STRUCTURE OF THE BASIN OF MEXICO CITY AND ITS RELATION TO DESTRUCTION IN THE EARTHQUAKE OF 1985.

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ABSTRACT

In spite of the large population in the basin of Mexico and the recurrent seismic destructions of Mexico city, few efforts have been made to define the basin's structural characteristics and how these relate to earthquake hazards. Lakes covered the surface of the basin until about three centuries ago. Although the lake waters have evaporated, the saturated zone comes close to the surface, rendering surface layers highly deformable by seismic waves. Mapping the damage produced by the September 15, 1985 earthquake in the most affected area revealed previously unnoticed patterns, which consist of lineaments of narrow (2m), vertical deformations which extend for distances of up to 1.5 km in a region of the saturated zone. The possibility that such patterns arise from interactions between incoming and reflected seismic pulses makes imperative to determine the presence of reflective horizons that may amplify groundmotion due to earthquakes. The gravimetric model of the eastern part of the basin of Mexico corresponding to Texcoco Lake, shows that the basinal sediments approach 3000 m in thickness and reveals the actual dimensions of Huatepec volcano, a structure that is almost completely buried by sediments. A buried canyon on the NW part of the modeled area is also defined, as well as an unidentified concealed structure, probably volcanic, that rises from the floor of the central-western original Texcoco basin. The gravimetric data of the Texcoco basin is correlated with stratigraphic data of a deep well and with three seismic refraction profiles obtained elsewhere. Comparison with a recent model of the western area of the basin of Mexico shows consistency between the two sets of results; in this area the deepest section reaches 1250 m according to the model. An isopach map of the western and eastern portions is constructed from the gravimetric models. Comparing results between the western and eastern portions of the basin is of importance since in the former there are no other geophysical surveys to correlate with. According to these results, the western and southern parts of the basin of Mexico must be considered as high-risk seismic areas owing to the presence of buried and outcropping volcanic formations that constitute the flanks of sediment-filled canyons which can trap and amplify seismic energy coming from the south-southwest. The structural characteristics of Mexico City may serve as an example for other high-risk, earthquake areas such as the San Francisco-Oakland, and Tokyo areas in which considerable construction has taken place on unconsolidated materials.

INTRODUCTION

Interaction between the Cocos and the North American plates is largely responsible for the active volcanism and tectonism present in Mexico throughout the last 10 million years. During late Quaternary, subduction along the line of interaction has produced a large number of earthquakes (Nixon, 1982), some of which exceed 7.0 on the Richter scale. Figure 1 shows the relation of the Acapulco Trench to the central part of Mexico. Subduction also gave rise to the Trans-Mexican Neovolcanic Axis (TNA) a structure of about 1000 km which runs across Mexico in the E-W direction at about N20^o latitude. The TNA was formed mainly in the Cenozoic, with extensive eruptions from diverse volcanic structures. The basin of Mexico, often called the Valley of Mexico despite lacking a river, is located in the southern portion of the TNA at 19.5N, 99.1W. Prior to the formation of the TNA the region SW of Mexico City to the Pacific Coast, was a marine environment. Marine sediments were deposited during the Jurassic, and Upper and Lower Cretaceous over a Precambrian metamorphic basement. In addition to the extensive volcanism, tectonism during the Cenozoic produced a series of grabens along the TNA.

The basin of Mexico (Figure 2) is one of such grabens, whose present morphology defines it as a basin with SW-NE dimension of 100 km and approximately 80 km in the E-W direction. It is completely surrounded by high sierras averaging 3000 m in altitude; in the SE portion one finds two of the highest volcanoes in Mexico: Popocatepetl (5400 m), and Iztaccihuatl (5286 m). Mexico City is located on the SW portion of the basin at an average altitude of 2400 m.

From Oligocene to Mid-Miocene tectonism created in the basin a horst and graben structure. The formation of Sierra de Guadalupe starts, and continues through Upper-Miocene. As will be seen, this is a structure of great relevance for seismological effects on Mexico City; it is located north of the city and consists mostly of of andesite, dacite, and latite lava flows. During the Lower-Pliocene two additional, important structures were formed; the Sierra Nevada and Sierra de las Cruces. They constitute the western flank of Mexico City and of the Mexico basin. Mooser (1956) proposed that prior to the Quaternary two rivers flowed to the south in the western and eastern flanks of the basin. On the western portion the river flowed along the foothills of the sierras Nevada and De las Cruces. During the Quaternary, however, a large series of volcanic eruptions gave rise to Sierra del Chichinautzin (Martín Del Pozzo, 1982), which is located south of Mexico City; this sierra blocked off the drainage of both rivers to the south transforming the region in a closed basin. Approximately 0.7 m.y. ago, drainage closure initiated a rapid process of deposition which began covering the older structures. Volcanic eruption episodes were abundant and significantly contributed to the filling of the graben; the last manifestations in the basin have been the eruptions of Xitle volcano 2422 $\pm$ 250 years ago (Herrero-Bervera et al., 1986) and Popocatepetl's eruption in 1920.

Bribiesca (1960) reports that E. Shilling reconstructed several stages of the lake area starting from glacial periods in the Late Pleistocene, after the closure of the basin, until the late nineteenth century (Figure 3). The lake area evolved from initial dimensions of approximately 60 km in the N-S direction and 32 km in the E-W direction for the southern portion and 20 km for the northern part. The southern portion of the basin corresponds to the Mexico-Texcoco lakes and the northern portion to the Zumpango-Xaltocan lakes.

In the sixteenth century the lake in the northern part of the basin had significantly decreased in area while the one in the southern part, although smaller, remained connected the Mexico and Texcoco lakes. By the nineteenth century the lake surface was completely broken up into smaller water bodies; the lake of Mexico was already dessicated. The Xochimilco-Chalco lake on the southern portion was separated from the larger Texcoco lake and the northern lakes reduced their areas even further. The present day situation is one of practical disappearance of the lakes, perhaps with the exception of a few areas in the Texcoco lake that are being regenerated by Proyecto Texcoco (1969), and of Xochimilco lake that has maintained a few channels of interest to visitors.

Beginning with the earliest Aztec settlement of the lake of Mexico, a continuous struggle has taken place to control the waters of the basin. The city of Mexico-Tenochtitlan was founded on one of three primitive islands of the lake; it was eventually connected to mainland by means of embankments. The Aztecs built various protections against floods incluiding one, known as Dike of Nezahualcoyotl, of 16 km in length that separated the salty waters of lake Texcoco from the fresh waters of the lake of Mexico. This construction was operative when the Spaniard conquistadores arrived in Mexico City in 1519 and was subsequently abandoned by them. The flooding problem became fairly systematic despite attempts to control them. In 1789 a drainage canal out of the basin was succesfully completed after 150 years of interrupted attempts. On the northern portion of the basin the thoroughway for the water was named Tajo de Nochistongo. With it started the systematic drainage of the basin; the sewage from Mexico City went to the Gran Canal or Great Channel (Figure 2) that connected Mexico City to Tajo de Nochistongo. With the population boom in Mexico City large amounts of water have to be pumped into the basin from distant places, increasing thus the amount of water that has to be disposed of; the mean annual water flow is of approximately 90 million cubic meters. In recent times a new drainage was designed and built, known as Drenaje Profundo or Deep Drainage (Figure 2). It consists of a tunnel of approximately 70 km in length that carries the waters to discharge out of the basin in its NW part.

In spite of such works, of the intensive exploitation of the local aquifers, and of the dessication of the lakes, there are extensive areas in the previous lake bed in which soil saturation still ranges from 100 to 400 percent in weight (i.e., the weight of water in a given volume exceeds the weight of solids in the same volume by the indicated percentage) (Del Valle, 1986). This layer is known as the compressible clay layer, and is a highly plastic, highly deformable surface layer. Its depth varies from 10 to 40 m, and it is confined at depth by another, thin layer known as the first hard layer. The first hard layer presents a variable thickness of a few meters; it is on this layer that piles of some large buildings rest. The first hard layer actually constitutes the container in which the deformable clays are located; the topography of such a layer is consequently of great relevance to surficial seismological phenomena.

Thus, one can describe the basin of Mexico as a sediment filled area with high water saturation coming close to the surface in places. A portion of Mexico City is built on these water saturated and deformable sediments. Seismic waves arriving from epicentral distances ranging from 250 to 400 km reach the basin and excite particularly strong surface waves in the saturated sediments, causing a large amount of damage. In Figure 1 a series of isoseismal lines show the intensity of the 1985 earthquake in Central Mexico. It is interesting to note the anomalously high values in Mexico City, a distant place from the epicenter in which the intensity is enhanced by the deformable clay layer. In order to visualize the type of interactions that can occur in the basin to the arriving seismic waves it became apparent, after damage mapping and field observations of the 1985 earthquake (Alvarez, 1986), that it is necessary to know what kind of obstacles they can find in their trajectories within the basin; such obstacles are covered by sediments and thus one needs indirect means to map them. Utilization of geophysical techniques is a most convenient means to define the characteristics of the basin at depth.

GEOPHYSICAL SURVEYS

The basin of Mexico has been the subject of various geophysical studies, the first of which appears to be a complete regional gravimetric survey (Marsal and Mazari, 1969); it is reproduced here in Figure 4. There was no quantitative interpretation available for these data previous to the unusual amount of damage produced by the 1985 earthquake, which restated the need to determine the morphological characteristics of the basin. An interpretation of such data on the western portion of the basin was performed (Alvarez, 1988a) corresponding to the area of largest damage; the present work extends the modeling toward the eastern portion of the basin. The area of largest damage ends precisely along the NNW line joining Cerro del Peñón to Sierra de Guadalupe (Figures 8 and 9). However, it can be seen from Figure 2 that the city extends beyond such a line from one to two kilometers; since the upper 50 m of sediments are similarly saturated on both sides of the line it is of great importance to determine what differences, if any, occur at greater depths in order to explain why damage ended at such a location. It is probably as important to determine why damage occurred in one area as to explain why it did not occur in another one of similar surface properties. Study of the eastern portion of the basin is of additional interest since it is only in this area in which one can make comparisons with other geophysical methods.

The eastern portion of the basin corresponds to the area of Texcoco Lake; this is an area of low population density on its central and eastern portions, that has become the subject of various geological and geophysical studies owing to a project to regenerate the lake. The project is known as Proyecto Texcoco and the geophysical surveys included seismic refraction, geolectric soundings, gravimetry, and magnetometry. In addition, a series of shallow holes less than 100 m deep were drilled to characterize the surface sediments. A deep hole (PP-1) was drilled on a gravity low and reached 2065 m but did not penetrate basement. After 1985 a new series of exploratory wells were drilled throughout the urban area, and additional seismic refraction and geoelectric studies were performed by Pemex and by Comisión Federal de Electricidad. These survey data and results are not yet available.

The mechanical properties of the uppermost 80 m of sediments in the lake area of Mexico City are fairly well known. A large number of exploratory holes drilled for civil engineering purposes allow for the characterization of the area; contoured maps are available of the depth to the first hard layer, of water content in the compressible clay layer, as well as a host of values of the density of solids in the soil, shear stress coefficients, etc., (*e.g.*, Del Valle, 1986). However, to understand seismic wave propagation in the basin one also needs information on its deeper structure. The gravimetric models may help fulfill the necessary information in spite of the very scant data on the physical characteristics of the layers at depth. The model of the eastern portion of the basin, is developed herein, relating it where appropriate to the model of the western portion.

Within the scope of Texcoco Project, and from the central part of Texcoco basin toward the NE, 26 Schlumberger geolectric soundings were made at spacings of 500 m. The theoretical penetration of these sounding of 300 m, and thus they were much too shallow to be of help in correlating results with gravimetry. Consequently they will not be included in this discussion. However, the set of three seismic refraction profiles across the basin, as shown in Figure 4, are most valuable for correlation purposes, and the interpretation of such profiles is reproduced in Figure 5. The main results are the presence of two refractors; designated refractor A for the shallow one and refractor B for the deep one. Also at the NE end of Line 3 it was found that high-velocity layers were approaching the surface; in fact the existence of a buried volcano was proposed, which has a very modest surface expression with two outcrops: Cerro Huatepec and Cerro Tepetzingo. On the shallowest layer, which corresponds to the saturated layer of approximately 30 m in depth, propagation velocities ranged from 600 to 900 m/s according to the Proyecto Texcoco (1969) report, while beneath such a layer there was a second, low-velocity layer ranging from 1550 to 1900 m/s reaching depths between 300 and 400 m. Between refractors A and B a layer of 2900 to 3100 m/s was defined, and below refractor B a layer of 4500 to 4600 m/s continues to undetermined depths. Table 1 summarizes these results.

The above results can be correlated with information from the deepest well in the area, hole PP-1 . This hole reached 2056 m and its stratigraphic column is described in Table 2. Several samples obtained from such a well were dated, allowing for correlation with neighboring geological formations. Well PP-1 intersected 13 igneous flows of various thicknesses, which confirm volcanic activity in the basin throughout the last 30 m.y. Of particular interest are a series of lava flows found between depths of 814 to 1030 m which are compositionally similar to two outcropping Miocene volcanoes, Cerro de Huatepec and Cerro de Tepetzingo. These lava flows are interleaved with thick tuffs and deposits of pyroclastic materials. It is interesting to note that while on the surface the propagation velocities correspond fairly well to saturated and dry sediments, in the lowest formations the higher propagation velocities would make one expect igneous materials and yet the results from well PP-1 show clastic materials. From the results on Line 3, for the materials below refractor B, it is clear that there is practically no difference between the propagation velocity of the averaged properties of clastic materials interleaved with lava flows and that of the andesites of Cerro de Huatepec and Cerro de Tepetzingo.

Table 1. Seismic refraction characteristics of the Texcoco basin (After Proyecto Texcoco, 1969).

Layer	Layer Depth at PP-1 (m)	Average velocity (m/s)	Geological remarks
Surficial	0 - 30	600	Highly compressibe clay, water saturated.
First	30 - 520	1700	Unconsolidated clay-sandstone, water saturated
Refractor A	520		
Second	520 - 1445	2900	Consolidated tuffs interleaved with sandstone horizons.
Refractor B	1445	–	
Third	1445 - ?	4500	Highly consolidated rock, possibly igneous.

THE TEXCOCO MODEL

The gravimetric response of the basin was reported by Marsal and Mazari (1969), and a second overlapping set of measurements was obtained in the Texcoco area (Proyecto Texcoco, 1969). Both results are very similar, but no quantitative gravimetric model was produced. Figure 4 shows the results of the first report; the area modeled in the present study is located in the eastern rectangle and it will be referred to as the Texcoco area since it corresponds to the bed of the Texcoco lake. As it can be seen in Figure 2 the urban area is partially located in the Texcoco area; however, population concentration is smaller than on the western portion of Mexico City and consequently the seismic risk is smaller in spite of having the same type of saturated surface layers. The central portion of the western rectangle in Figure 4 corresponds to the area where the maximum earthquake damage was sustained during the September 19, 1985 earthquake (Figures 8 and 9).

Three-dimensional modeling of the gravimetric results has been performed in both areas. 3-D modeling is carried out by means of right-rectangular prisms of appropiate dimensions, density contrasts, and depths of burial. For the model of the western portion of the basin there were no deep control points, such as the deep well PP-1 in the Texcoco basin, neither were available any additional geophysical surveys to correlate with. Under such circumstances the 3-D modeling was restricted to reproduce the geographical position of maxima and minima, and to reproduce the significant gradients obtained in the survey; the density contrast were assigned on the basis of representative values available in the literature for comparable geologic materials. A process of trial and error finally yielded the reported results. Those results can be refined when actual values of density are obtained and when a denser mesh of field data is obtained. The discussion of the western area will be limited to a few comparisions with the results obtained for the eastern, or Texcoco area, since there we can make correlations with the seismic refraction results and with the only deep well drilled in the basin.

Table 3. Model parameters of the prisms in Figure 6b.
The coordinate system is the same as for the contoured values of Figure 6a.
The Z-coordinate is positive downwards.

Prism	X_1	X_2	Y_1 (km)	Y_2	Z_1	Z_2	Density Contrast (g/cm^3)
1	15.0	20.0	-5.0	-1.0	0	2.0	-0.20
2	25.0	28.0	-1.5	1.5	0	1.0	0.10
3	20.0	28.0	1.5	12.0	0	0.5	-0.30
4	20.0	30.0	14.0	20.0	0.3	1.5	0.15
5	20.0	26.0	16.0	19.0	0.05	0.3	0.15
6	13.0	17.0	4.5	7.0	0.5	3.0	-0.15
7	26.0	28.0	16.0	19.0	0	0.3	0.18
8	13.0	17.0	12.0	17.0	0.2	1.5	0.10
9	11.0	17.0	17.0	22.0	0	1.5	0.10
10	14.0	20.0	-1.0	3.0	0	0.5	-0.30
11	14.0	20.0	-1.0	3.0	0.5	2.2	-0.15
12	20.0	24.0	-1.0	1.5	0	1.7	-0.20
13	10.0	20.0	3.0	7.0	0	0.5	-0.30
14	17.0	20.0	3.0	7.0	0.5	0.8	-0.15
15	17.0	20.0	7.0	10.0	0.5	1.6	-0.20
16	18.0	20.0	10.0	18.0	0.5	2.2	-0.15
17	17.0	20.0	7.0	20.0	0	0.5	-0.35
18	13.0	17.0	3.0	4.5	0.5	1.3	-0.15
19	10.0	13.0	5.0	7.0	0.5	1.3	-0.15
20	28.0	36.0	1.5	13.0	0	0.4	-0.30
21	28.0	33.0	1.5	11.0	0.4	2.1	-0.15
22	11.0	17.0	7.0	10.0	0	1.2	-0.20
23	20.0	28.0	12.0	14.0	0	0.3	-0.30
24	20.0	28.0	12.0	14.0	0.3	1.5	0.15
25	20.0	28.0	1.5	7.0	0.5	2.3	-0.15

Table 3 shows the parameter values for the model of the Texcoco basin referred to the coordinate system defined in Figure 4. The density contrasts appear associated to each prism. The trial and error procedure was applied to the model of 25 prisms; a mesh of 225 (15 x 15) stations was computed in each trial. The results were further interpolated and contoured following a method described elsewhere (González-Casanova and Alvarez, 1985). The map with the modeled contoured values corresponding to the final model is shown in Figure 6a.

A plan view of the matching prisms is shown in Figure 6b. The main features of the gravimetric response for Area B in Figure 4 are reproduced by the model of Figure 6. The gravity low running in the SW-NE direction correlates well in shape and dimensions with the field data. Several prisms (11, 25, and 21) are needed at depth in order to simulate the main low; prism 25 is the deepest, reaching 2300 m. PP-1 was drilled to 2065 m without reaching basement, thus the model agrees with such a restriction; the density contrast corresponds to consolidated sediments. The gravity high toward the NE is also reproduced as well as the gradient from the central low to the NE high. On the NW portion an undetermined geologic feature distorts the contour lines of the field survey; the modeled data shows that it is a region corresponding to a narrow canyon formed probably by a river discharging from the northern part of the basin into the Texcoco basin, excavating the canyon, which was subsequently filled up by sediments. The canyon will be called Cañón del Caracol or Snail Canyon, owing to its proximity to an evaporation plant whose geometry resembles that of a snail (Figure 4). This explanation is supported by the presence of two flanking, massive, igneous formations: Sierra de Guadalupe outcropping to the west, and Huatepec volcano to the east, most of which is presently covered by sediments. These structures would channel the river at the indicated location. The presence of this Miocene volcano was suggested by seismic refraction Line 3 and it is corroborated by the present model, which requires of prisms 4, 5, and 7 to reproduce the local Bouguer anomaly. The density contrast of + 0.15 g/cm^3 for the igneous materials in the region appears as a rather low value, but attempts at using larger values result in unacceptable gradients and much higher values for the maxima.

To reproduce the response of the central-western portion of the anomaly, a body is required approaching the surface in the neighborhood of coordinates (17500, 500) (*i.e.*, below prism 14). Apparently the basin was elongated originally in the NW direction, as suggested by the relative gravity low in that area; subsequently a structure probably raised the floor. The western end of seismic refraction Line 2 shows that refractors A and B raise in that location indicating a good correlation with gravimetric requirements. In Figure 7 cross-section Y=19.0 km cuts across Cañón del Caracol and cross-section Y=27.0 cuts across the deepest portion of the basin and across the Huatepec volcano; cross-section X=6.0 cuts thruogh the deepest area of the modeled area.

Finally, comparing the results of the eastern portion of the basin to the model results of the western portion (Figure 8a) it is convenient to note that the same range of density contrasts have been used in both data sets, including the low positive density contrasts for igneous materials; the consistency between such data is of basic importance, especially since there were no control data for the western portion. The deepest area in the western region corresponds to prism 9 of that model (Figure 8b), reaching 1250 m in depth, while the deepest area in the eastern region corresponds to prism 6 of that model, reaching 3000 m in depth. The quadrilateral in Figures 8a and b corresponds to the area of maximum damage in the September 19, 1985 earthquake; it provides a reference to correlate the results shown in various figures in this work.

Figure 9 shows the three types of soil in which the city has been divided: the hills area, the transition area, and the saturated lake deposits area; these areas are also referred to, in the geotechnical literature, as Zones I, II, and III, respectively. The seismic responses are known to be different in the three soil types (Marsal and Mazari, 1969). The area where earthquake intensity reached maximum levels in the September 19, 1985 earthquake is shown hashed; it was restricted to approximately 50 km^2 of saturated lake deposits, or about 5 percent of the total urban area. However, the area of the city built on saturated lake deposits exceeds a few fold the area of maximum damage. The question thus arises of why some saturated lake deposits were more excited than others during the earthquake.

The hashures in Figure 9 define a quadrilateral. The western side of the quadrilateral coincides with the contact between the transition area and the saturated lake deposits. The seismic response is considerably smaller in the transition area than in the sediments, providing thus a preliminary explanation for the change in the level of damage between the two areas. For the north side the correlation between the area of largest damage and the termination of the saturated deposits is not as neat as in the previous case; this is partly due to the necessary simplification made when defining the quadrilateral; in any event, the perimeter of strong damage is closely associated with the perimeter of the lake deposits in this area, the correlation between the perimeters further improves if one includes the area of light damage in that neighborhood.

For the eastern and southern sides of the quadrilateral a radically different situation exists; the strong damage stops at these boundaries for no apparent reason, since there are no contacts or geological features on the surface that can be correlated with them. It is clear, thus, that there are areas in which there should be damage and yet little or no damage was experienced. One must look for additional reasons in order to explain the lack of damage beyond the eastern side of the quadrilateral and the lack of strong damage below its southern side.

From the results of the models of areas A and B an isopach map has been generated; Figure 10 shows the isopach map as well as the quadrilateral of maximum damage and the three refraction lines. The western half of the map is considerably shallower than the Texcoco basin. The isopachs indicate that the area between Cerro del Peñón and Sierra de Guadalupe represents an obstacle for surface waves propagating in the W-E direction being a possible site of reflexions. The epicentral direction of the September 19, 1985 earthquake roughly coincides with the southern side of the quadrilateral.

Figure 11 shows three depth profiles according to the isopach map corresponding to seismic Lines b, 2, and 3. Comparing them with the seismic interpretation of Proyecto Texcoco (Figure 5) one appreciates some common trends between them, although reflector depths cannot be correlated with the gravimetrically defined bottom of the sediments. In Figure 5, Line b, both refractors show a tendency to reach the surface to the NW of PP-1 and to the SE they become deeper; the corresponding results in Figure 10 show the same tendencies around PP-1 but it shows additionally that the bottom deepens again further to the NW, a result that apparently was not resolved seismically. Line 2, immediately to the W of PP-1 shows in both results, a sharp rise;

however, it appears that the gravimetric model better defines the presence of the rising body. The seismic interpretation misses the presence of the deepest sediment deposits in the area, at the western end of Line 2. Refraction Line 3 was not completely interpreted in the Texcoco Project report, since its representation in Figure 5 stops around 1 km to the SW of PP-1; Figure 10 shows the sediments thinning out to the SW. Toward the NE the behavior of refractor B roughly coincides with the sediment depths defined gravimetrically.

ENVIRONMENTAL RELEVANCE

The extraordinary damage intensity induced by the September 19, 1985 earthquake in Mexico City has brought new attention to various topics previously researched. Among them is the problem of modeling the seismic response of the basin; Sánchez-Sesma et al. (1988) report that 1-D models of shear-wave propagation predict with reasonable accuracy the first part of the accelerations recorded in such an earthquake in the unconsolidated sediments; however, the length of the records is much larger than predicted by the models. They suggest that lateral inhomogeneities may be responsible for energy trapping in areas of the basin which focus the incoming seismic energy in certain places. They also report late arrivals of large amplitude which may be linked to Love waves on the surface of the saturated sediments. Based on the gravimetric evidence that the western portion of the basin is divided at depth by Sierrita del Peñón (Alvarez, 1988b), which is in fact the continuation to the South of Sierra de Guadalupe corresponding to prisms 1, 2 and 4 in Figure 8b, Sánchez-Sesma et al., (1988) conclude that the existence of such an obstacle would help explain the damage concentration in the area of maximum damage, owing to seismic bidimensional effects. It would also explain damage in two additional areas to the south in which narrow corridors of sediments are found between igneous formations; one is the area between Cerro de la Estrella and Xotepingo (Figure 4), and the other is the area between Xochimilco and Chalco (Figure 2) on the southernmost part of the basin. These authors report that 2-D and 3-D seismic models are needed, in order to adequately reproduce the responses and that such the models are presently being developed. In any event, the seismological models will require of geometrical constrains, which can only be adequately defined by geophysical means.

In Figure 11 a schematic geologic cross-section between the epicenter location and Mexico City is shown, as well as a group of seismic trajectories along such materials. Energy from the earthquake's focus radiates in all directions; the waves that travel through the earth's interior are the body waves, P and S; they travel to a given point in the surface through a specific trajectory and usually are of short duration and small amplitude. Of particular interest is the wave that travels vertically from the focus to the epicenter, since it gives rise to surface waves that travel parallel to the surface through low-velocity materials taking longer than P and S waves to arrive to the given point on the surface. Consequently, surface manifestations of an earthquake strongly depend on the generation mechanism, the propagation media, and the local conditions of energy liberation on the surface. Surface effects may vary widely from one location to another.

Surface waves, especially Love waves, may be channeled and multiply reflected before arriving to the target, effectively increasing the earthquake's duration. Yamamoto (1988) reports that the phase L_g dominates over P and S seismic phases, at distances typical of earthquakes generated in the Pacific coast and Mexico City (i.e. around 350 km) and that any attempt at predicting the motion of the ground at such distances requires of a previous analysis of the L_g phase, its transmission mechanisms and its attenuation characteristics. The phase L_g corresponds to a wave train which is a superposition of higher modes of Love and Rayleigh waves, traveling with group velocities between 3.1 and 3.5 km/sec, although velocities as low as 2.8 km/sec can be observed in the seismograms (Ruzaikin et al., 1977). They are transmitted only in the continental crust, arriving from 1 to 2 minutes after the first arrival, and having dominant periods between 0.5 and 6.0 seconds.

In the case of Mexico City surface waves probably arrived through different trajectories, changing direction upon reflexions and refractions. It can be appreciated from Figure 11 that a thick sedimentary section under Mexico City may have played an important role in extending the earthquake's effects on the surface by trapping energy in multiple reflexions and refractions. A strong evidence of this phenomenon is provided by the records obtained in various places in the city, showing a sequence of events that repeat themselves in the seismograms (Quaas et al., 1985). Surface waves traveling horizontally may experience similar effects in the basin, which coupled to the presence of a highly plastic surface layer may unchain the strong damage experienced in buildings and constructions.

As an example of the gravimetric definition of constrains to surface seismic wave propagation let us consider the case of area A in Figure 4. A series of field observations immediately after the earthquake (Alvarez, 1986) suggested that a peculiar interaction mechanism was operating that produced damage in previously unnoticed patterns (Alvarez, 1988b). The mechanism required the interaction of incoming and reflected waves in order to explain the appearance of damage alignments on the surface of the saturated sediments consisting of narrow (2m), vertical deformations which extended for up to 1.5 km. At the time it was a difficult task to imagine where the reflected waves could be coming from, since based on surficial geology the basin appeared to extend for about 32 km in the direction of the incoming waves. The gravimetric map of Figure 4 suggested in a qualitative fashion the presence of a massive formation under the sediments at a distance of only 7 km from the western margin of the basin, and the model confirmed it, as previously discussed. After further analysis of the gravimetric response in that area it became apparent that Sierra de Guadalupe represents a similar obstacle to waves arriving from epicentral directions directly south of Mexico City. Comparison between damage of the 1957 (M_s = 7.5) and 1985 (M_s=7.6) earthquakes, that originated in the Pacific, to the south and southwest of the city respectively, shows that the epicentral direction definitely influences the shape of the affected area (Alvarez, 1988b).

From the gravimetric models of the Texcoco area and of the western portion of the basin we can conclude that waves traveling in the NE direction would be blocked by a dense formation within the basin in the first 10 km, except in the area between Cerro del Peñón and Cerro de la Estrella (Figure 4) where they would continue without obstacles until reaching Texcoco City. One expects, thus, that the western and southern portion of the basin are seismic high-risk areas, owing to energy trapping in narrow, buried canyons. The area to the south, corresponding to Xochimilco-Chalco, will be the subject of a future study. This area is one of rapid population growth, although it does not yet have the large population concentration of the western and northern portions of Mexico City. At this time it would be most desirable to define the major risk areas in order to prevent the construction of large buildings. The main seismic obstacle in the Texcoco basin is probably the buried structure of Huatepec volcano.

CONCLUSIONS

Mexico City is possibly the largest urban conglomerate in the world; and the projections of population growth indicate that it will continue to grow. The area has been inhabited for over 2400 years, as evidenced by flows from the Xitle volcano which buried the ceremonial city of Cuicuilco, part of whose edifices have been discovered to the south of Ciudad Universitaria. Part of Mexico City is located on lake sediments which are highly saturated; these sediments are responsible for the amplification of the horizontal components of seismic waves entering the western section of the basin. The deformable sediments are limited at depths of 30 to 40 m by the first hard layer. On the western margin of the basin this layer tends to reach the surface and the saturated sediment thickness decreases consequently. It has been proposed (Del Valle, 1986) that Seiche waves can be formed when surface seismic waves travel through the sediments approaching the shallowest regions, where their amplitude would increase. Given the strength and the length of over two minutes of the September 19, 1985 earthquake, it is highly possible that incoming and reflected waves interacted in the surface causing the observed patterns of damage. Since adequate seismological models are not yet available for reproducing the full response of the sediments, a complete explanation of the phenomenon is not yet possible. However, the characteristics of the basin at basement depths must be determined in order to be able to apply the proper constraints to the seismological models. In the present study, the gravimetric modeling of the eastern part of the basin has been carried out in order to better understand wave propagation effects in the basin.

These analyses coupled to previous observations have shown that the epicentral direction is of major importance for determining the pattern of damage in the affected area of the City; they have also shown some areas that can be considered of minor risk owing to the relative protection that the underground obstacles would provide to them, when an epicentral direction is given.

Although wave interaction phenomena in the basin of Mexico has taken place since the closure and filling of the basin, starting about 0.7 m.y. ago, it is until recently that population density has made its effects highly catastrophic. There are many other areas in the world in which seismic risk and population are high; the case of Mexico City can help visualize some effects that seismic energy may unchain in such areas.

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FIGURE LEGENDS

1 Central Mexico and the Acapulco Trench. Contours correspond to isoseismal lines in the Mercalli scale for the September 19, 1985 earthquake, whose magnitude was M_s = 8.1 and its epicentral location was 17.6 N, 102.5 W. The anomalously high values at (19.5 N, 99.1 W) correspond to Mexico City. Open stars represent landslides, solid stars represent tsunamis, and v's represent stratovolcanoes. (After F. Ortega, personnal communication).

2 The main geological formations in the basin of Mexico (After Mooser, 1974).

LEGEND

Alluvial deposits   Qb Young tuffs and lavas

Lake deposits   Qp, Qcb Cones

Pheno-basaltic lavas and tuffs: Pliocene to Quaternary

Major volcanic cones: Upper Pliocene to Lower Quaternary

3 Evolution of the lakes in the basin of Mexico. A) Late Pleistocene, B) 16th century, C) early 19th century, and D) 1889. After a reconstruction from E. Shilling (Bribiesca, 1960).

4 The gravimetric response of the basin of Mexico. Contour values are in geophysical units (1 gu = 0.1 milligals) Two areas have been modeled gravimetrically: Area A on the western portion of the basin has been already reported (Alvarez, 1988a), area B is the subject of the present study. Three refraction seismic lines are labeled b, 2, and 3; its intersection corresponds to hole PP1. Along Line 3 occur the minimum (16 mGal) and maximum (36 mGal) gravity values in area B. After Marsal and Mazari (1969).

5 Seismic refraction profiles across the Texcoco basin corresponding to lines shown in the map of Figure 4. Velocity units are m/s.

6a) Contoured values of the Bouguer anomaly in mGals, corresponding to area B of Figure 4: the Texcoco basin. b) Plan view of the prisms described in Table 3.

7 Three cross-sections of the model of Figure 6.

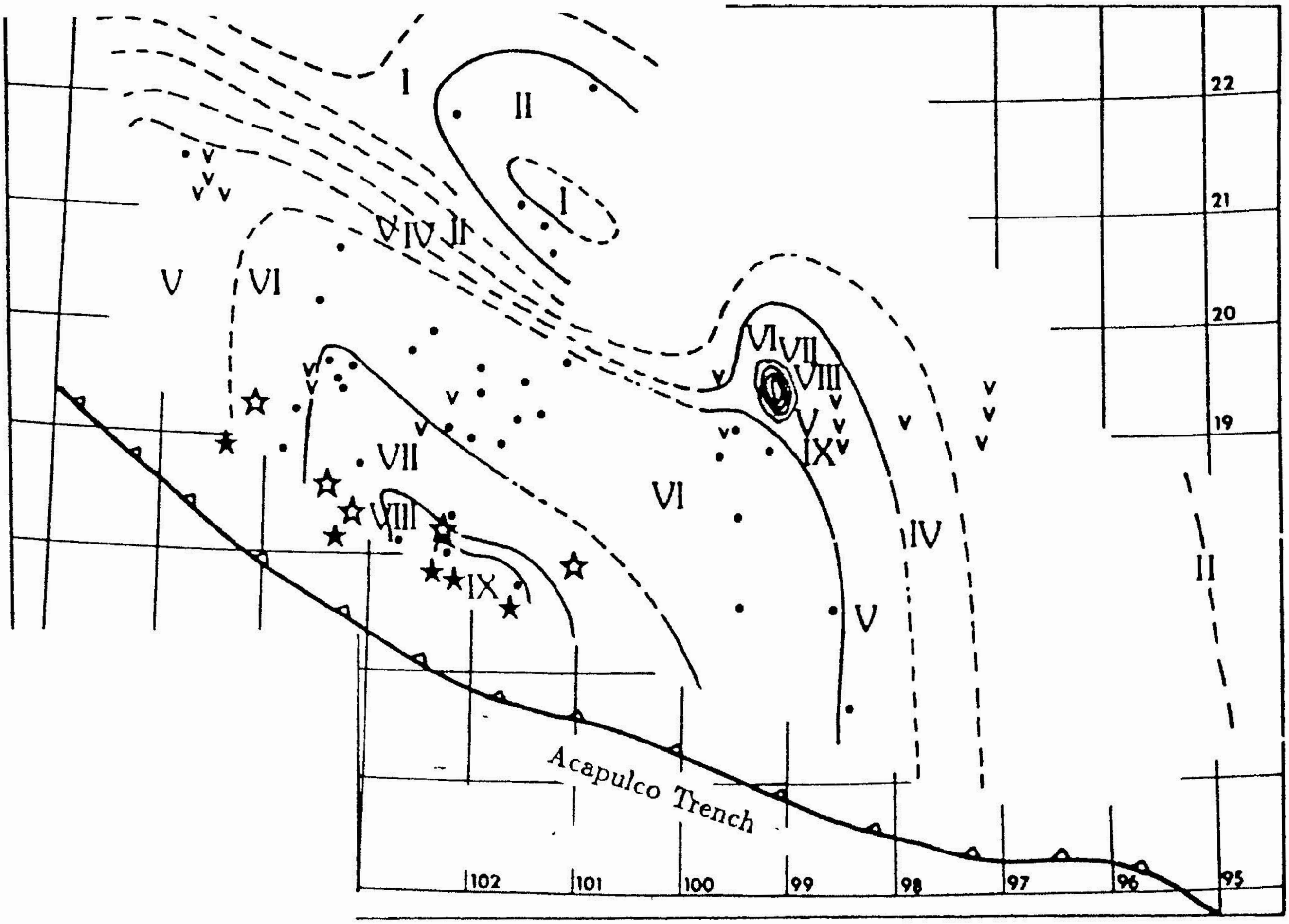
8 a) Contoured values of the Bouguer anomaly model area A in Figure 4, which includes the area of maximum damage of the September 19, 1985 earthquake shown as a quadrilateral. b) Prism model devoid of sediments under area A; the hashed sections from north to south correspond to outcrops of Sierra de Guadalupe, Cerro del Peñón, and Cerro de la Estrella. The quadrilateral shown corresponds to the one shown in a).

9 Mexico City is built on three types of terrain: the hilly area, the transition area, and the saturated lake deposits area. The area of maximum damage in the September 19, 1985 earthquake is defined by the hashed quadrilateral.

10 From the gravimetric models in areas A and B of Figure 4 an isopach map of basin-filling rocks has been constructed. The quadrilateral corresponds to the hashed quadrilateral of Figure 9. The three seismic refraction lines in Figure 4 are shown; its intersection defines the location of deep well PP1. This portion of the basin is divided by Sierrita del Peñón, running from Cerro del Peñón to Sierra de Guadalupe. The eastern section is considerably deeper than the western one.

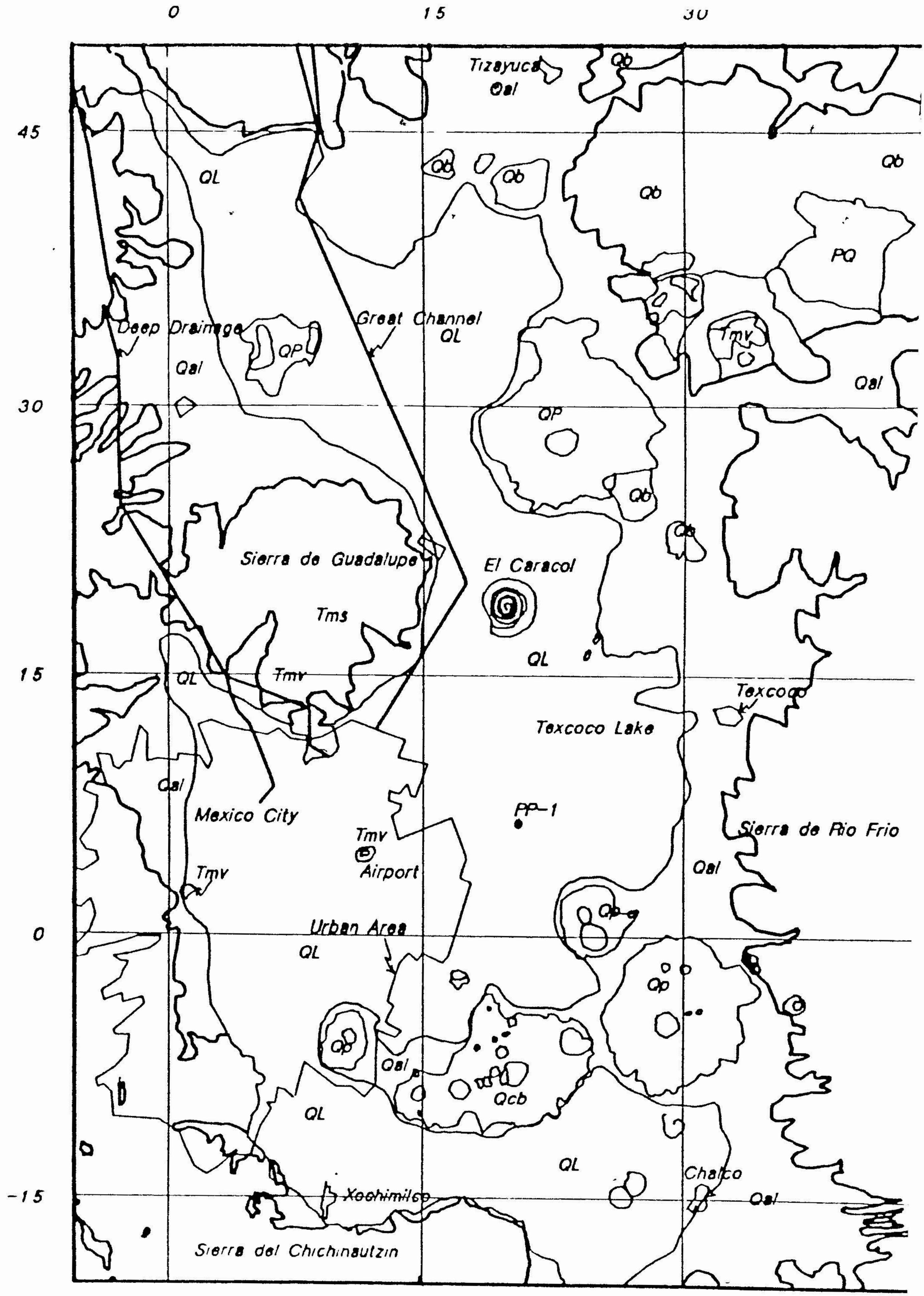
11 Three cross-sections along Lines b, 2, and 3 in Figure 10, show the depth profiles of the sediments. The location of deep well PP1 is shown in each case.

12 Schematic geologic cross-section between the epicenter location of the September 19, 1985 earthquake and Mexico City and various seismic trajectories along it, corresponding to surface and body waves. The thick limestone sedimentary section under the basin of Mexico probably produced channeling and multiple reflexions and refractions of the seismic waves. After Del Valle, 1986.

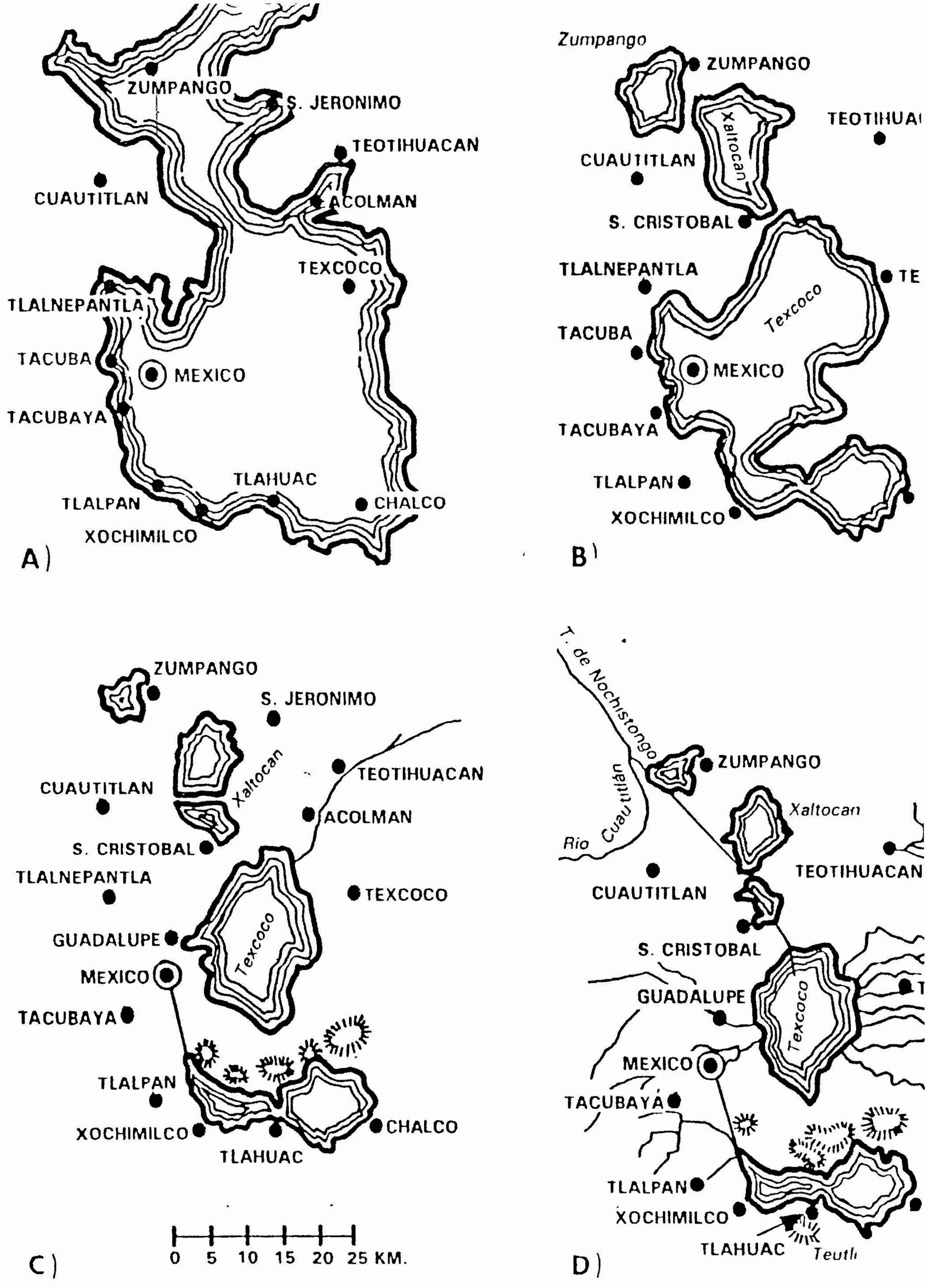


Acapulco Trench
22
21
20
19
102
101
100
99
98
97
96
95
I
II
V
VI
VII
VIII
IX
IV

Fig. 1

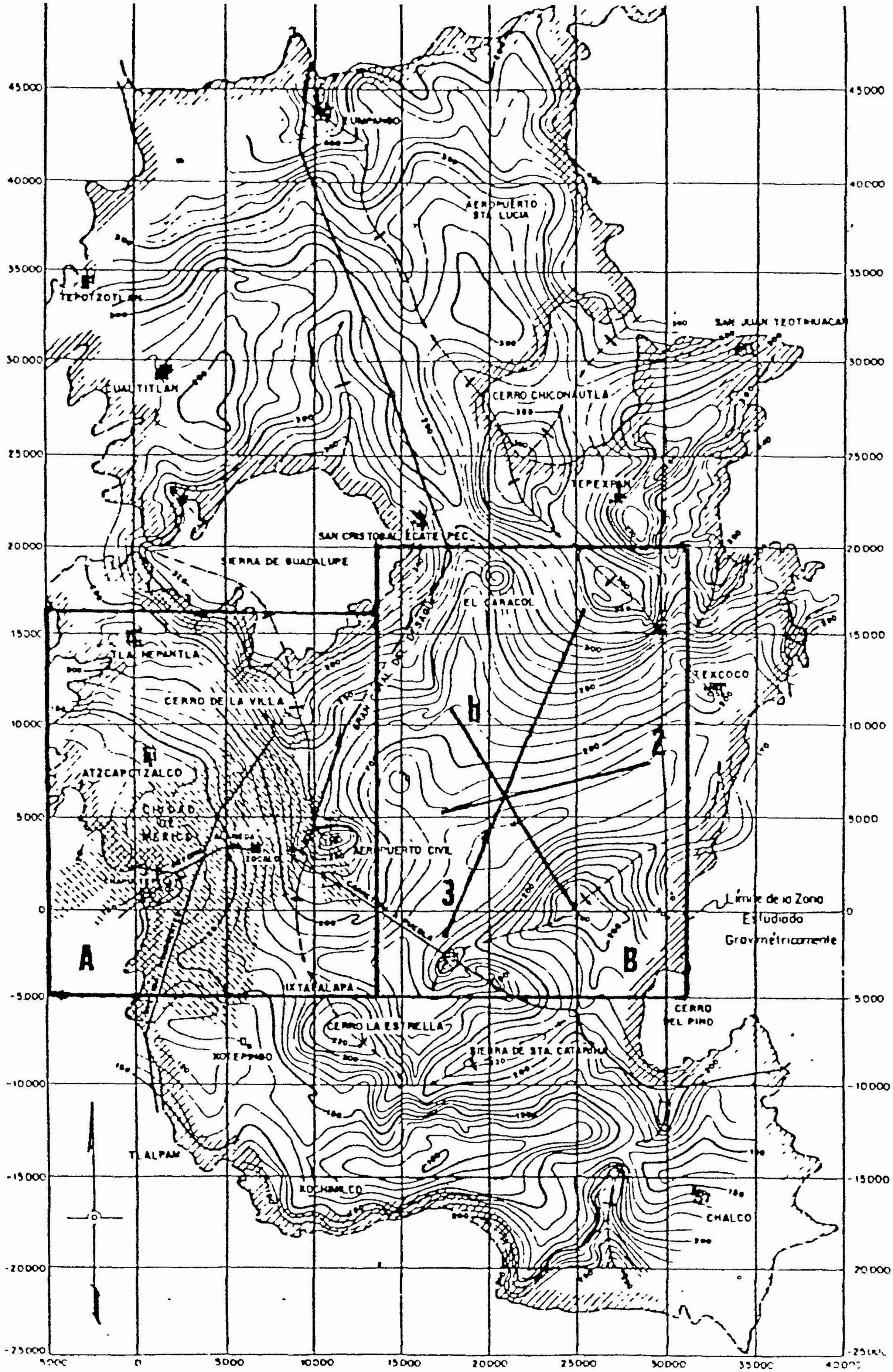


0
15
30
45
30
15
0
-15
Tizayuca
Qal
Qb
Qb
Qb
Qb
Qb
QL
PQ
Deep Drainage
QP
Great Channel
QL
Tmv
Qal
Qal
QP
Qb
Qb
Sierra de Guadalupe
El Caracol
Tms
QL
QL
Tmv
Texcoco
Texcoco Lake
Qal
Mexico City
PP-1
Tmv
Sierra de Rio Frio
Airport
Qal
Tmv
Qp
Urban Area
QL
Qp
Qp
Qal
Qcb
QL
QL
Chalco
Xochimilco
Qal
Sierra del Chichinautzin



ZUMPANGO
S. JERONIMO
TEOTIHUACAN
CUAUTITLAN
ACOLMAN
TEXCOCO
TLALNEPANTLA
TACUBA
MEXICO
TACUBAYA
TLAHUAC
TLALPAN
CHALCO
XOCHIMILCO
A)
Zumpango
ZUMPANGO
Xaltocan
CUAUTITLAN
S. CRISTOBAL
TLALNEPANTLA
Texcoco
TACUBA
MEXICO
TACUBAYA
TLALPAN
XOCHIMILCO
B)
ZUMPANGO
S. JERONIMO
Xaltocan
TEOTIHUACAN
CUAUTITLAN
ACOLMAN
S. CRISTOBAL
TLALNEPANTLA
TEXCOCO
GUADALUPE
Texcoco
MEXICO
TACUBAYA
TLALPAN
XOCHIMILCO
TLAHUAC
CHALCO
0 5 10 15 20 25 KM.
C)
T. de Nochistongo
ZUMPANGO
Río Cuautitlán
Xaltocan
TEOTIHUACAN
CUAUTITLAN
S. CRISTOBAL
GUADALUPE
Texcoco
MEXICO
TACUBAYA
TLALPAN
XOCHIMILCO
TLAHUAC
Teutli
D)

Fig. 3



ZUMPANGO
AEROPUERTO STA. LUCIA
TEPOTZOTLAN
SAN JUAN TEOTIHUACAN
CUAUTITLAN
CERRO CHICONAUTLA
TEPEXPAN
SAN CRISTOBAL ECATEPEC
SIERRA DE GUADALUPE
EL CARACOL
TLALNEPANTLA
TEXCOCO
CERRO DE LA VILLA
ATZCAPOTZALCO
CIUDAD DE MEXICO
ZOCALO
AEROPUERTO CIVIL
Límite de la Zona Estudiada Gravimétricamente
A
B
IXTAPALAPA
CERRO DEL PINO
CERRO LA ESTRELLA
SIERRA DE STA. CATARINA
XOCHIMILCO
TLALPAM
CHALCO

Fig. 4

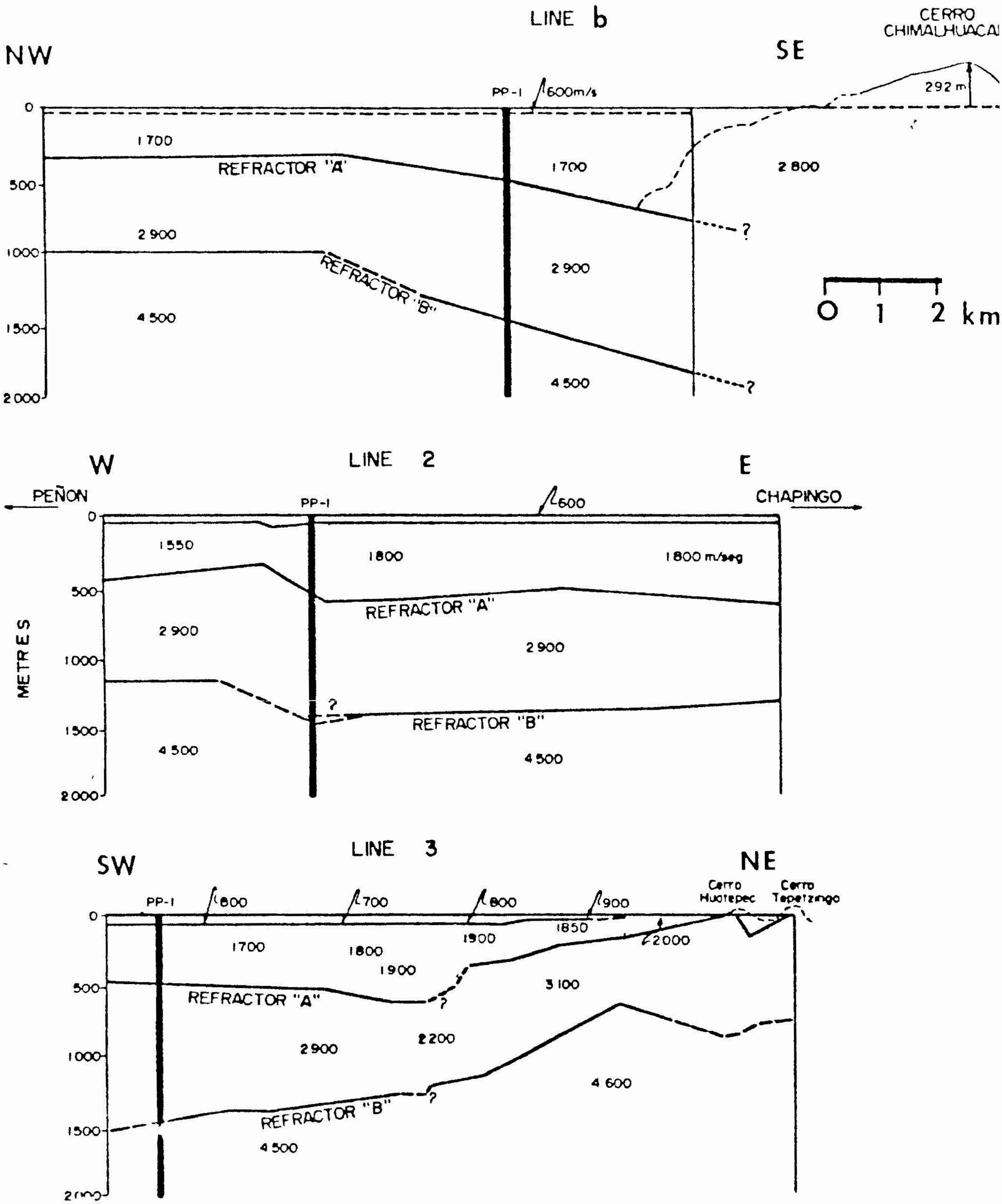
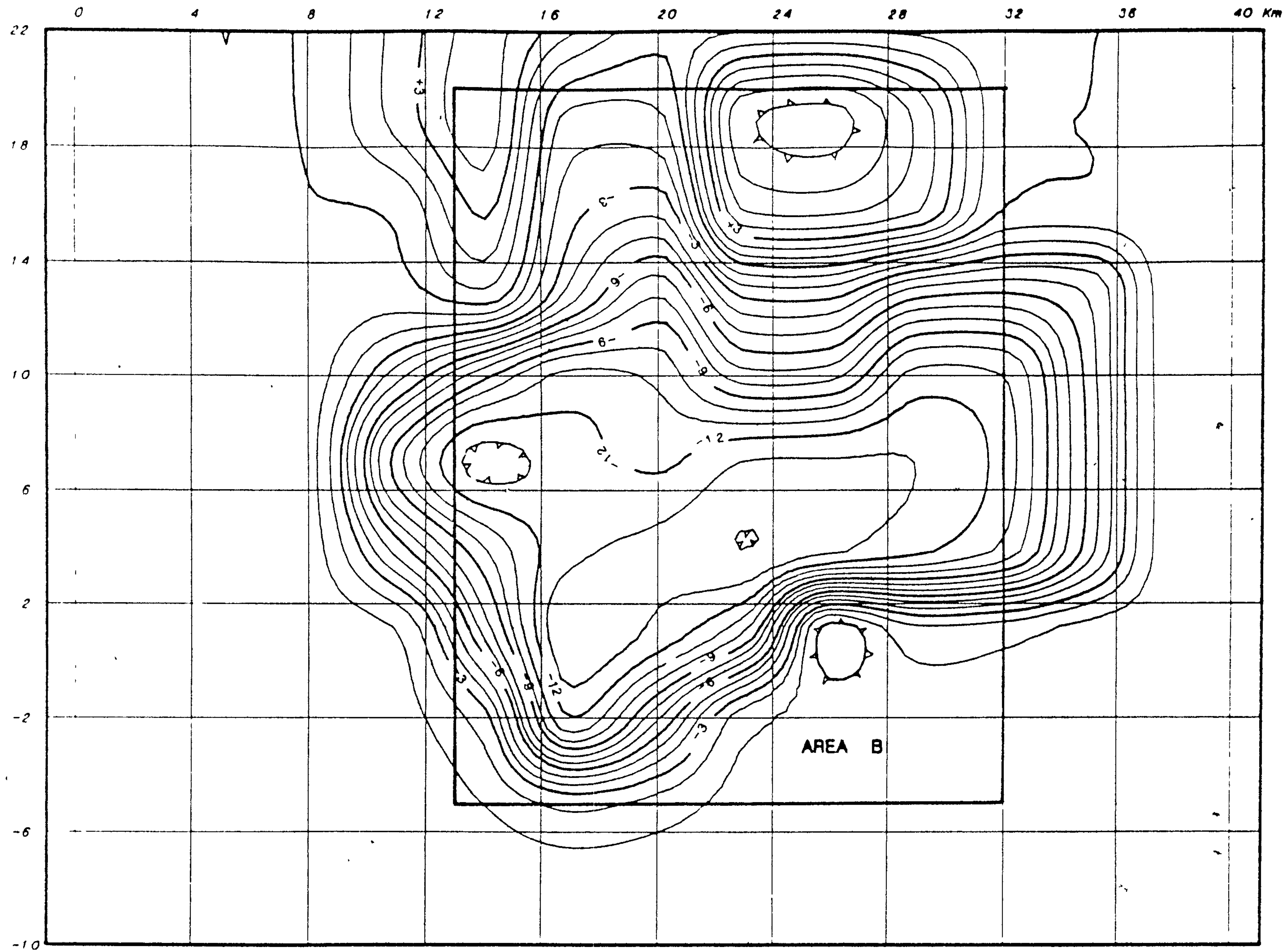

LINE b
NW
SE
CERRO CHIMALHUACA
292 m
PP-1
600m/s
1700
1700
2800
REFRACTOR "A"
2900
2900
REFRACTOR "B"
4500
4500
0 1 2 km
0
500
1000
1500
2000
LINE 2
W
E
PEÑON
CHAPINGO
PP-1
600
1550
1800
1800 m/seg
REFRACTOR "A"
2900
2900
REFRACTOR "B"
4500
4500
METRES
LINE 3
SW
NE
Cerro Huatepec
Cerro Tepetzingo
PP-1
800
700
800
900
1700
1800
1900
1900
1850
2000
3100
REFRACTOR "A"
2200
2900
4600
REFRACTOR "B"
4500

Fig. 5



0
4
8
12
16
20
24
28
32
36
40 Km
22
18
14
10
6
2
-2
-6
-10
+3
-3
-6
-9
-12
AREA B

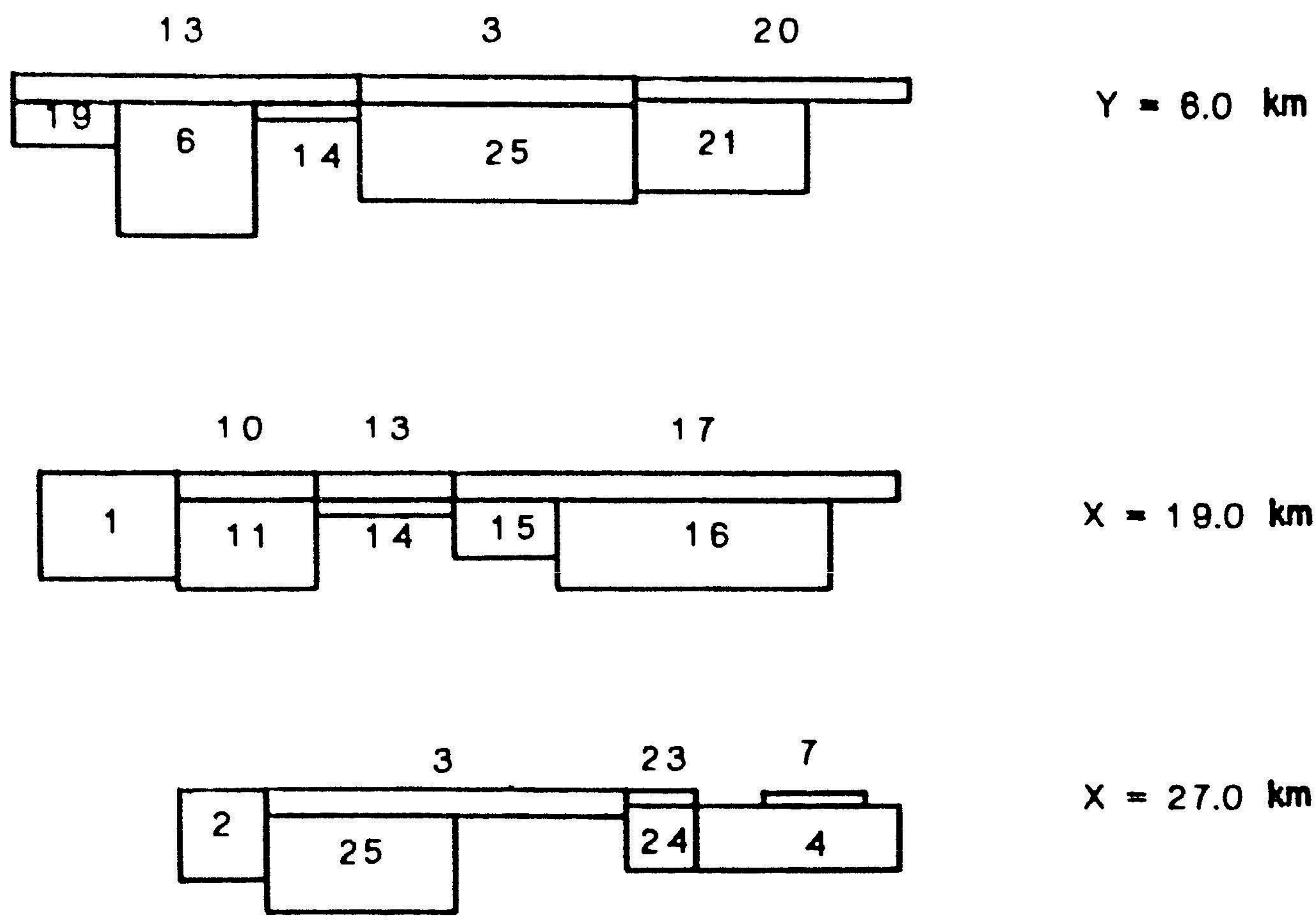

13
3
20
19
6
14
25
21
Y = 6.0 km
10
13
17
1
11
14
15
16
X = 19.0 km
3
23
7
2
25
24
4
X = 27.0 km

Fig. 7

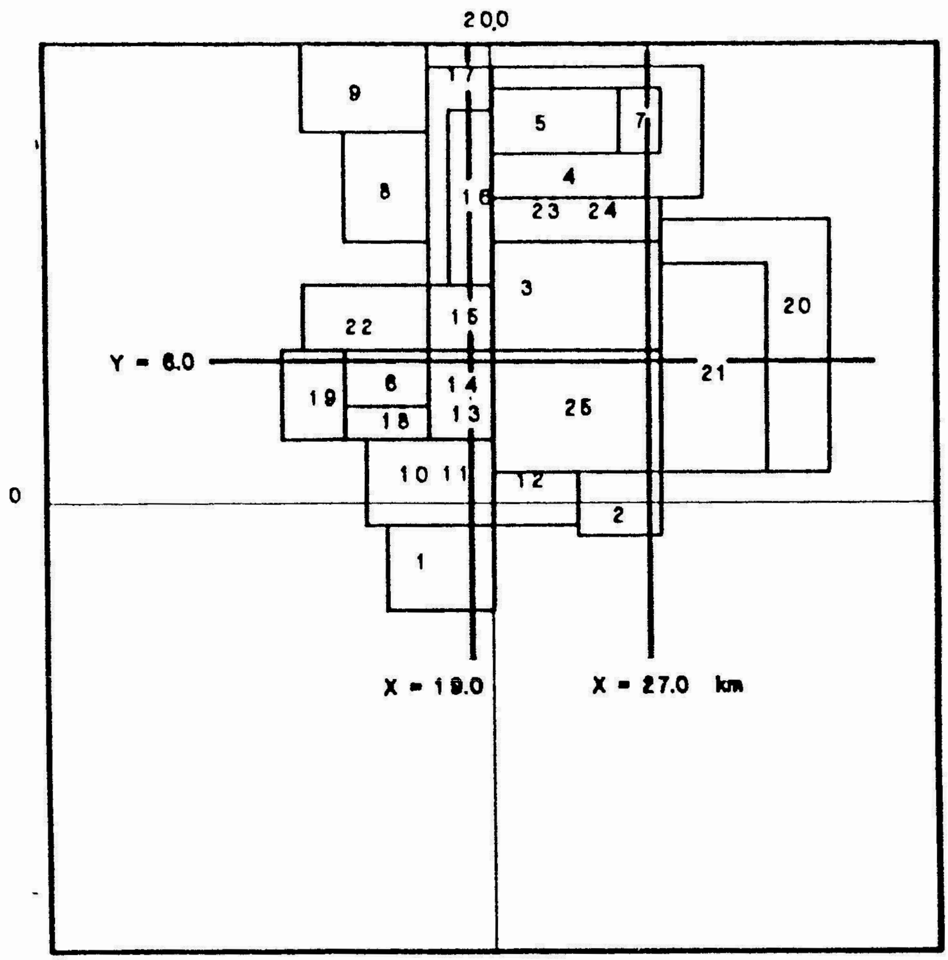
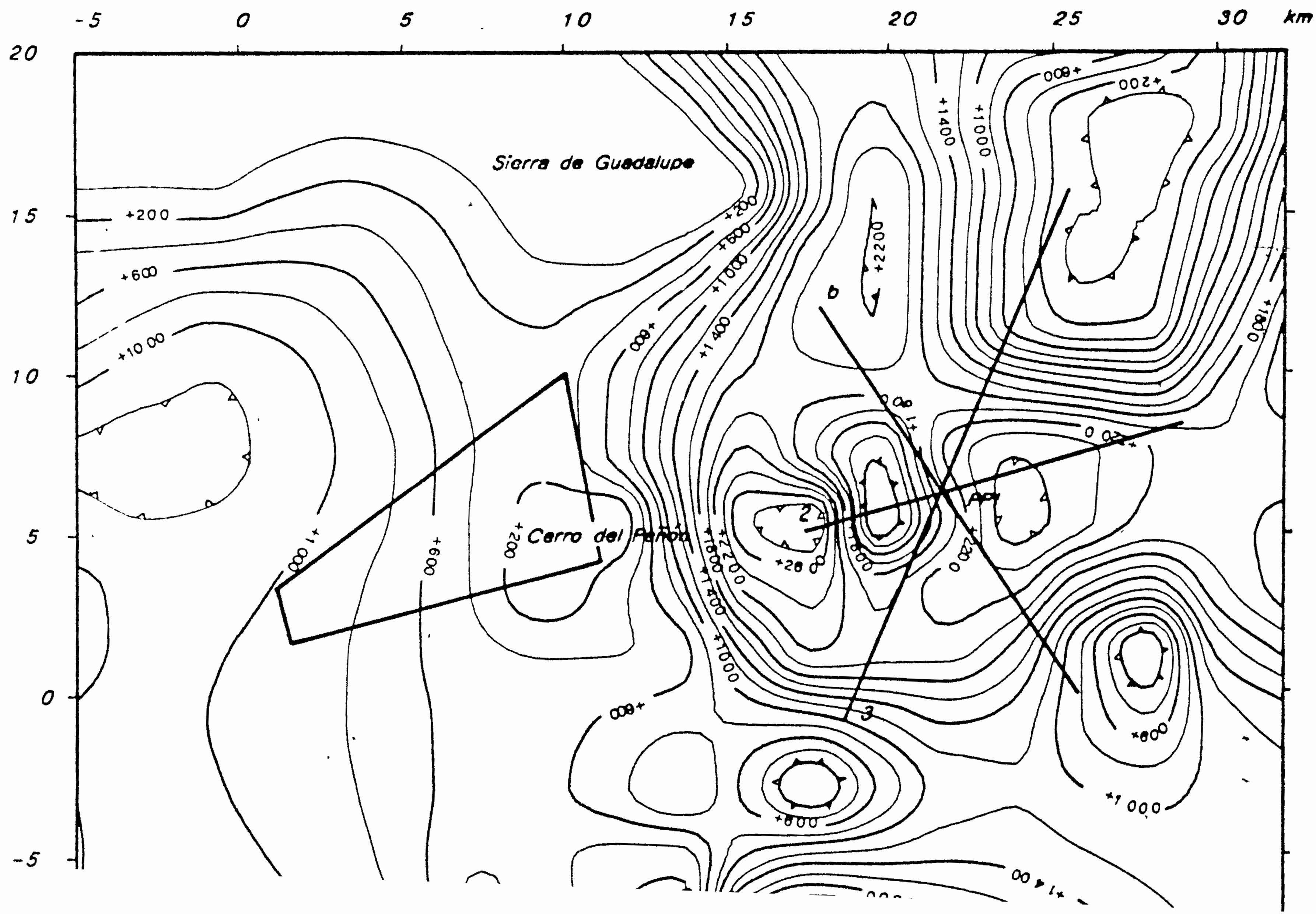

20.0
9
17
5
7
8
4
16
23 24
3
20
22
15
Y = 6.0
19
6
14
21
18
13
25
10 11
12
0
2
1
X = 19.0
X = 27.0 km

Fig. 6b

ISOPACHS OF BASIN-FILLING ROCKS IN THE MEXICO-TEXCOCO AREA



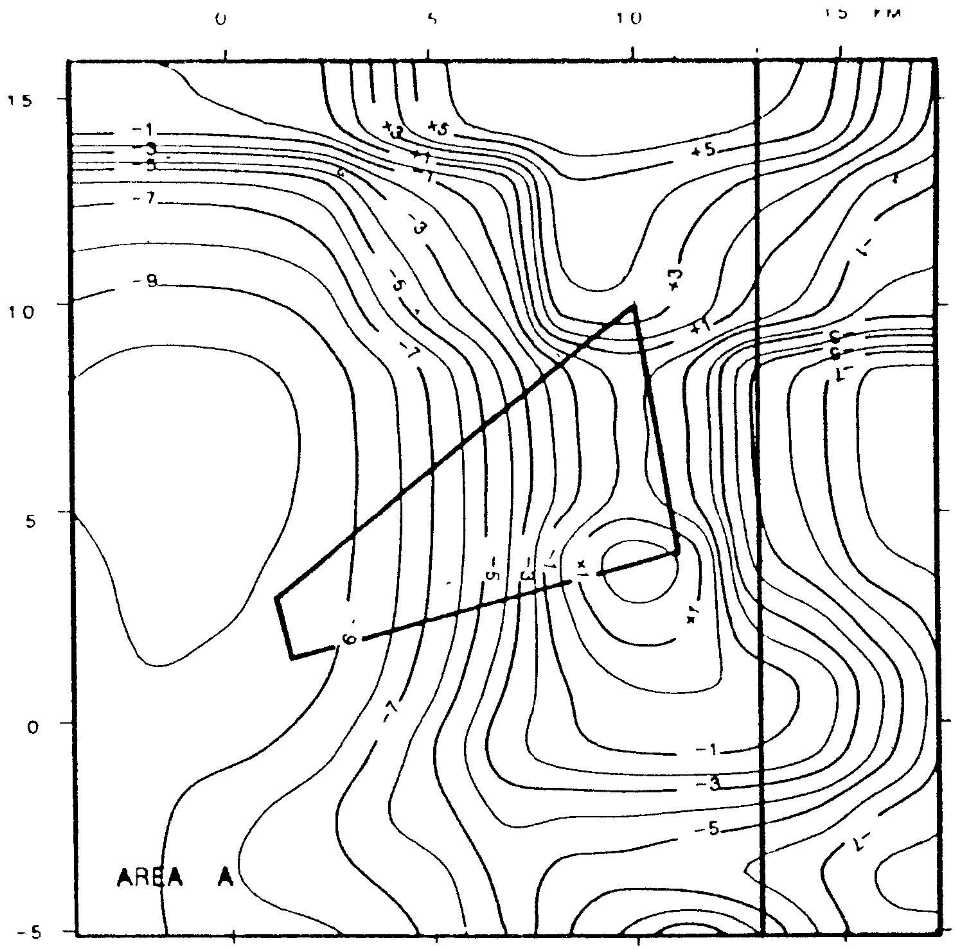
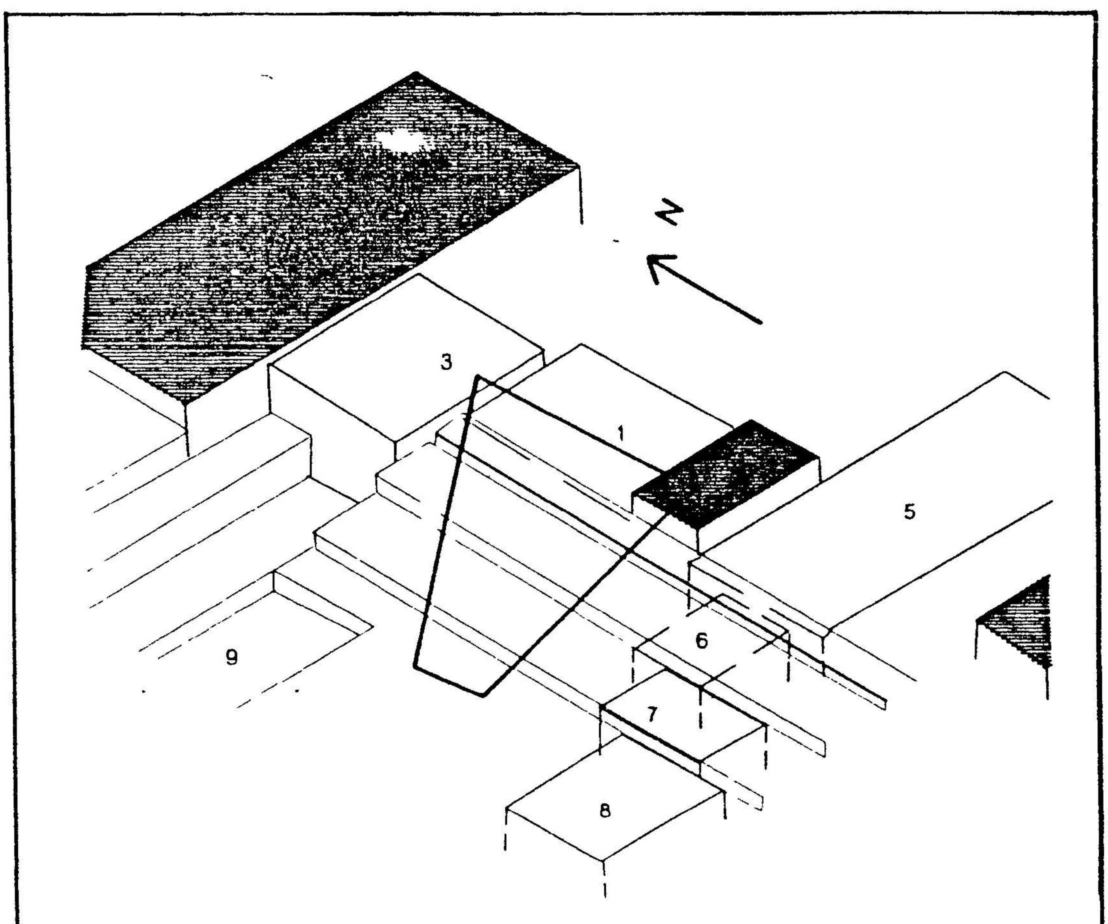
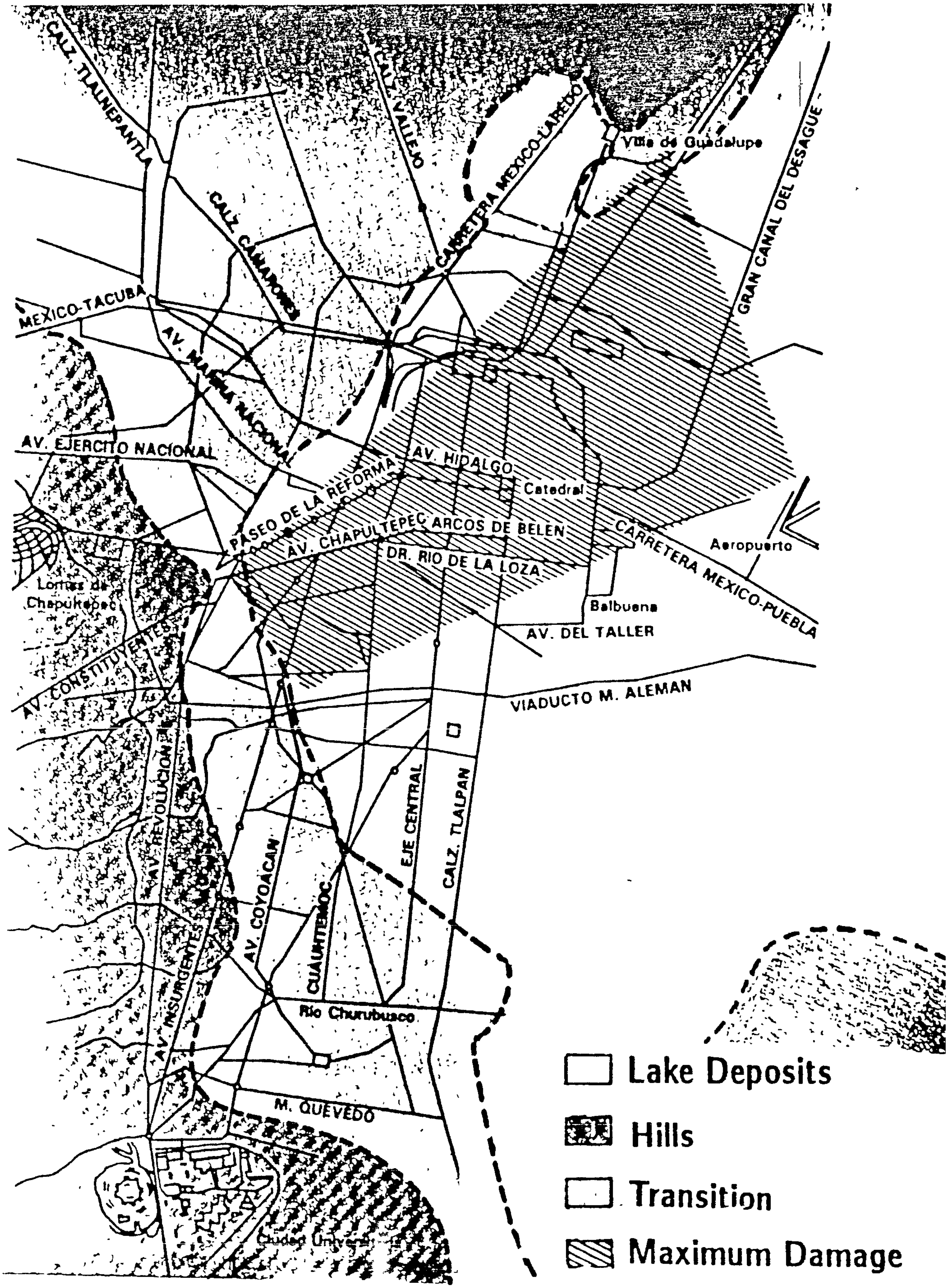


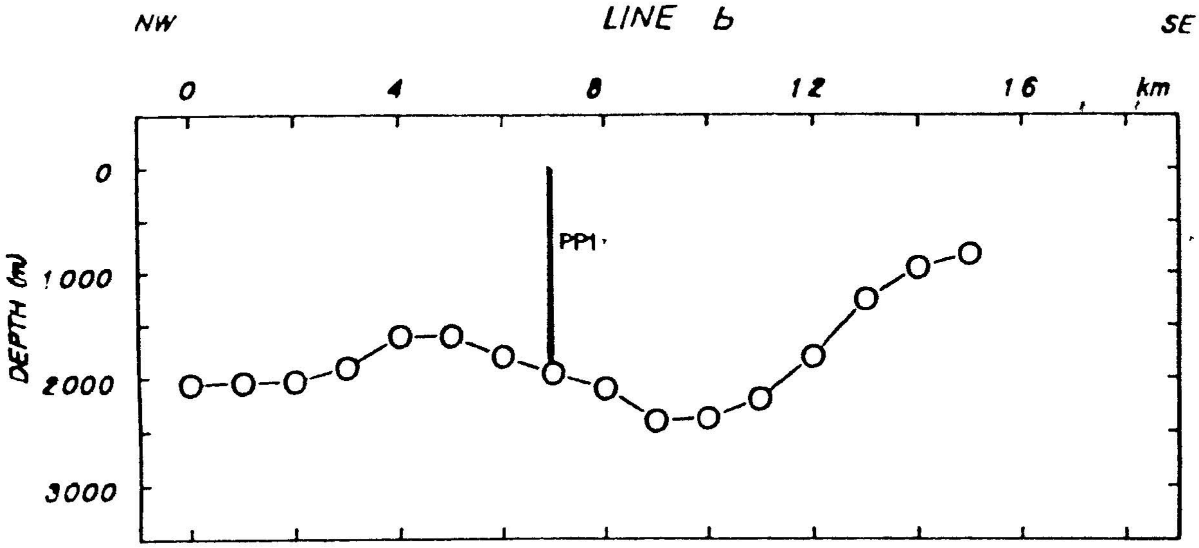
Fig. 8a

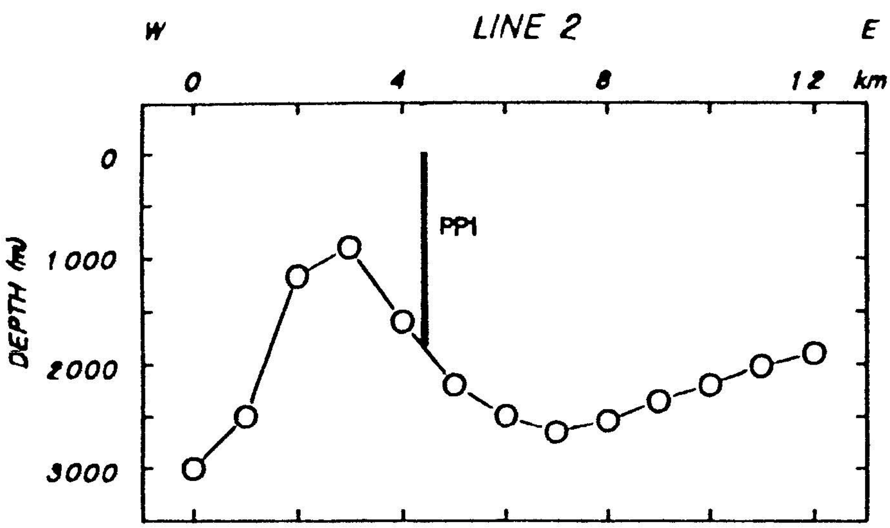


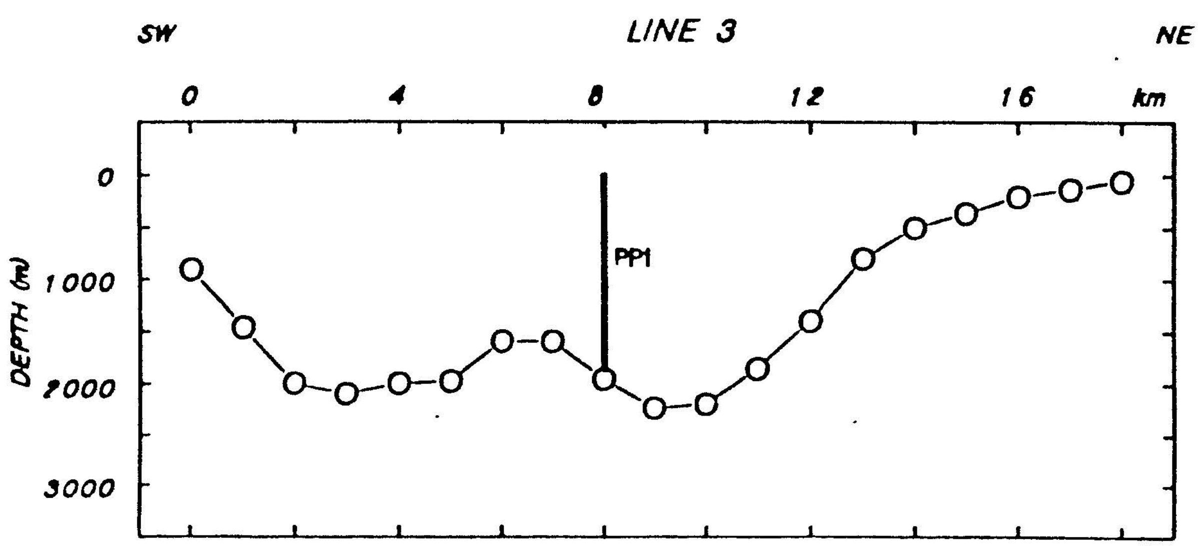


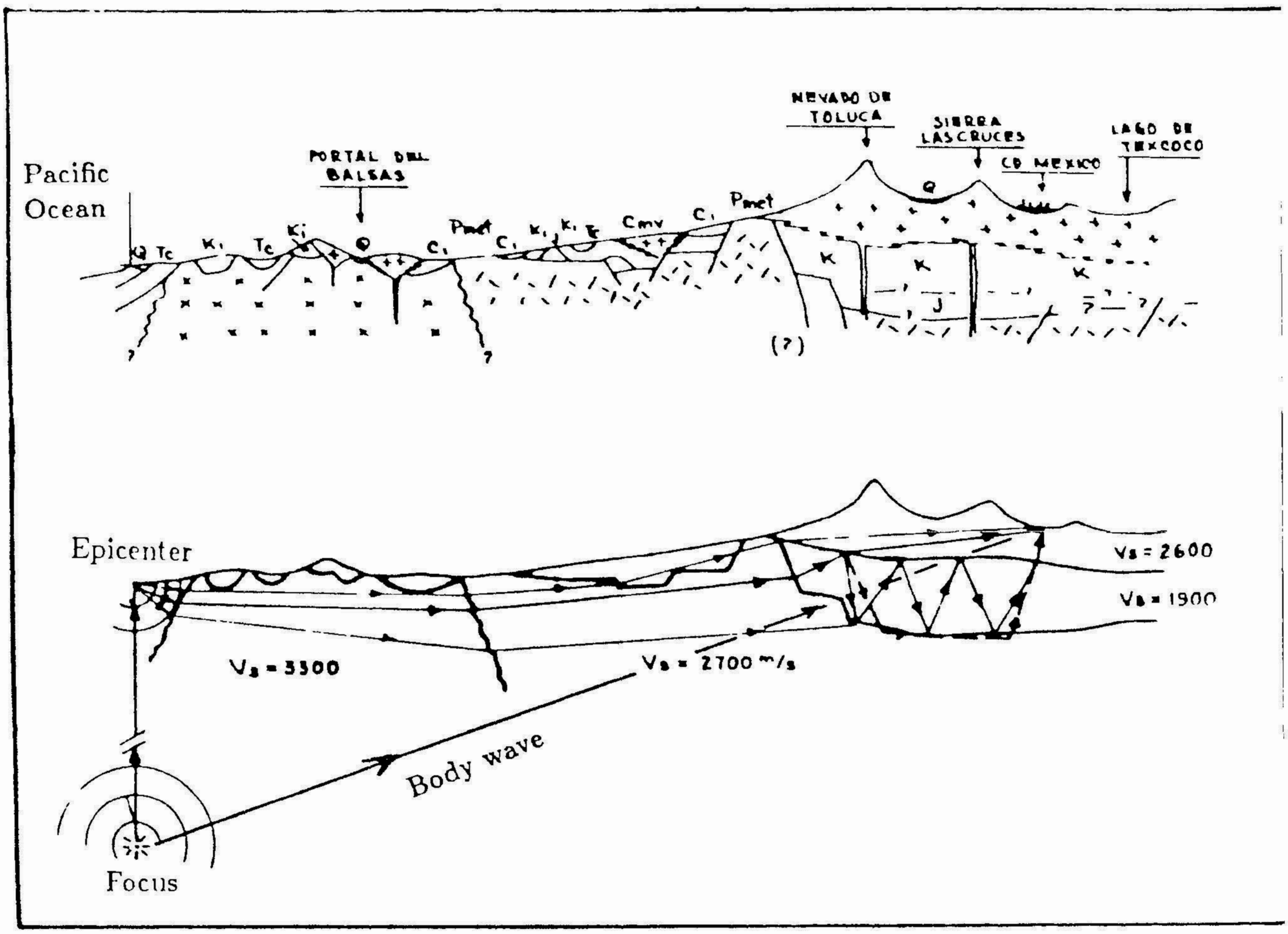
CALZ. TLALNEPANTLA
CALZ. VALLEJO
CARRETERA MEXICO-LAREDO
Villa de Guadalupe
GRAN CANAL DEL DESAGUE
CALZ. CAMARONES
MEXICO-TACUBA
AV. MARINA NACIONAL
AV. EJERCITO NACIONAL
PASEO DE LA REFORMA
AV. HIDALGO
Catedral
AV. CHAPULTEPEC
ARCOS DE BELEN
CARRETERA MEXICO-PUEBLA
Aeropuerto
DR. RIO DE LA LOZA
Balbuena
AV. DEL TALLER
AV. CONSTITUYENTES
VIADUCTO M. ALEMAN
AV. REVOLUCION
AV. INSURGENTES
AV. COYOACAN
CUAUHTEMOC
EJE CENTRAL
CALZ. TLALPAN
Rio Churubusco
M. QUEVEDO
Lake Deposits
Hills
Transition
Maximum Damage

Fig. 9


NW
LINE b
SE
0
4
8
12
16
km
0
1000
2000
3000
DEPTH (m)
PP1


W
LINE 2
E
0
4
8
12
km
0
1000
2000
3000
DEPTH (m)
PP1


SW
LINE 3
NE
0
4
8
12
16
km
0
1000
2000
3000
DEPTH (m)
PP1


NEVADO DE TOLUCA
SIERRA LASCRUCES
LAGO DE TEXCOCO
PORTAL DEL BALSAS
CD MEXICO
Pacific Ocean
Epicenter
Vs = 2600
Vs = 1900
Vs = 3300
Vs = 2700 m/s
Body wave
Focus