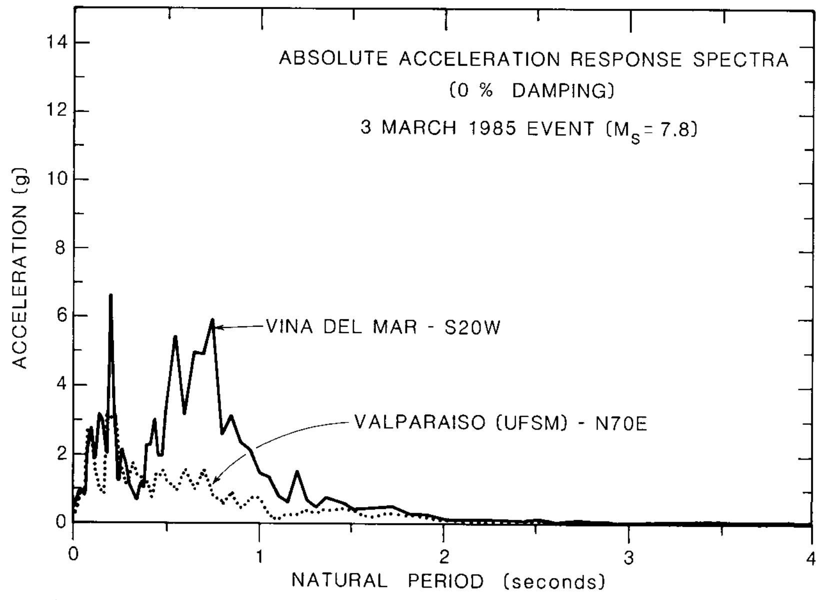

FIG. 20. Absolute acceleration (horizontal) spectra (0 per cent damping) of records obtained at Valparaiso (rock site) and Viña del Mar (alluvial site) during the main event of 3 March 1985 (M_S = 7.8) (from Saragoni *et al.*, 1985).

that the spectral ratios presented herein serve the purpose well by qualitatively identifying the frequency ranges for which amplification of motion takes place in different localities of different topography and geology. The user of these results should be careful not to generalize these phenomena to all sites without careful evaluation and correlation with the similarities of the sites in question. Furthermore, the user should always note that while these results can be used to increase seismic design forces in one way or another, it is just as important to provide adequate quality control into the details of design and construction practices. In other words, frequency-dependent amplification, while influencing the performance of structures in central Chile during the 3 March 1985 event, should not be taken as the sole contributor to the damages and destruction experienced and observed.

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