A DETAILED ANALYSIS OF GROUND MOTION IN MEXICO CITY DURING THE 4.25.89 GUERRERO EARTHQUAKE

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ABSTRACT

The 4.25.89 (Ms=6.9) event that occurred in the subduction zone in the Pacific coast of Mexico produced more than 60 digital acceleration records in Mexico City. We present a detailed analysis of these records. A first necessary step was to assign common time that was lacking for the records. This was possible by the unambiguous identification of the long period (7 to 10 s), fundamental Rayleigh wave in almost all the records, independent of station location. Phase velocity for this pulse was assigned based on standard, average dispersion curves that have been validated for paths between the Pacific coast and Mexico City. After that, we examined the records in different frequency bands, looking for significant energy arrivals, coherent among several stations. The best results were obtained in the period band 3 to 4.5 s. In this period band, three significant pulses were identified and interpreted as Rayleigh waves. The first two propagate essentially in the epicentral direction. They seem to have been generated by local (in the order of tens of km) heterogeneities of the structure, and have wavelengths of several km. These Rayleigh waves are not related with the geotechnical zoning, as they are observed indistinctly in the three different geotechnical zones. The third Rayleigh pulse could be identified only at four stations. Its propagation velocity is very low (of the order of 100 m/s) and seems to be generated by the contact between the lake bed and transition zones. Their propagation velocity and arrival time indicate that the three Rayleigh pulses identified are not a multipathing effect, but are locally diffracted by lateral heterogeneities related to the deep basin structure (in the order of 1 to 4 km depth) of Mexico City. Our observations support a hypothesis, advanced by Chávez-García *et al.* (1995), that suggests that long durations in the lake bed zone of Mexico City result from the interaction of deeply guided surface waves with local 1D resonance.

KEYWORDS

site effects, Mexico City, 4.25.89 event, acceleration records, time-frequency analysis, lateral heterogeneities.

INTRODUCTION

In 1985, 11 strong motion instruments recorded ground motion for the large (Ms=8.1) Michoacán earthquake that caused significant damage and more than 10,000 casualties in this city, more than 300 km from the epicenter. Since then, a substantial effort has allowed to increase strong motion instruments in Mexico City by an order of magnitude. In recent years a number of earthquakes have triggered the Mexico City Acceleration Network (MCAN) producing a large number of high quality digital records. This database has been very useful to study lateral variation of the response within the valley relative to firm soil sites, allowing even to predict ground motion at sites that are not instrumented. However, up to date, this data has not been used to explore the nature of seismic ground motion in Mexico City, nor has it been used to evaluate to what extent are 1D models valid for Mexico City valley. This is important, as 1D models have been largely used, even though they have been shown to be inadequate to model ground motion in the time domain (Chávez-García and Bard, 1994).

The objective of this study is to make a detailed analysis both in frequency and time domains of the acceleration records obtained in Mexico City for the 4.25.89, Guerrero, earthquake. This event occurred at 19 km depth at 16.579°N and 99.462°W, and was recorded by more than 60 digital accelerographs in Mexico City. The azimuth from the source to Mexico City was N5°E and epicentral the distance was 306 km. One important limitation of this data set is the lack of common time for the stations. We overcome this difficulty by imposing a phase velocity to the fundamental mode of Rayleigh waves, which can be identified in almost all of the stations. We then examined the records filtered in a series of frequency bands. For each band, we examined the records searching significant pulses that could be correlated among neighboring stations. The best results were obtained in the 3 to 4.5 s period band. Our results show that lateral heterogeneities affect significantly ground motion in Mexico City. This lateral effects are not related to the geotechnical microzonation of the city, but rather reflect larger scale heterogeneities. Our results demonstrate the importance of surface waves in the seismic response of Mexico City valley, point to the importance of lateral heterogeneity in a scale larger than previously thought, and show the impossibility of explaining ground motion in the valley using one reference station. Finally, they support the hypothesis that suggests that long durations in the lake bed zone of Mexico City result from the interaction of deeply guided surface waves with local 1D resonance.

ANALYSIS

Assigning Common Time

The MCAN was maintained by four different institutions in 1989: Fundación ICA, CIRES from Fundación Javier Barros Sierra, CENAPRED, and Instituto de Ingeniería, UNAM. After compilation of the records, the original sampling rates (varying between 100 and 250 Hz) were homogenized, and the records were decimated to a sampling rate of 10 Hz. Finally, samples were added to each record so as to complete 4,096 samples. The total of records was 63, but three of them (stations 57, 58, and CD) had to be dropped because of glitches in the original data. Fig. 1 shows the distribution of the 60 stations used in the analysis.

The main difficulty regarding a detailed analysis of acceleration records from MCAN is the lack of common time. To overcome this difficulty, we followed the procedure applied by Chávez-García *et al.* (1995) to the strong motion records obtained in Mexico City for the 9.19.85, Michoacán, earthquake. We examined the records in the 7 to 10 s period band and identified the fundamental mode of Rayleigh waves propagating from the source. This pulse has a very large coherence among all the stations both in the radial and vertical components, regardless of geotechnical conditions at the station. If we assign a propagation velocity to this pulse, we may impose a common time base for all the records. Based on the results of Chávez-García *et al.* (1995), we imposed a phase velocity of 3.17 km/s to this mode. This velocity corresponds to a minimum of the group velocity dispersion curve, where we may expect large amplitudes in the records (Fig. 2). The resulting seismic section for the vertical component is shown in Fig. 3 (results for the radial component are very similar). Amplitude scale is common to all the records. Fig. 3 shows that we may have large confidence in the procedure followed. We measured the propagation velocity of the envelopes of the traces and obtained a group velocity of 2.6 km/s, in good agreement with the theoretical curve shown in Fig. 2. Once we prescribed common time for the records, it is possible to analyze them using time-distance plots along different directions, and animated pictures of ground motion on a computer in different frequency bands.

Time-Distance Plots

We analyzed our data base in different period bands, from 7 down to 2 s. The better results were obtained filtering the records in the period band 3 to 4.5 s. For longer periods, the energy is concentrated in the fundamental Rayleigh wave, and no other significant arrivals can be identified in the records. For shorter periods, coherence among the records drops and it becomes difficult to identify common wavetrains in the records.

One we had filtered the records, directions of analysis were chosen. To this end, we analyzed particle motion of the largest pulses within the whole record, looking for systematic orientation of horizontal ground motion in any group of stations closely spaced. Once this direction was identified, records were rotated to the radial and transverse direction relative to the direction of elongation of particle motion. Finally, the resulting time-distance sections were plotted for the resulting three components of motion.

RESULTS

Pulse 1

The first significant arrival in the period band 3 to 4.5 s (called pulse 1) could be correlated among 32 stations, mainly located on the West of the city (Fig. 4). Pulse 1 could be observed both in the North-South and in the vertical components of the accelerograms. The envelopes of this pulse are in advance respect to the envelopes of the envelope for the fundamental Rayleigh pulse between about 13 to 20 s, and propagate with a velocity of the order of 3 km/s. The time difference between the arrival times of the envelopes for the fundamental Rayleigh mode and those of pulse 1 increases to the North suggesting that both the fundamental Rayleigh wave and pulse 1 propagate in the same direction. Pulse 1 arrives at our stations between 13 and 20 s before the fundamental Rayleigh mode. If they both came from the source (306 km away) the time difference between them should be almost 30 s, given their respective group velocities. This indicates that pulse 1 was generated some place along the road by a faster travelling wave and is then a converted wave. Let us now look at the phases of this pulse. Fig. 5 shows the polarization and contours of arrival time of a common phase. Polarization changes gradually from South to North. This suggests that pulse 1 deviates across the valley and thus, that local conditions related to microzonation of the city affect its propagation. Phase velocity of pulse 1 also changes from a large value not well constrained (between 3.8 and 4 km/s) to the South of the basin to about 2.6 km/s to the North. This change is reflected by the more closely spaced contours to the North in Fig. 5. Station distribution does not allow to reflect the polarization change in the wavefront distribution.

Pulse 2

Pulse 1 could be identified at 20 stations, in the Noth-South and vertical components. These stations are a subset of those where pulse 1 could be identified (see Fig. 4 for the time-distance section). Pulse 2 arrival occurs more than 32 s after arrival of pulse 1. It seems to propagate in the same direction as pulse 1. Group velocity for pulse 2 is comprised between 1.1 and 1.7 km/s, and its phase velocity between 2 and 2.2 km/s. Therefore, its wavelength is comprised between 6 and 10 km. Fig. 6 shows that, similar to pulse 1, its polarization in the horizontal plane changes gradually from South to North. The time contours shown on Fig. 6 suggest that, contrary to pulse 1, pulse 2 increases its phase velocity from South to North, as shown by the more loosely spaced contours to the North. However, the precision that can be attained is less than that for pulse 1. Again, given the spatial distribution of stations, it is not possible to relate the change in polarization with a change of orientation of the wavefronts.

Pulse 3

The final pulse could be identified only in four records obtained in the lake bed zone, very close to the transition zone. Direction of horizontal polarization was N55°E. Thus, we rotated horizontal components and verified that the pulse appears in the vertical component and in motion radial to the direction of propagation, N55°E. Fig. 7 shows the time-distance section for the vertical and radial components of motion. The prominent late pulse can be interpreted as a Rayleigh wave. The velocity of this last pulse is remarkably low, between 100 and 110 m/s. This pulse is also very late, occurring more than 40 s after pulse 1. Given its low velocity, this Rayleigh wave must be related to the shallow soil structure that characterizes the lake bed zone, where S-wave velocity has been measured to be as low as 60 m/s. It is also remarkable that this wave only appears at four stations, very near the transition zone. This seems to confirm the theoretical results of Chávez-García and Bard (1994), who based on results from numerical models, predicted that surface waves related to the lateral heterogeneity of the lake bed zone would be significant only very close to the contact between lake and transition zones.

Additional Observations

No other significant, isolated pulses could be identified in the East-West component or for other frequency bands. However, an additional observation can be made for 7 of the stations in the lake bed zone (from North to South, stations 39, 12, 42, 10, 29, 19, and 80). For these stations, in the period band 3 to 4.5 s, the records show significant amplitudes but no distinct arrival. Rather, ground motion has a monochromatic character. All of these stations are located in the lake bed zone, where dominant periods of the topmost soil column ranges between 2 and 4 s according to Lermo and Chávez-García (1994). Our interpretation is that the guided waves, shown in some of the other stations, propagated guided by deeper layers towards the center of the lake bed zone. The 1D resonant frequency of the topmost layers in this zone increases towards the center, because the thickness of the clay layers increases. At some point the dominant frequency of the laterally propagating waves coincides with the local 1D resonant frequency of to the surficial soft clay layers, and ground motion changes its character from a propagating wave to resonant, monochromatic motion.

The possible interaction between guided waves and local 1D resonance could solve a paradox concerning Mexico City response. This paradox consists in the impossibility of sustaining 1D resonance with body wave incidence in the time domain (shown among others by Kawase and Aki,1989, and Chávez-García and Bard, 1994) with the very good results that have been obtained using the 1D model in the frequency domain (see, *e.g.*, Seed *et al.*, 1988). This paradox was thoroughly discussed by Chávez-García (1991), and was later declared inexistent by Singh and Ordaz (1993). The arguments presented by Singh and Ordaz (1993) were discussed by Chávez-García *et al.* (1994) and Chávez-García *et al.* (1995), who showed that the problem had not been solved. The interaction that we propose between laterally propagating guided waves and local 1D resonance is, as we have shown, supported by the strong-motion data set we have analyzed. We believe that this is the explanation of the peculiar seismic response of Mexico City basin.

CONCLUSIONS

We have shown that, in the long period band, ground motion in Mexico City is independent of local geotechnical conditions, and that it consists of the fundamental Rayleigh mode in the radial and vertical components. The Love wave fundamental mode was not excited by the earthquake, as shown by the very small amplitudes of ground motion of the transverse component in that period band. At shorter periods, we observe surface waves in different directions, common to several of the records, and not related to geotechnical zonation of the city. This shows the significance of the large scale structure of Mexico City's valley (in the order of tens of km in the horizontal direction and 1 to 4 km in the vertical direction) in its seismic response. Our results show that 2D effects are indeed very important in this valley, although they are not only related to the lateral geological variations between the lake bed and the hill zones. Rather, 2D effects are related to the larger structure of the valley. Based on our results, we suggest that a way to reconcile local 1D response in the lake bed zone with large duration of strong ground motion is to consider local 1D resonance excited by laterally propagating, deeply guided surface waves.

The importance of site effects in Mexico City is widely recognized, but not fully understood. Significant advances can be made by careful analysis of acceleration records obtained by MCAN during recent subduction earthquakes. We have shown that it is possible to assign absolute time to these records, opening exciting perspectives for the analysis of the already rich acceleration data base (we have already begun analysis of 9.14.95 event, better recorded than the event analyzed in this paper). Our results suggest that 2D site effects are significant at a scale that was not suspected previously, and open the way towards the possibility of modelling ground motion in this basin for future earthquakes.

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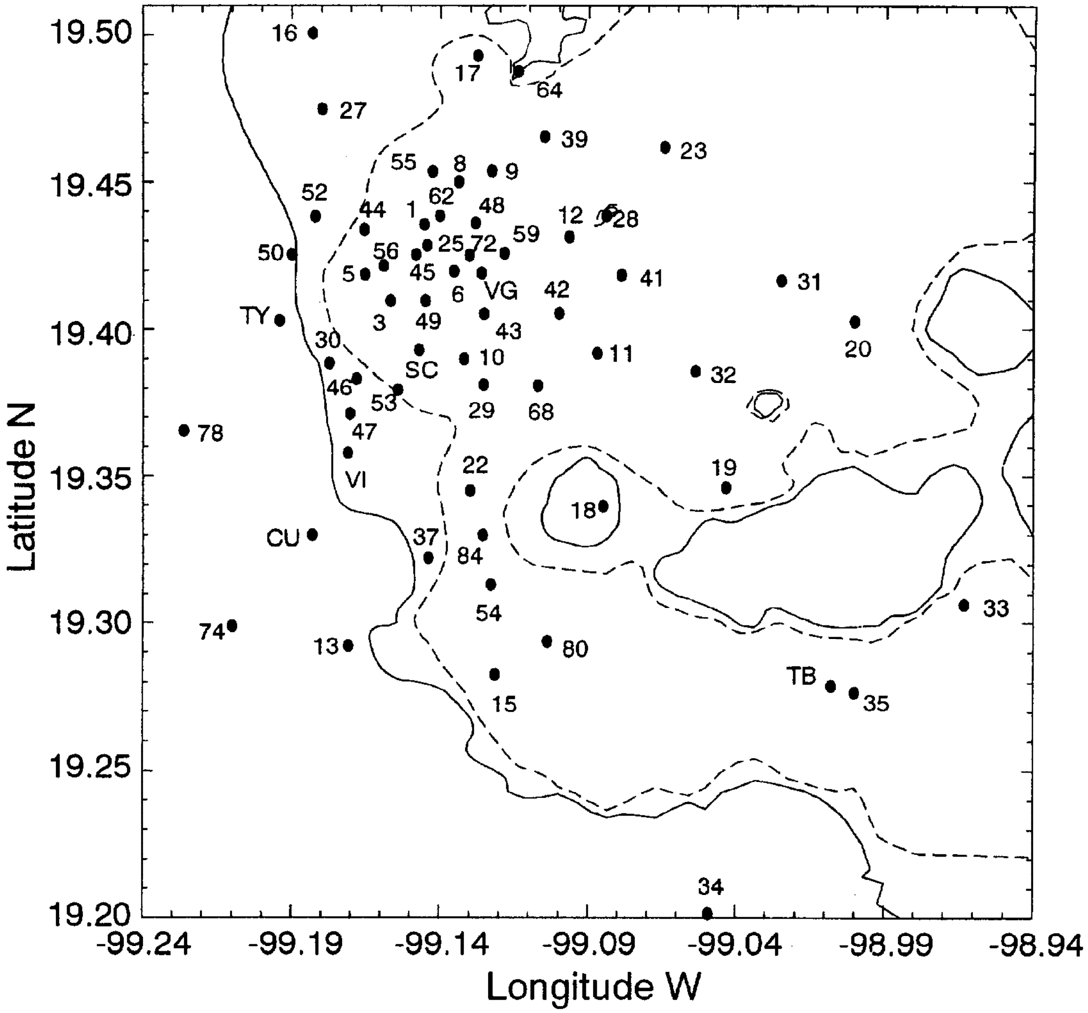

Fig. 1. Location of 60 acceleration stations that recorded the 4.25.89 event, and whose records were used in the analysis. The solid line shows the limit between hill and transition zones according to standard geotechnical microzonation of Mexico City. The dashed line indicates the limit between transition and lake bed zones.

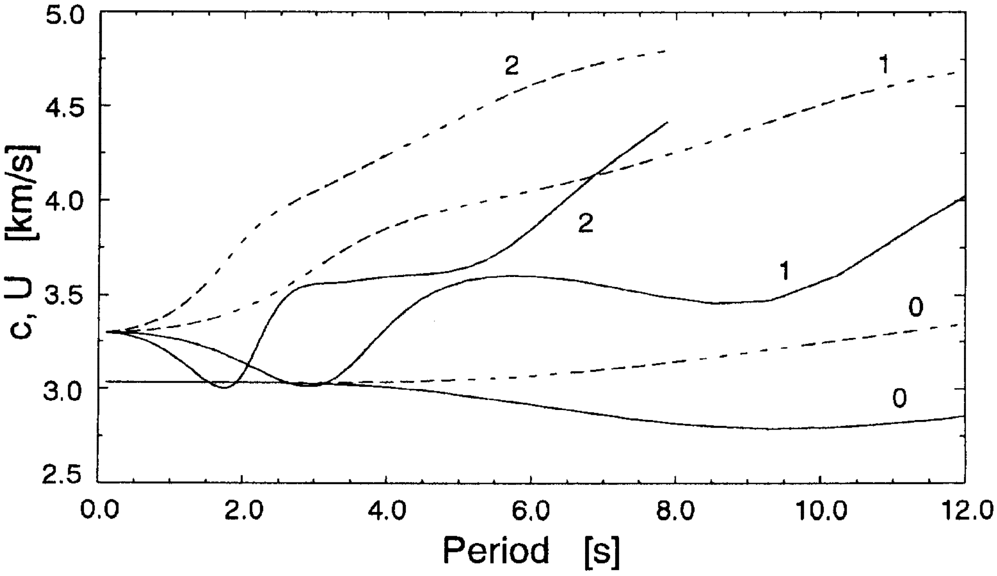

Fig. 2. Dispersion curves of group (U, solid lines) and phase (c, dashed lines) velocity for the average crust model between the Pacific coast and Mexico City proposed by Campillo *et al.* (1989). We show the fundamental (indicated as 0) and two higher modes (indicated as 1 and 2).

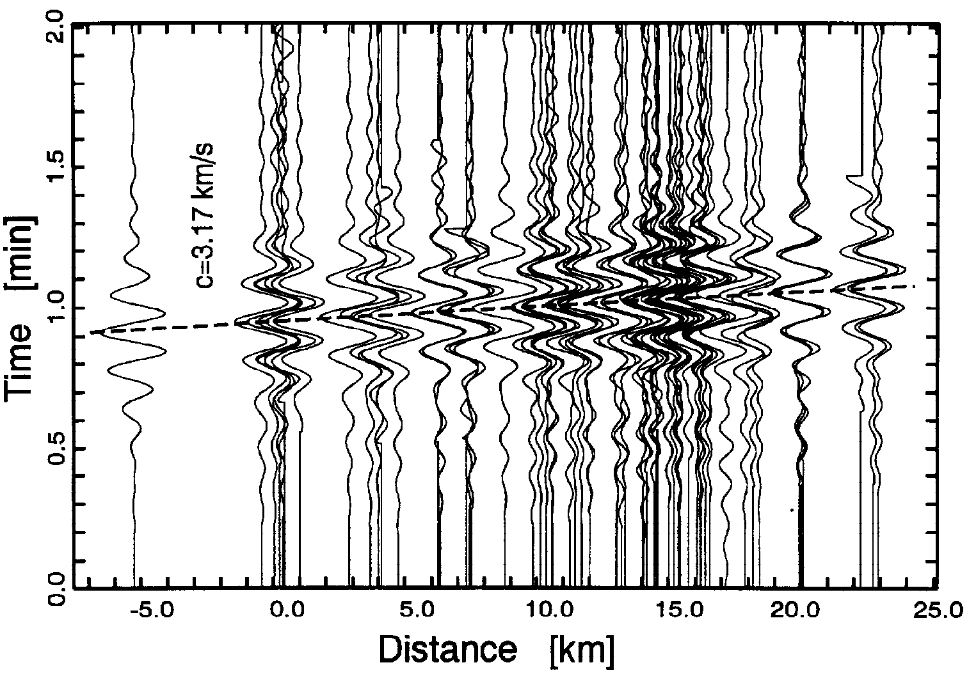

Fig. 3. Seismic section of vertical ground motion of the Mexico City records of the 4.25.89 event. Amplitude scale is common to all the records. Ground motion has been band pass filtered between 7 and 10 s period. Distance is measured in the South-North direction from an arbitrary origin.

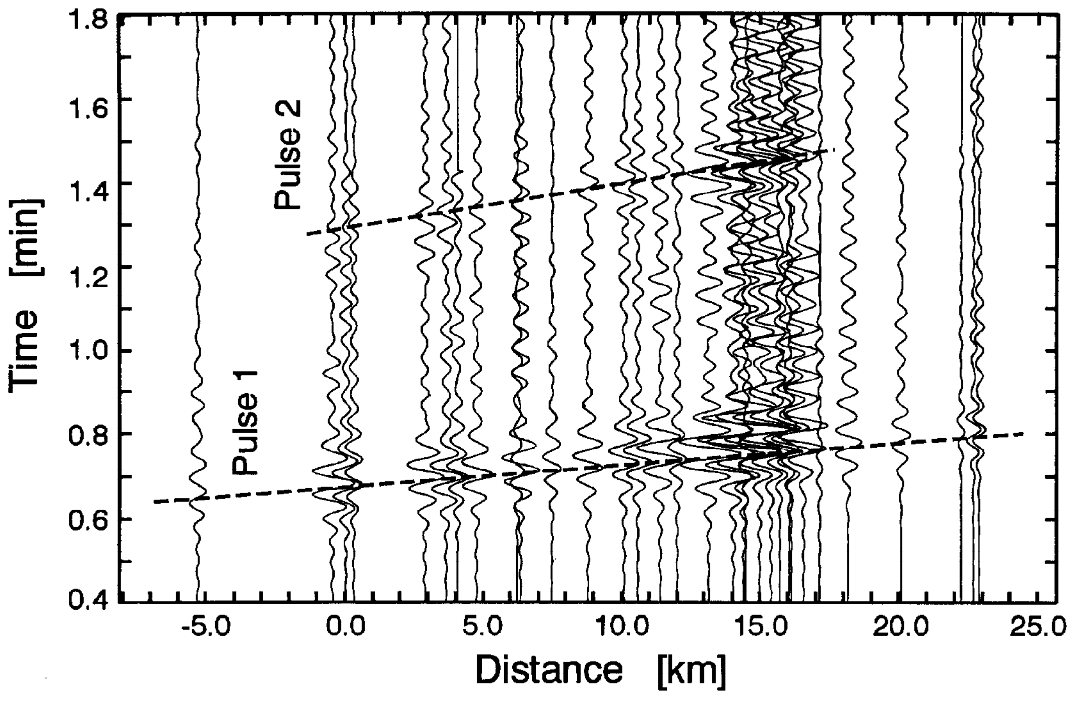

Fig. 4. Seismic section of North-South component of motion for 32 of the Mexico City records of the 4.25.89 event. Amplitude scale is common to all the records. Ground motion has been band pass filtered between 3 and 4.5 s period. Distance is measured in the South-North direction from an arbitrary origin. Time scale is common to that of Fig. 3. The second pulse could be identified in only 20 of these stations.

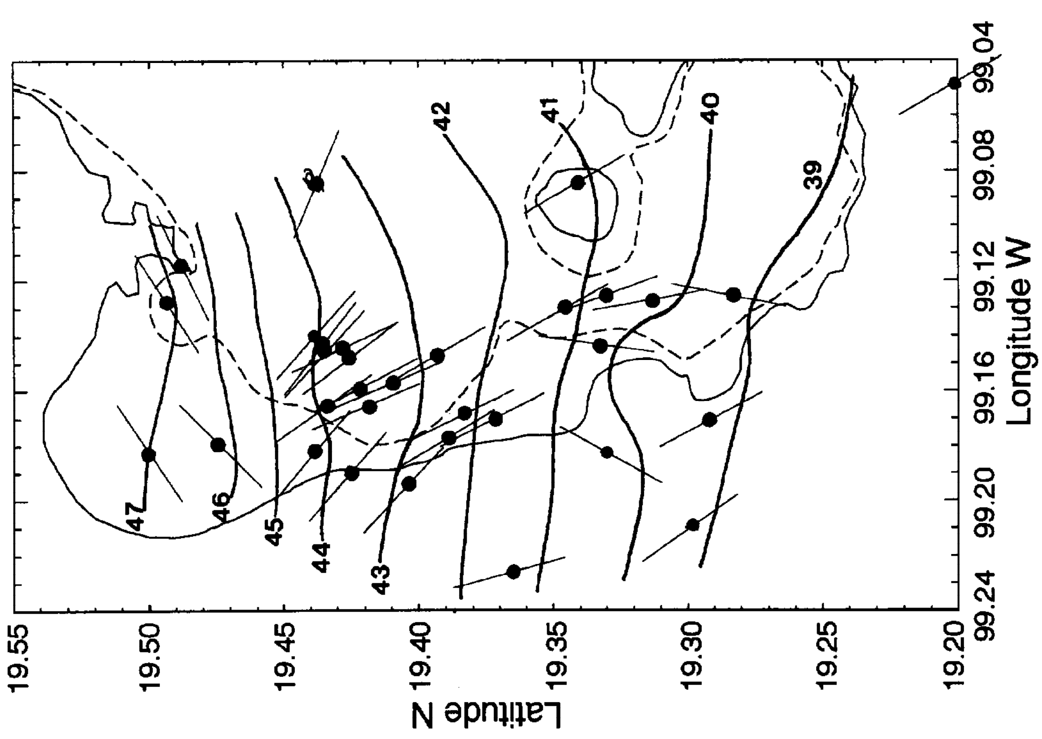

Fig. 5. Map showing the 32 stations (solid circles) where the first pulse could be identified. The short lines at each station indicate the direction of maximum elongation of horizontal polarization for this pulse. Thick solid lines are contours of arrival time for a common phase. Microzonation of the city is indicated as in Fig. 1.

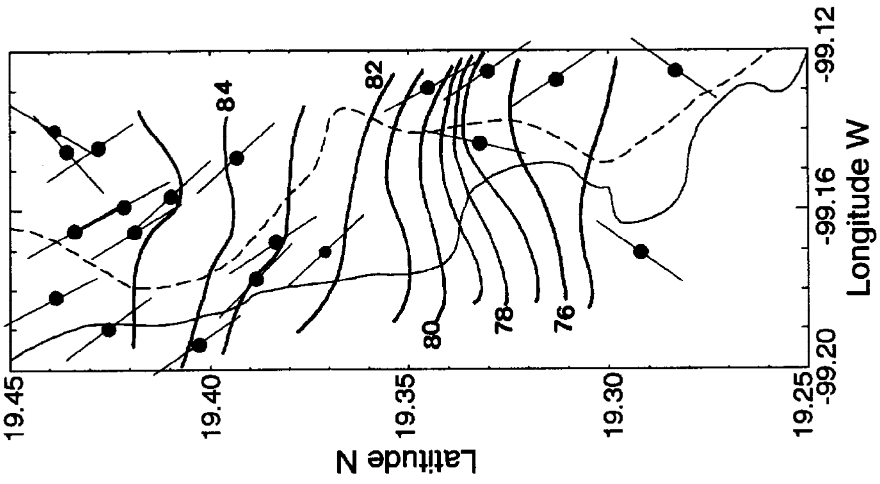

Fig. 6. Map showing the 20 stations (solid circles) where the second pulse could be identified. The short lines at each station indicate the direction of maximum elongation of horizontal polarization for this pulse. Thick solid lines are contours of arrival time for a common phase. Microzonation of the city is indicated as in Fig. 1.

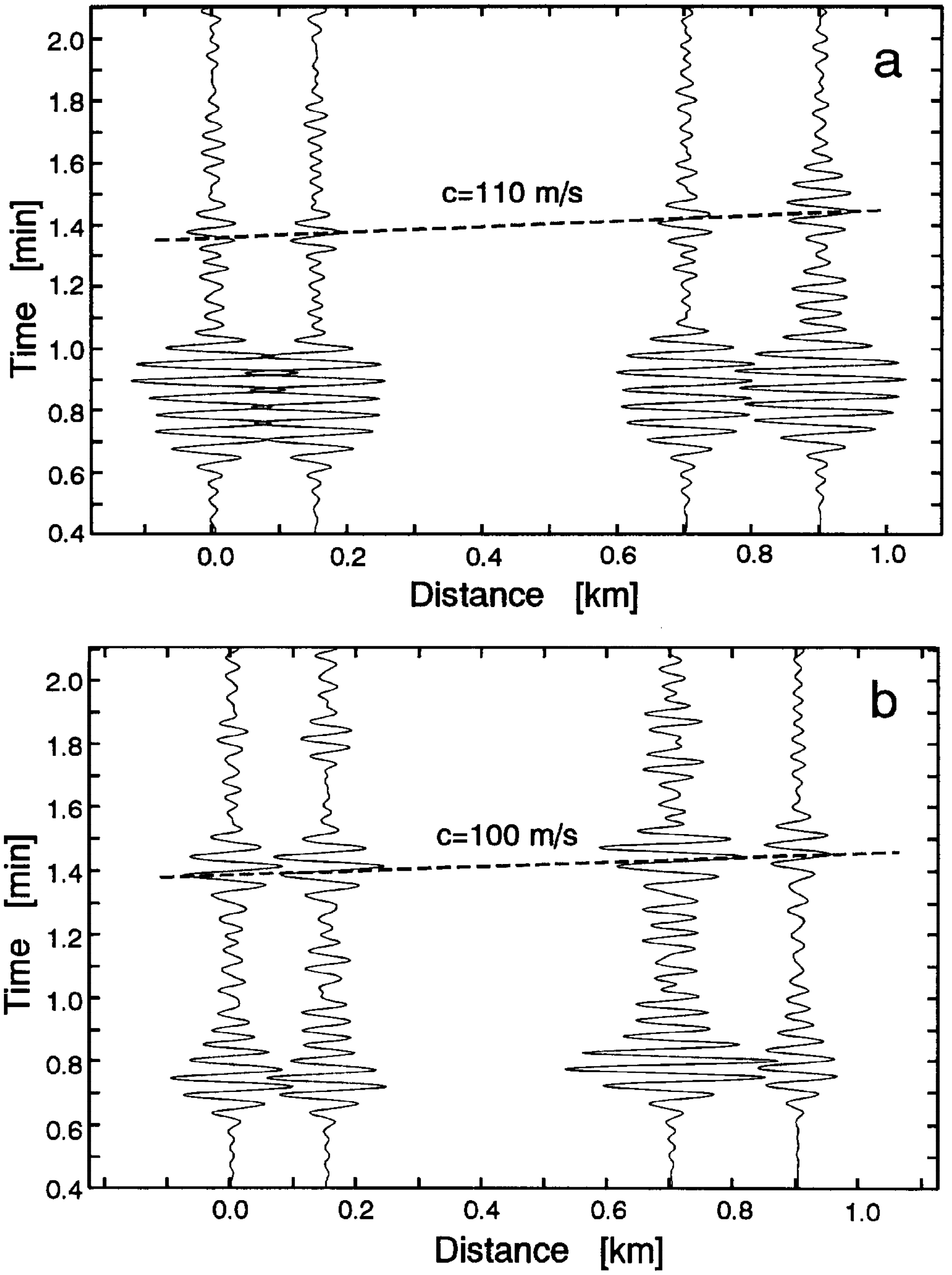

Fig. 7. Time-distance section along a N55°E direction. Amplitude scale is common to all of the records in each section. (a) Vertical component. (b) Horizontal motion in the direction N55°E. The number on each trace indicates the number of the corresponding station.