Geofísica Internacional (2003), Vol. 42, Num. 1, pp. 3-24

Subsurface structure of the Tecocomulco sub-basin (northeastern Mexico basin), and its relationship to regional tectonics

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Received: September 30, 2000; accepted: March 11, 2002

RESUMEN

Con base en estudios geofísicos (gravimetría, magnetometría, resistividad de corriente directa, y VLF), mapeo geológico detallado y análisis de lineamientos regionales establecimos la estructura sub-superficial de la subcuenca de Tecocomulco (porción noreste de la cuenca del Valle de México). De acuerdo con nuestros resultados, hacia el sur la estructura de la sub-cuenca es del tipo de semigraben. Hacia el este, tres fallas caracterizan el semigraben. Sin embargo, sólo una falla lo delimita hacia el oeste. Hacia el norte, la cuenca se ensancha. Estas fallas que delimitan el semigraben, así como el alineamiento de varios conos de cenizas, y las montañas vecinas que limitan la cuenca tienen una orientación NE-SW.

La estructura de semigraben debe su origen a la inclinación hacia el NW de bloques regionales corticales someros. Aun si una cadena de conos de ceniza interrupte el drenaje superficial hacia el sur en dirección de la subcuenca vecina de Apan, inferimos una comunicación a profundidad entre estas dos subcuencas a través de un graben estrecho. Las fallas afectando la sub-cuenca de Tecocomulco podrían todavía estar activas tal como se infiere por una actividad sísmica de bajo nivel. El estudio resistivo por corriente directa ayudo a caracterizar la secuencia estratigráfica del relleno volcanosedimentario. De acuerdo con nuestro estudio, la caldera de Acoculco no es una caldera típica de pistón, sino una caldera del tipo de graben subsidido. La caldera de Chichicuautla fue seccionada por una falla NW-SE, su porción sur habiendo subsidido. La firma gravimétrica de la porción sur de esta caldera está enmascarada por la presencia de un alto estructural o cuerpos máficos.

PALABRAS CLAVE: Estructura subsuperficial, semigraben, fallas y lineamientos NE-SW, geología de detalle, estudios geofísicos.

ABSTRACT

Gravity, magnetics, DC resistivity, VLF profiles, geologic mapping, and analysis of regional lineaments in the Tecocomulco sub-basin of the northeastern Mexico Basin were carried out. To the south, the structure is of the half-graben type. To the north, the basin gets wider. Three NW-SE faults bound the half-graben to the E while only one delimits it to the W. Faults delimiting the half-graben, as well as several cinder cones and the neighboring ranges delimiting the basin, have a NE-SW orientation. The half-graben structure is due to tilting towards the NW of regional shallow crustal blocks. A chain of cinder cones interrupts the southward surficial drainage towards the neighboring Apan Basin, but we infer a communication at depth between these two sub-basins through a narrow graben. The faults in the Tecocomulco basin might still be active, as inferred by low-level seismic activity. DC resistivity helped to characterize the stratigraphic sequence of the volcano-sedimentary infill. The Acoculco caldera is not a piston-like caldera but a collapsed graben caldera. The Chichicuautla caldera has been downfaulted to the south by a NW-SE fault. The gravity signature of the southern half of this caldera is masked by the presence of a structural high, or by mafic bodies.

KEY WORDS: Subsurface structure, half-graben, NE-SW faults and lineaments, detailed geology, geophysical studies.

INTRODUCTION

With a population of about 20 million, Mexico City is one of the largest cities in the world. One of the major problems is the supply of drinking water. Sixty percent of the water is extracted from subsurface aquifers, mainly beneath the city or from the Chalco sub-basin (Figure 1).

Extensive pumping has caused a decline of the groundwater level and has induced in the Chalco sub-basin a ground

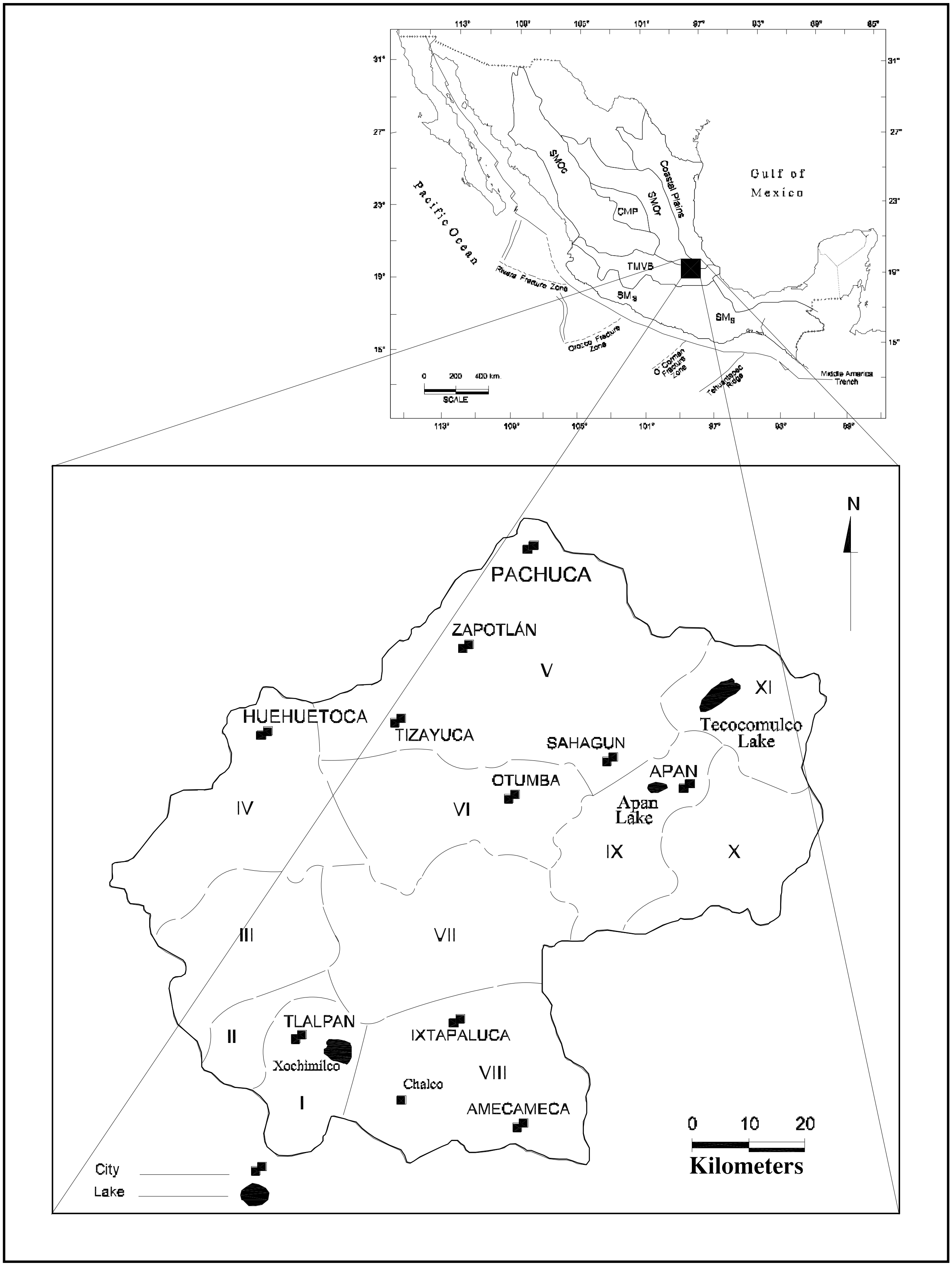


Fig. 1. The hydrographic division of the Basin of Mexico (taken from Bellia *et al.*, 1992). In the inset the location of the study area in the central Trans-Mexican Volcanic Belt close to the Sierra Madre Oriental physiographic province.

subsidence of about 0.4 m per year (Ortega-Guerrero *et al.*, 1993). The anthropogenic processes defining the urban and industrial development influence the quality of life and represent a pollution source for underground water resources.

The basin of Mexico City comprises 11 sub-basins (Figure 1). Most of the studies have been focused on the aquifers beneath the city itself (e.g., Herrera, 1989) or in Chalco (e.g., Huizar-Álvarez, 1989 and 1993; Ortega-Guerrero *et al.*, 1993; Campos-Enríquez *et al.*, 1997). The sub-basins located northeast of the basin of Mexico City (Apan, Tochac and Tecocomulco) have been less extensively studied. Recently Huizar-Álvarez *et al.* (1997) made a geophysical and hydrogeological characterization of the sub-basins of Apan and Tochac.

In this paper we report the results of a multidisciplinary geophysical study using gravity, magnetics, DC-resistivity and VLF to establish the main features of the subsurface structure of the Tecocomulco sub-basin.

GEOLOGIC SETTING

The Tecocomulco sub-basin is located in the east-central Trans-Mexican Volcanic Belt (TMVB), close to the Sierra Madre Oriental (SMOr) (Figure 1). It has an elliptic shape with a NE-SW orientation. Its interior is at 2550 m above sea level. The plain is surrounded by Tertiary and Quaternary volcanic ranges with the Chichicuautla range to the NW and to the southeast the Tepozan range (Figure 2).

La Paila volcano, the Chichicuautla caldera and cinder cones such as Tio Lolo, Coatzetzengo, and Seco constitute the southwestern relief of the Chichicuautla range (Figure 3). About 50 km to the northwest of this range is the Sierra de Pachuca.

The Tepozan range separates the Tecocomulco and Tochac sub-basins with the highest elevations (3300 m above sea level). To the northeast of this range are found the volcanoes of Cocinillas and Coyotes, south of the town of Tezoyo.

To the east the sub-basin is bounded by Tecoloquillo and Minilla volcanoes, and by the Acoculco caldera (López-Hernández and Castillo-Hernández, 1997; Verma, 2001). They are emplaced in a volcanic NW-SE plateau located near the Sierra Madre Oriental (SMOr).

To the southwest, the drainage between the sub-basins of Tecocomulco and Apan is partially interrupted by a NE-SW chain of quaternary cinder cones in the middle of the plain. Viejo de Tultengo is the northern most cinder cone in this chain.

Regional tectonics and geologic studies of the Valley of Mexico (Bryan, 1948; Arellano, 1953; Vázquez and Jaimes, 1989), and of the Tecocomulco sub-basin (Mooser, 1963 and 1975; Demant, 1981; Marín *et al.*, 1985; Ledezma-Guerrero, 1987) describe the area.

At a local and detailed level there are geologic studies of the Chichicuautla range (Castro-García and Córdoba, 1994), and of the Acoculco caldera (de la Cruz-Martínez and Castillo-Hernández, 1986; Castillo-Hernández, 1986; López-Hernández and Castillo-Hernández, 1997).

Because of the proximity of the SMOr, we infer that the basement is constituted by a limestone sequence. At the Texcoco-1, Tulyehualco-1, and EAC-1 wells drilled in the southern portion of the basin of Mexico (Pérez-Cruz, 1988), and in the Acoculco caldera (López-Hernández and Castillo-Hernández, 1997) the limestone is found at depths of 1980 m, 2100 m and 790 m respectively.

At the Acoculco caldera the limestone is metamorphosed and is underlain by a microgranite of late Cretaceous age. Resting on this local basement is a sequence of volcanic rocks as well as fluvial and lacustrine sediments.

The volcanic rocks range from Miocene to Holocene, and their composition ranges from acidic to basic.

The lower unit of the volcanic sequence is composed of andesite and rhyolite flows (Tomvp). It forms hills with heights of above 3000 m above sea level, up to 500 m above the basin floor. This unit, named El Peñón by Ledesma-Guerrero (1987), has been correlated with the Oligocene-Miocene Pachuca Group of Segerstrom (1961). The 200 to 250 thick Chignahuapan Formation (Tpch) overlies the El Peñón andesitic sequence, and is constituted by a sequence of rhyolites and hyalotrachytes, both of vitreous texture. These rocks form elongated hills and have been assigned a Pliocene age (Ledesma-Guerrero, 1987). According to Ledesma-Guerrero (1987) the outcroppings of these rocks in the Tepozan are mainly andesitic rocks. However, the stratigraphic relation we observed in this study was the opposite: the rhyolites constitute the base of this range. At km 1.5 before Tepozan, as one comes down from the Tepozan range on the Apan-Tepozan road, at the base of the range we observe horizontal flows of rhyolitic rocks with a thickness of up to 1 m, covered by rocks from the El Peñon andesites.

Ledesma-Guerrero (1987) reports a group of undifferentiated Tertiary volcanic rocks, Tpv, (including andesites, latites, rhyolites and rhyolitic tuffs) which outcrop over the study area. Here we differentiate the acidic (Tpr) from the intermediate-basic (Tpa) members of this group. At La Minilla volcano we observe andesitic blocks, with large pla-

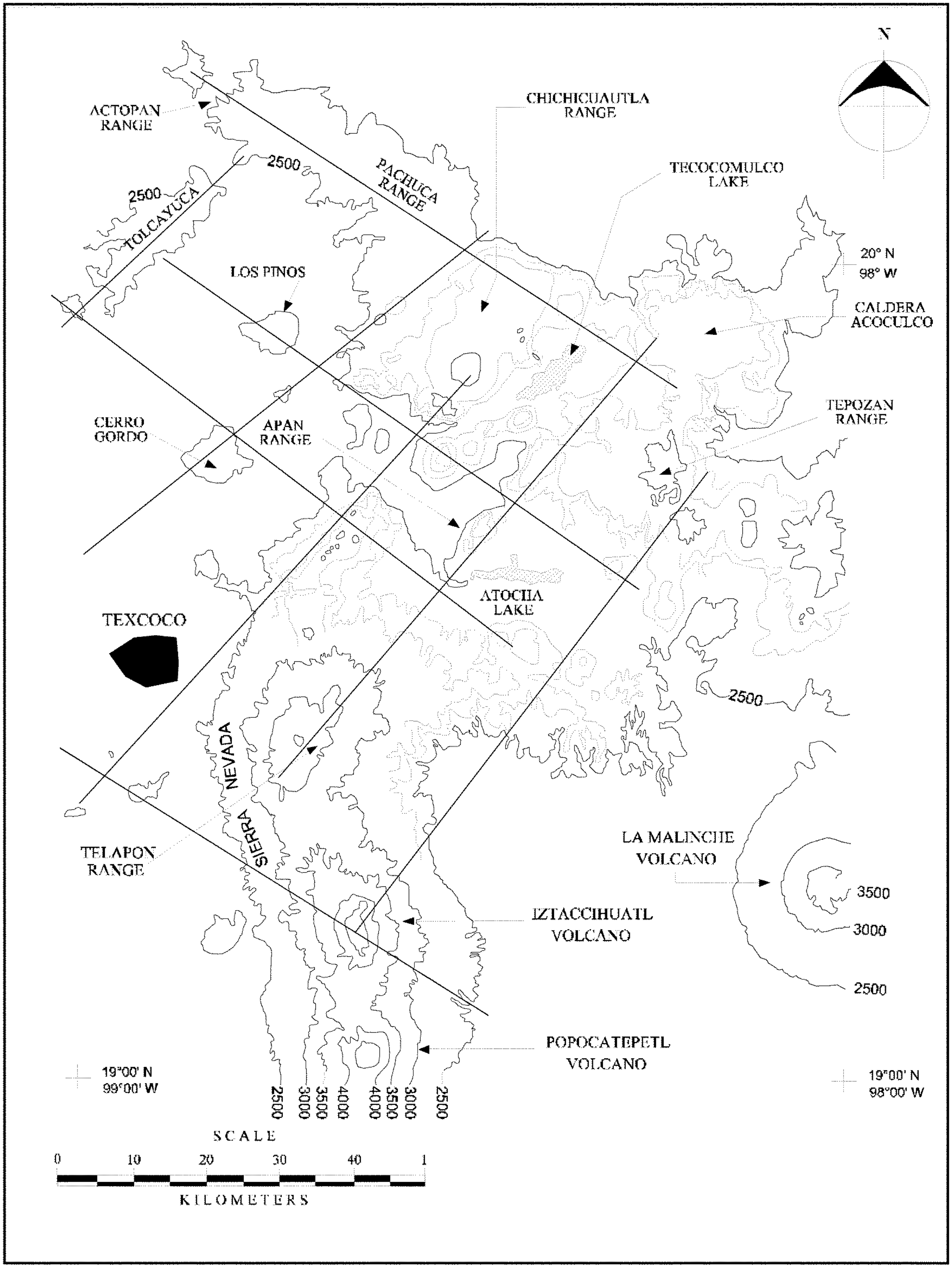


Fig. 2. The topographic and morphologic context of the study area. Inferred tectonic lineaments are indicated.

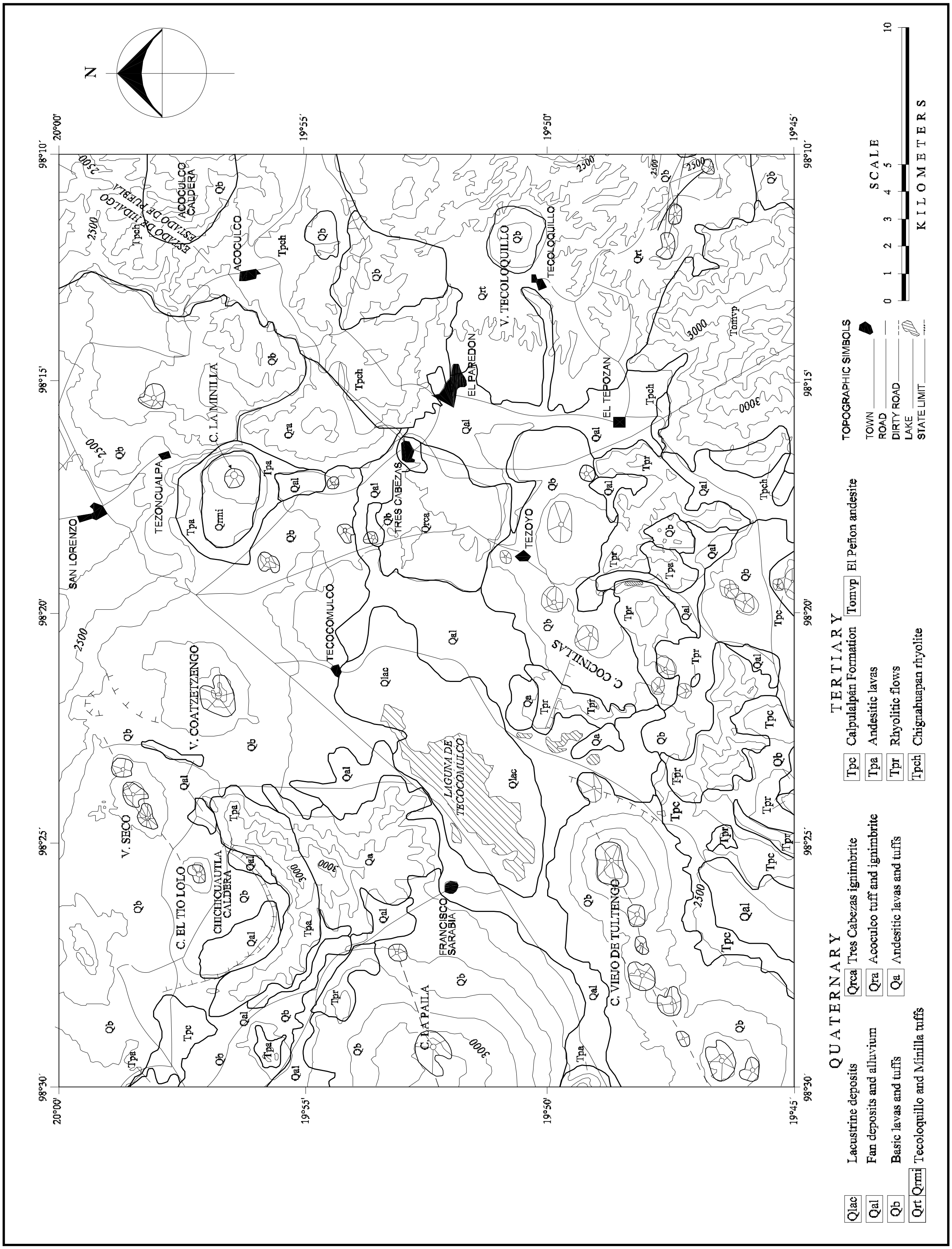


Fig. 3. Geologic map of the study area.

gioclase and hornblenda phenocrystals. These rocks (Tpa) form the Chichicuautla caldera.

They underlie the Quaternary products and represent the largest volumes in the study area. According to their stratigraphic relation they can be separated into a lower and an upper group.

The lower group includes the Acoculco ignimbrites (Qra) (López-Hernández and Castillo-Hernández, 1997), with a thickness of at least 150 m. West of Tres Cabezas there is a dome where we observe rhyolites (Quartz and Orthoclase) underlying pyroclastic flows (Qrca). These flows constitute an alternance of horizons of pumicitic tuffs and argillaceous tuffs.

In the area of Cocinillas volcano we have outcroppings of basalts and andesites (Qa). These rocks overly the Chignahuapan rhyolite.

The upper group is constituted by volcanic rocks (tuffs, basalts) and alluvium and lake deposits.

Large amounts of fine pumicitic tuffs overly the Chignahuapan rhyolites and the Acoculco ignimbrite, but underlay younger basic rocks. This tuff originated from Tecoloquillo (Qrt) and La Minilla (Qrmi) volcanoes. The thickness of these products is about 100 m. The later volcanic products are basalts and cinder cones (Qb) distributed in all the study area, mainly to the south, north and west. Huidobro-González and Lermo-Samaniego (1993) refer to these rocks as olivine basalts and assigned them to the Quaternary. The sequences of volcanoes (monogenetic and composite) present a NE-SW orientation.

Finally, the infill of this sub-basin is constituted by alluvium (Qal) and fluvial and lacustrian deposits (Qlac) including clays, limes, sands and conglomerates with variable thickness and extension. These products are interfingered with local lenses of pyroclast and with airfall tephras of Plinian eruptions (50 000 yr BP and 31 000 yr BP), probably from Tecoloquillo volcano (Early Pleistocene) and Acoculco caldera (Pliocene) (Caballero *et al*., 1999).

Inside the basin we observe two main fractures systems with NE-SW and NW-SE orientations. A NE-SW chain of cinder cones closes the drainage between the sub-basins of Tecocomulco and Apan. Cinder cones of the latest volcanic activity are aligned along the NE-SW direction.

The ranges bounding the Tecocomulco sub-basin present regional NE-SW and NW-SE orientations. The NE-SW lineaments of the Tepozan range can be traced to the southwest through the Apan range, to the Las Cruces and Sierra Nevada ranges (Figure 2).

García-Palomo *et al*. (2002) reports that most volcanos from this area are emplaced along NW-SE lineaments. Huizar-Álvarez *et al*. (1997) inferred that the Apan range is emplaced along a major NE-SW trending fault along the extension of the regional lineament joining the Tlaloc and Telapon volcanoes. Because the existence of low-level seismic activity immediately to the west of this fault (González-Pomposo and Valdés-González, 1995; Huizar-Álvarez *et al*., 1997), Huizar-Álvarez *et al*. (1997) infer that this system is still active.

The NE-SW orientation presented by the Chichicuautla range and volcanoes can be traced towards the southwest. Seismic activity is also associated with the southwestern trace of this chain. According to Ledesma-Guerrero (1987), these faults cut Miocene and Pliocene volcanic rocks.

The relief delimiting the basin to the NE presents a NW-SE orientation associated with the thrust and fold belts of the Sierra Madre Oriental (SMOr). To the NW of our study area, Sutter and Carrillo (1991) documented this system.

The Jurassic and Cretaceous rocks in the neighborhood also present these orientations.

Compressional tectonics during the late Cretaceous produced folds and reverse faults with NW-SE orientation. Immediately afterwards an extensional phase originated normal faults with the same direction and cutting the sedimentary sequence. A tectonic event during the Pliocene gave rise to the normal NE-SW fault and fracture system that affected the complete sequence. The Acoculco caldera was emplaced in the intersection of these two systems (López-Hernández and Castillo-Hernández, 1997).

GEOPHYSICAL STUDIES

Gravity and magnetic studies were conducted to infer the major sub-surface structural features of the Tecocomulco sub-basin. The area surveyed covers a surface of about 900 km^2. A Worden Master gravimeter was used. The separation between stations is about 500 m along polygons with a mean diameter of 5 km. The complete Bouguer anomaly (e.g., including drift, free-air, latitude, Bouguer and terrain corrections out to 20 km) was obtained with a reference density of 2670 kg/m^3. Topographic control was assured by first order leveling. Details are given in Alatriste-Vilchis (1999).

The Bouguer anomaly is shown in Figure 4. Bouguer anomaly values range between –235 and –195 mGal. The highest values are located at the northwestern, southwest-

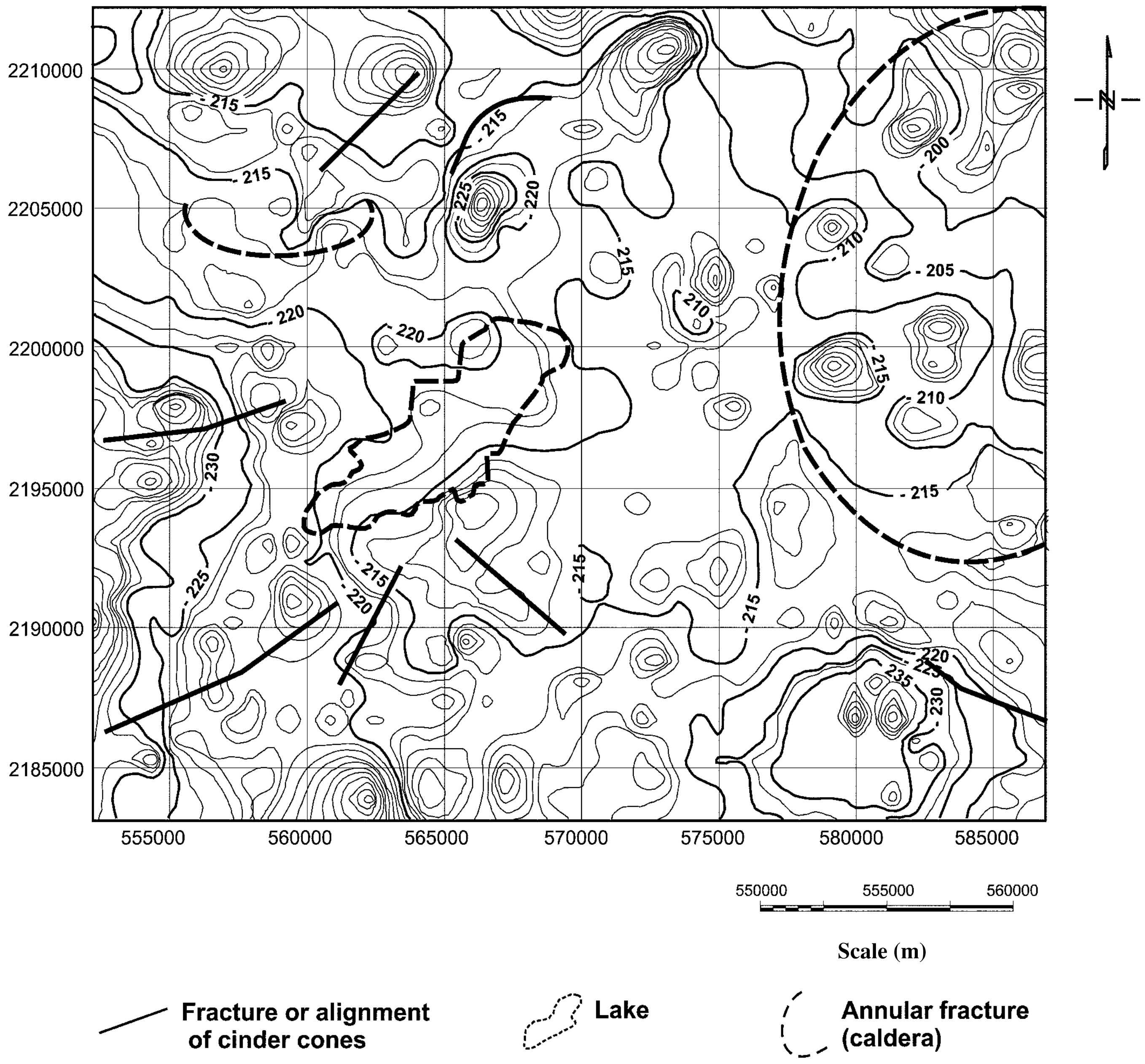


Fig. 4. Bouguer gravity anomaly of the study area. Contour interval is 5 mGal. Several minor anomalies are given each 1 mGal.

ern and northeastern corners; the lowest are located at the southeastern corner and at the western margin. The low gravity anomalies extend along two approximately linear belts that cross the study area. One band has a NW-SE orientation, and the other trends SW-NE. We adjusted a first order polynomial surface to the Bouguer anomaly data. This regional reproduces fairly well the thinning of the crust towards the Gulf of Mexico (Figure 5).

The main feature of the residual anomaly map is a large positive anomaly that crosses the study area from SW to NE (Figure 6). This anomaly narrows towards the NE, and in the northeastern portion it begins to broad again. Another positive anomaly is located at the northwestern portion of the study area and cover partially the Chichicuautla caldera.

The NW-SE belt of negative anomalies covers the extrapolated northern half of the Chichicuautla caldera. This NW-SE trending anomaly-belt intersects the large positive anomaly where it gets narrower. At the northeastern portion of the study area we have an alternance of positive and negative NE-SW oriented belts of anomalies. At the southeastern

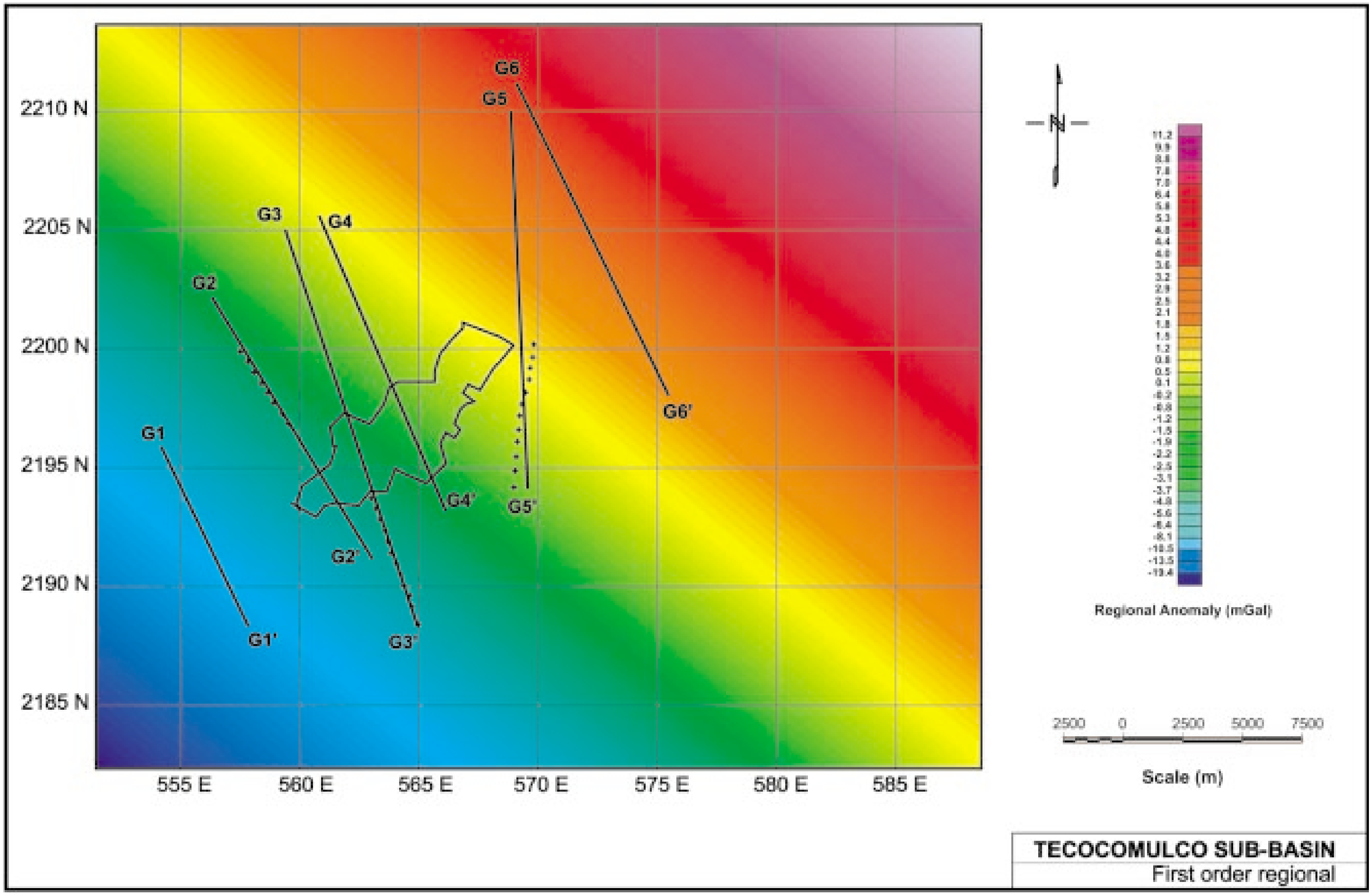


Fig. 5. First order regional gravity anomaly of the study area.

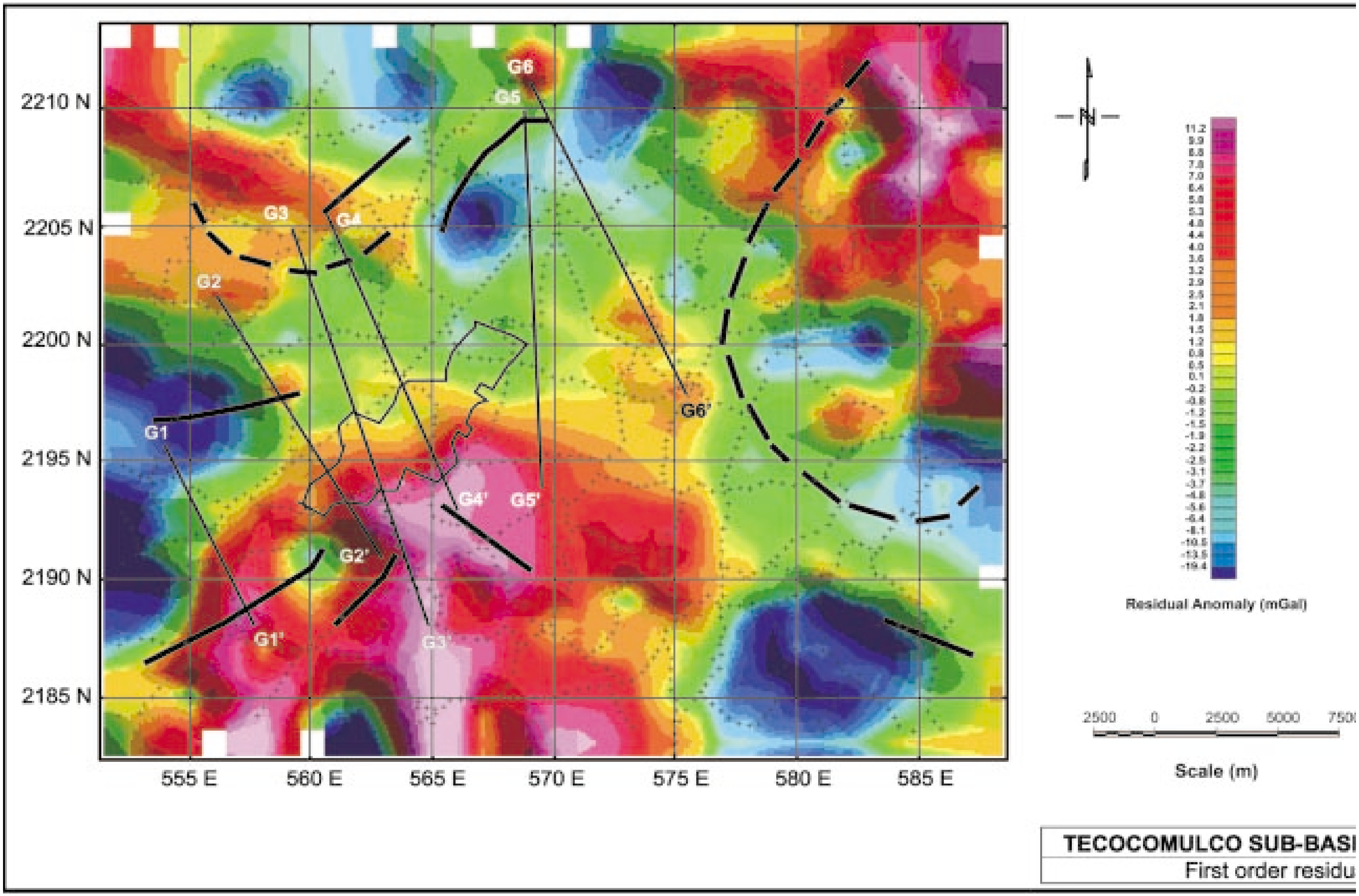


Fig. 6. First order residual gravity anomaly of the study area. The location of the gravity stations and of the interpreted gravity profile is indicated.

portion we have a large negative anomaly. As already mentioned along the NW-SE belts of negative anomalies are emplaced composite volcanoes.

Most lineaments have a NE-SW orientation and correspond with the belts of negative values. The large positive anomaly is delimited by lineaments of both systems. The positive anomaly on the southern half of Chichicuautla caldera is interrupted by a gravity low. We interpret that a NW-SE fault has cut this caldera in half. The northern half is depressed, while the southern half is masked by a structural high.

The Acoculco caldera is associated with alternating NE-SW positive and negative anomalies, correling with a caldera of the collapsed graben type (Walker, 1984).

We selected six gravity profiles perpendicular to the NE-SW lineament and approximately normal to the central gravity high (Figures 5, 6 and 7). The profiles were selected to pass through gravity measurements (Figure 5). The anomalies can approximately be interpreted as 2 1/2-D anomalies. Three profiles coincide in part with magnetic profiles.

We modified a 2 1/2 D Talwani type algorithm (Talwani *et al*., 1959) to fit the topography. Available surface geology and borehole data were used to constrain the models. The densities assigned to the different geologic units were obtained from rock samples, and are similar to the ones obtained by Pérez-Cruz (1988) from cores from wells in Mexico City, and to the density values used by Huizar-Álvarez *et al*. (1997) in the sub-basins of Apan and Tochac. The models (Figures 8 to 13) include: 1) a limestone basement (2.87 gr/cm3); (2) an undifferentiated sequence representing the Tertiary to Quaternary units constituting the volcano-sedimentary infill (2.52 gr/cm^3), (3) local volcano-sedimentary infill (2.39 gr/cm^3), and (4) local igneous intrusives (2.87 gr/cm^3).

The Tecocomulco sub-basin corresponds to a half graben, trending NE-SW orientation and bounded to the E by three sets of faults (F1, F2, and F3). To the west it is delimited by one fault (F4) (Figure 14). The faults define basement blocks tilting W (Figures 8 to 13). The inferred faults present together an approximately NE-SW orientation, implying a complex 3-D fracturing. They coincide with lineaments of Quaternary cinder cones, and with the extension of the lineaments joining several volcanic structures. Thus Tecocomulco is a closed sub-basin with a narrow communication towards the SW with the Apan sub-basin. It widens to the N and opens to the west. Along this narrow half-graben is emplaced the NE-SW chain of Quaternary (Qb) cinder cones that obstructs the drainage towards the Apan sub-basin.

We conducted magnetic measurements along portions of three of the gravity profiles (Figure 5 and 6), using an EG&G Geometrics proton precession magnetometer (model G856A) every 100 m. An EG&G Geometrics model G816 instrument was used at the base station to monitor the diurnal variations. Diurnal corrections and removal of the regional geomagnetic field according to the IGRF yield the total field anomaly shown on the profiles (Figures 9, 10 and 12).

Profile M1-M1' coincides with a portion of the northern half of gravity profile G2-G2'. Profile M2-M2´coincides with the southern tip of gravity profile G3-G3´, and profile M3-M3´coincides with the southern portion of gravity profile G5-G5´. Joint gravity and magnetic models were obtained. We assumed that the measured magnetic profiles are 2-D in nature. Remanent magnetism was neglegted, and the magnetic sources were assumed at the basement. A 2-D Talwani type algorithm was used (Talwani, 1965).

The magnetic anomalies are interpreted in terms of tabular magnetic intrusions along or around the inferred faults, or affecting the basement. In profile M1-M1´a magnetic intrusive can be interpreted as a conduit feeding one of several coalescent small craters through which the La Paila and neighboring Cerro Viejo volcano erupted.

For the stratigraphic sequence of the volcano-sedimentary infill of the sub-basin, we conducted 14 vertical electric soundings (VES). We used a Scintrex IPC-7 (2.5 kW) instrument and an IPR-10A receiver. A Schlumberger configuration with electrode spacings of up to 2000 m was used. Figure 7 shows the location of the resistivity soundings, in the plain around Tecocomulco lake. One geoelectric profile approximately perpendicular to the graben trend is shown in Figure 7. Profile E1-E1' has an approximately E-W direction and comprises VES's 10, 6, 2, 3 and 1, with a total length of 8.5 km.

In a preliminary step we conducted a 1-D inversion of the VES's. Master curves (Orellana and Mooney, 1966), a constrained least-squares iterative procedure (Tejero-Andrade *et al*., 1987) and Resix Plus^{TM} resistivity software (Interpex Limited, 1992) were used in this work. We obtained a geoelectric section by pasting together the 1-D models.

According to this interpretation we find four geoelectric units (Figure 15). The shallowest has resistivities between 12 and 30 Ω-m, and a thickness of 5 to 25 m. The second geoelectric unit, with a thickness between 10 and 20 m, shows resistivities from 45 to 90 Ω-m. The next unit has a variable thickness and a resistiviy ranging from 150 to 470 Ω-m. The deepest unit is divided into two portions (IVa and IVb). Portion IVa with resistivities between 10 and 30 Ω-m is separated by an approximately vertical discontinu-

Fig. 7. Location of VLF, gravity and magnetic profiles interpreted in this study. Also indicated is the location of the Vertical Electric Soundings and of the VLF stations.

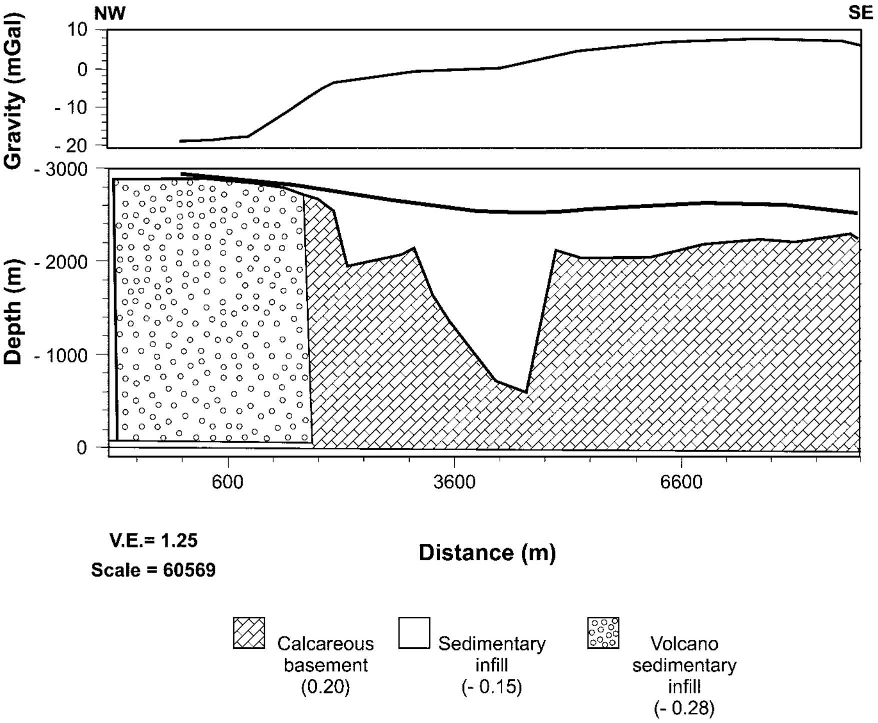


Fig. 8. Gravity model G1-G1'. Figures indicate density contrasts in gr/cm^3 with respect to a density of 2.67 gr/cm^3. See Figures 5, 6 and 7 for its location. a) gravity profile, b) gravity model.

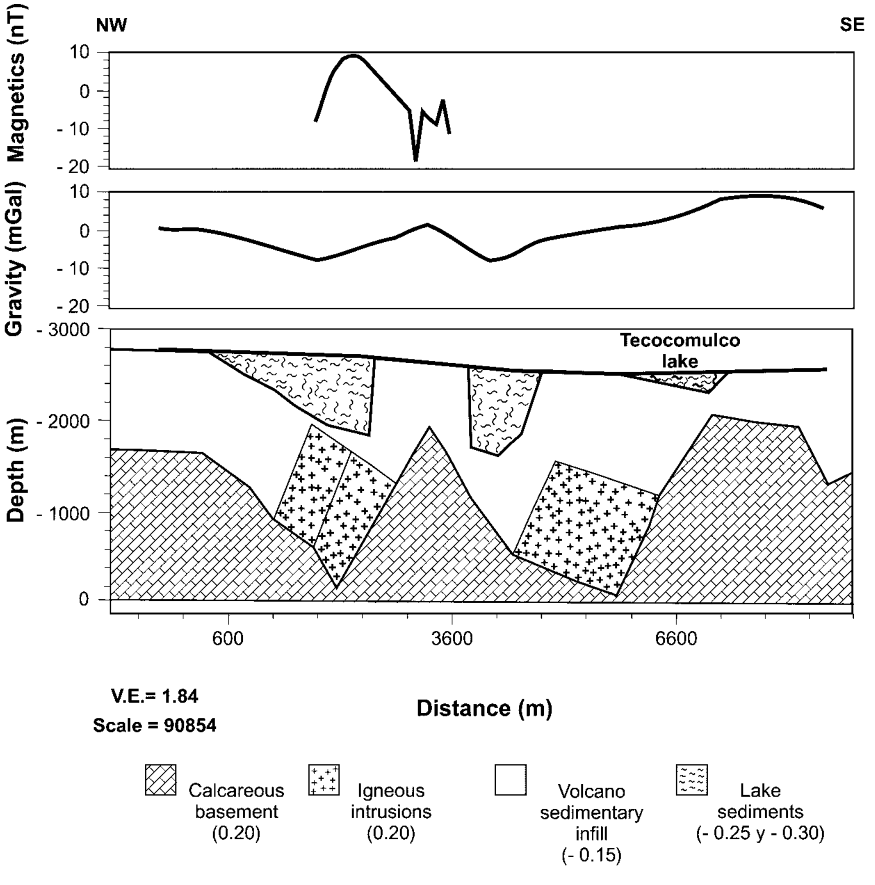


Fig. 9. Gravity model G2-G2'. Figures indicate density contrasts in gr/cm^3 with respect to a density of 2.67 gr/cm^3. See Figures 5, 6 and 7 for its location. a) magnetic profile, b) gravity profile, c) common gravity and magnetic model.

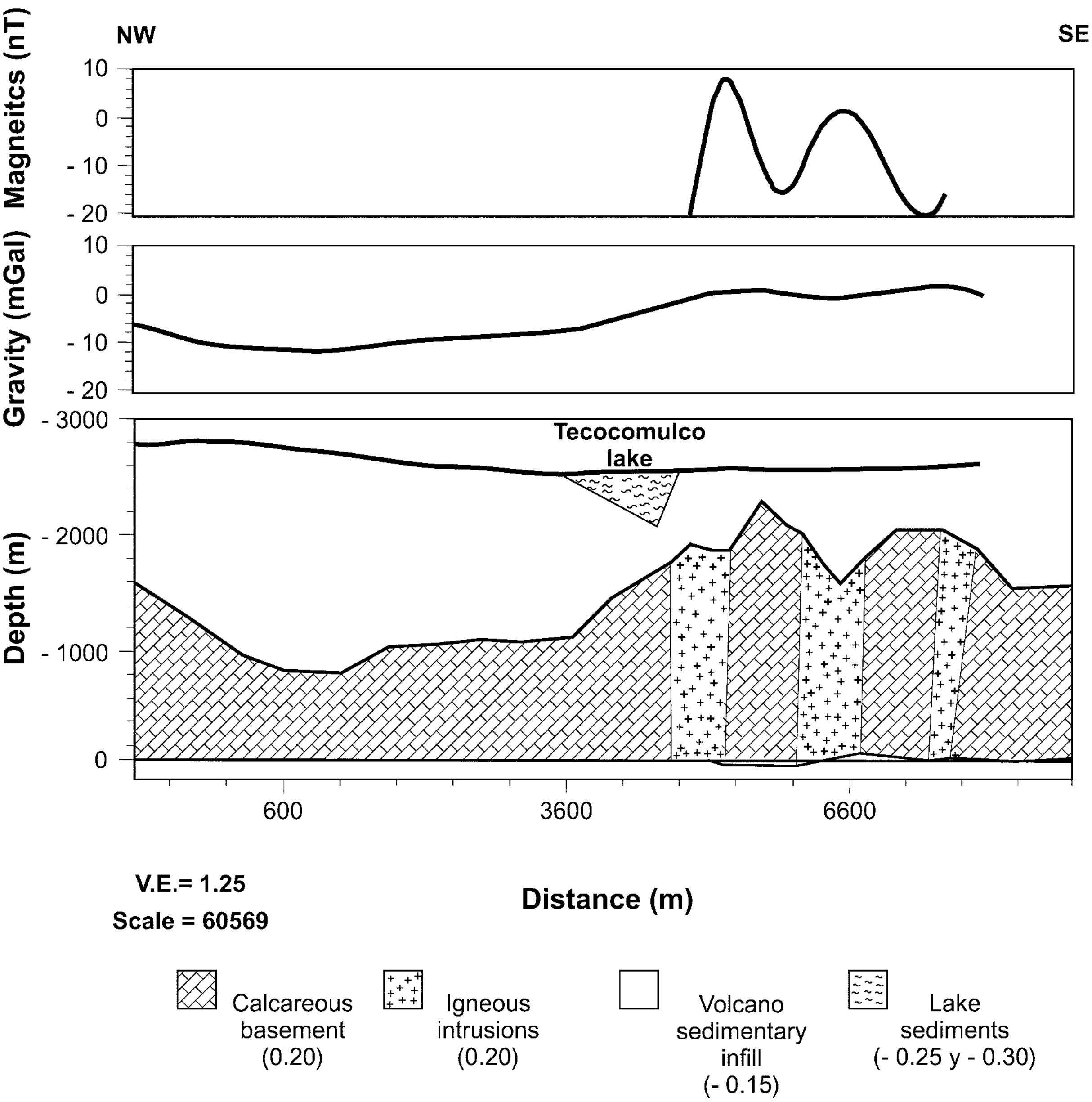


Fig. 10. Gravity model G3-G3'. Figures indicate density contrasts in gr/cm^3 with respect to a density of 2.67 gr/cm^3. See Figures 5, 6 and 7 for its location. a) magnetic profile, b) gravity profile, c) common gravity and magnetic model.

ity from portion IVb with a resistivity range from 65 to 130 Ω-m. The discontinuity correlates with the northeastward prolongation of fault F2 inferred from the gravity study.

We conducted a forward 2-D modeling of this profile. We implemented the finite difference frequency-domain 2-D algorithm developed by Dey *et al.* (1975) and Dey (1976). We projected the VES´s 10 and 6 to an average line through soundings 2, 3 and 1 (Figure 7).

The resulting 2-D geoelectric model (Figure 16) was obtained by trial and error. The fit is quite good. The 2-D model confirms the presence of geoelectric units inferred from the 1-D interpretation. However the 2-D model improves the interpretation of the discontinuity between the eastern and western portions of the fourth geoelectric unit. According to the 2-D modeling a resistivity low is observed at the base of this profile in its western portion.

In the eastern portion of the study area, between La Paila volcano and Chichicuautla caldera, we conducted VLF measurements along a SE-NW profile. Its southern portion is coincident with the M1-M1´ profile. It also coincides with the northern part of the G2-G2´profile (Figure 7). We used an OMNI Plus receiver manufactured by EDA Instruments Inc. with signals from three VLF transmitting stations: NPM

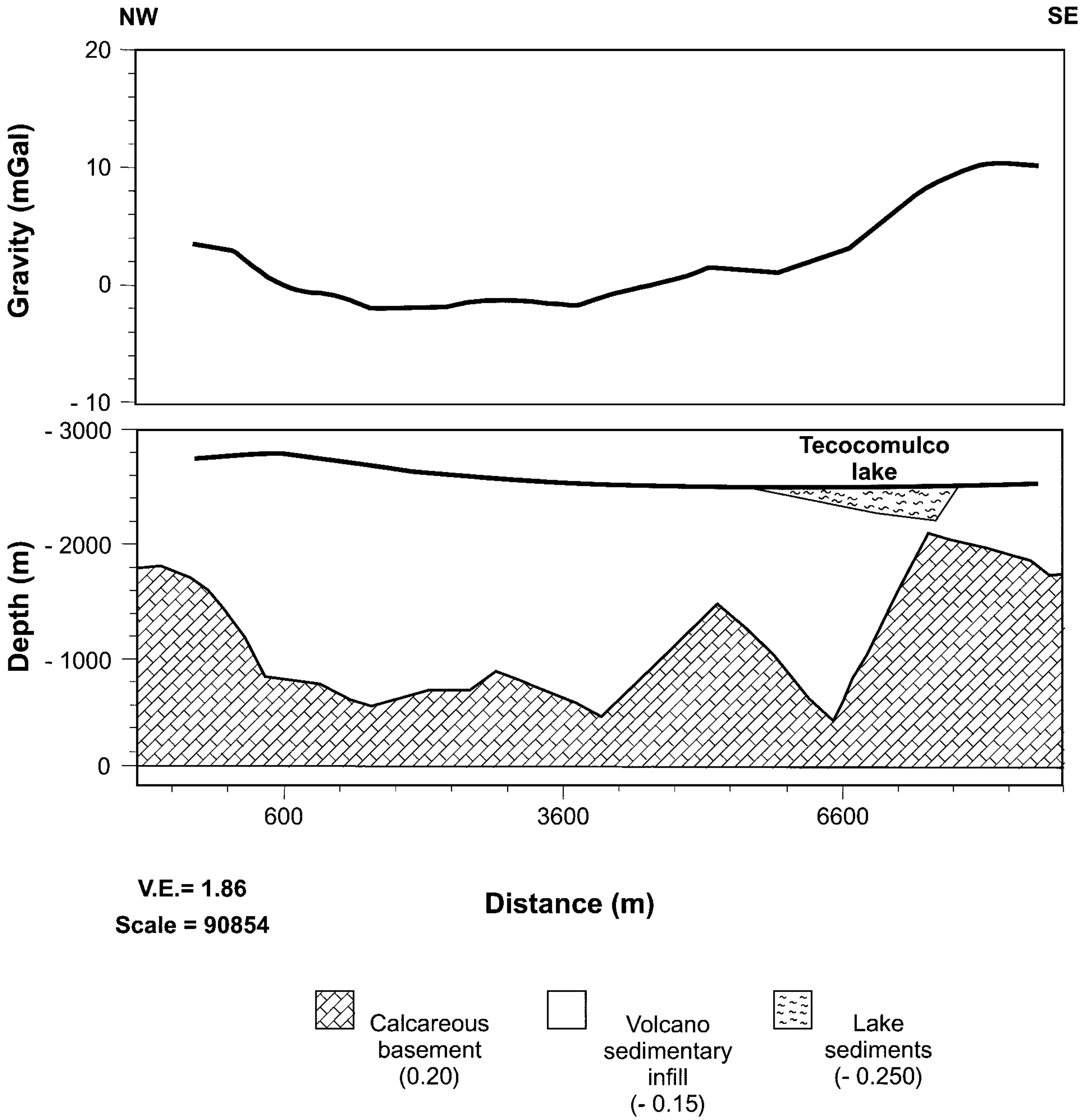


Fig. 11. Gravity model G4-G4'. Figures indicate density contrast in gr/cm^3 with respect to a density of 2.67 gr/cm^3. See Figures 5, 6 and 7 for its location. a) gravity profile, b) gravity model.

(Laulualei, Hawaii), NAA (Cutler, Maine) and NLK (Jim Creek, Washington). For each of these signals we obtained tilt, total magnetic field, in phase and in-quadrature components. The VLF profiles are shown in Figure 17.

Anomalies between stations 4 and 5 are interpreted as due to the high resistivity contrast between volcanic material and alluvium. Here the VLF profile crosses a contact between Tpa, Qb, and Qal outcroppings. The anomalies between stations 8 and 9 correlate with the continuation of a NW fault running NE from La Paila volcano (Figures 3, 7 and 14) and with fault F4 inferred from gravimetry. Where the NE prolongation of this fault crosses the above-mentioned profiles, we inferred a volcanic conduit. VLF data also detects this volcanic conduit. Fault F3 can also be associated with the anomaly between stations 13 and 14.The anomalies at the end of the VLF profile mark the contact between high-resistivity volcanic material and alluvium from the northern margin of Tecocomulco lake. These anomalies might also be associated with fault F2.

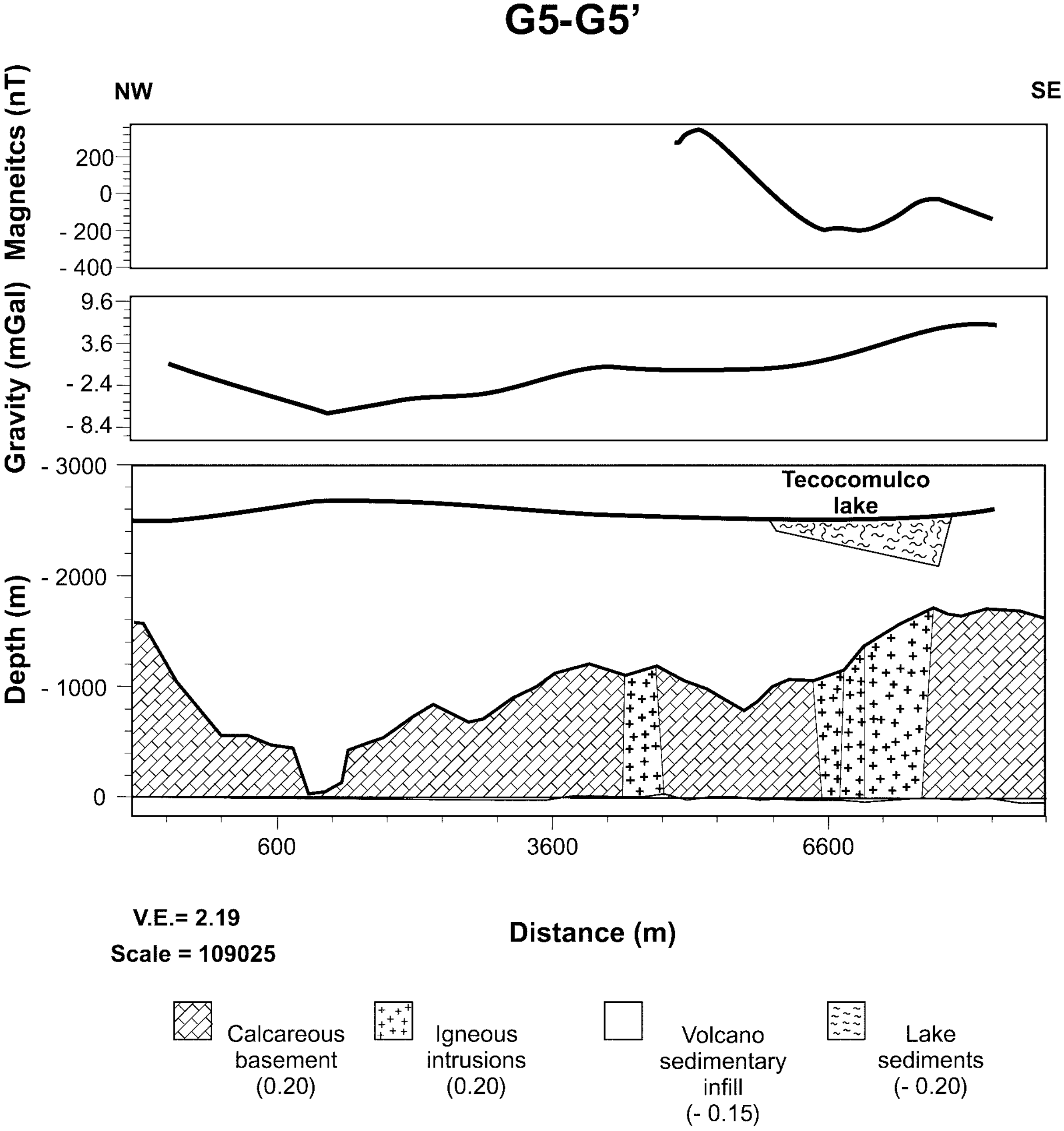


Fig. 12. Gravity model G5-G5'. Figures indicate density contrast in gr/cm^3 with respect to a density of 2.67 gr/cm^3. See Figures 5, 6 and 7 for its location. a) magnetic profile, b) gravity profile, c) common gravity and magnetic model.

CONCLUSIONS

Our gravity study suggests that the Tecocomulco sub-basin may have a structure of the half-graben type (Figure 14). The sub-basin gets narrow towards the SW. The faults delimiting the sub-basin have the same trend (NE-SW) as the alignment of cinder cones and the ranges delimiting the basin to the N-NW and S-SE. Jurassic and Cretaceous rocks in the neighborhood have the same trend. The half-graben is an expression of regional blocks tilted towards the NW.

A NE-SW chain of cinder cones (the northern tip of which is Viejo de Tultengo volcano) interrupts the surficial drainage between the Apan and Tecocomulco sub-basins. Gravity and magnetics suggest however, that there is a narrow communication at depth. The southward prolongation of this lineament is associated with low seismicity. It could be active. The sub-basin gets broader towards the NE.

The gravity study also enables us to infer the structure of the Chichicuautla and Acoculco calderas. Acoculco

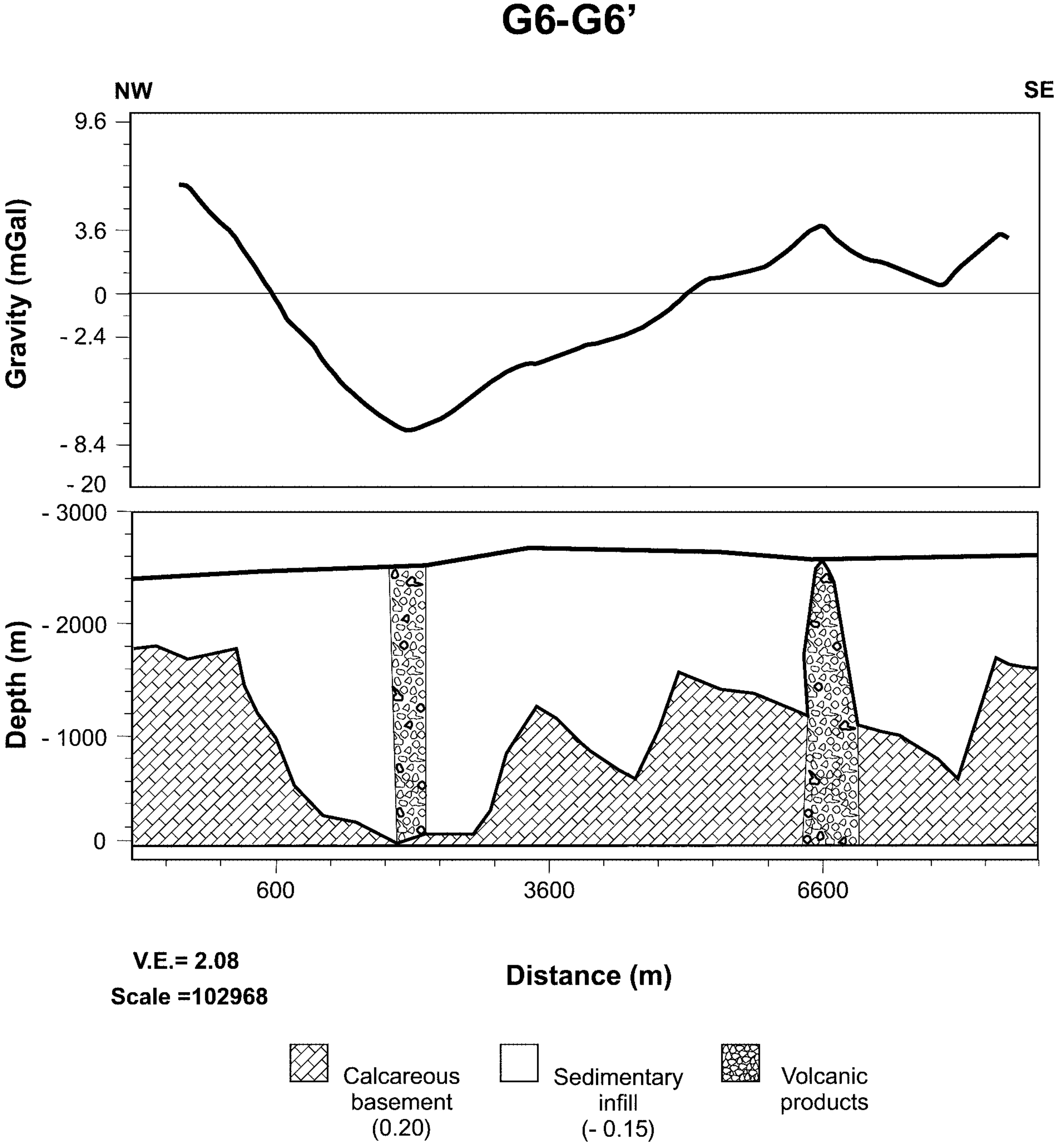


Fig. 13. Gravity model G6-G6'. Figures indicate density contrasts in gr/cm^3 with respect to a density of 2.67 gr/cm^3. See Figures 5, 6 and 7 for its location. a) gravity profile, b) gravity model.

Caldera is not a piston-type caldera but is associated with an alternance of positive and negative linear anomalies. One NE-SW gravity low coincides with an apical graben. Hence we infer that this structure corresponds to a collapsed graben caldera. The Chichicuautla caldera is cut in half by a NW-SE fault. Its southern portion is downfaulted. The gravity signature of the northern half of this caldera is masked by a structural high or by mafic bodies.

The DC resistivity study helped to characterize the stratigraphic sequence of the volcano-sedimentary infill. The 1-D and 2-D interpretation of the VES supports the existence of the NE-SW trending fault F2 featuring a half-graben to the east. The 2-D interpretation confirmed the 1-D geoelectric models and contributed with details to the sections studied. Fault F4 can also be inferred from the VLF study.

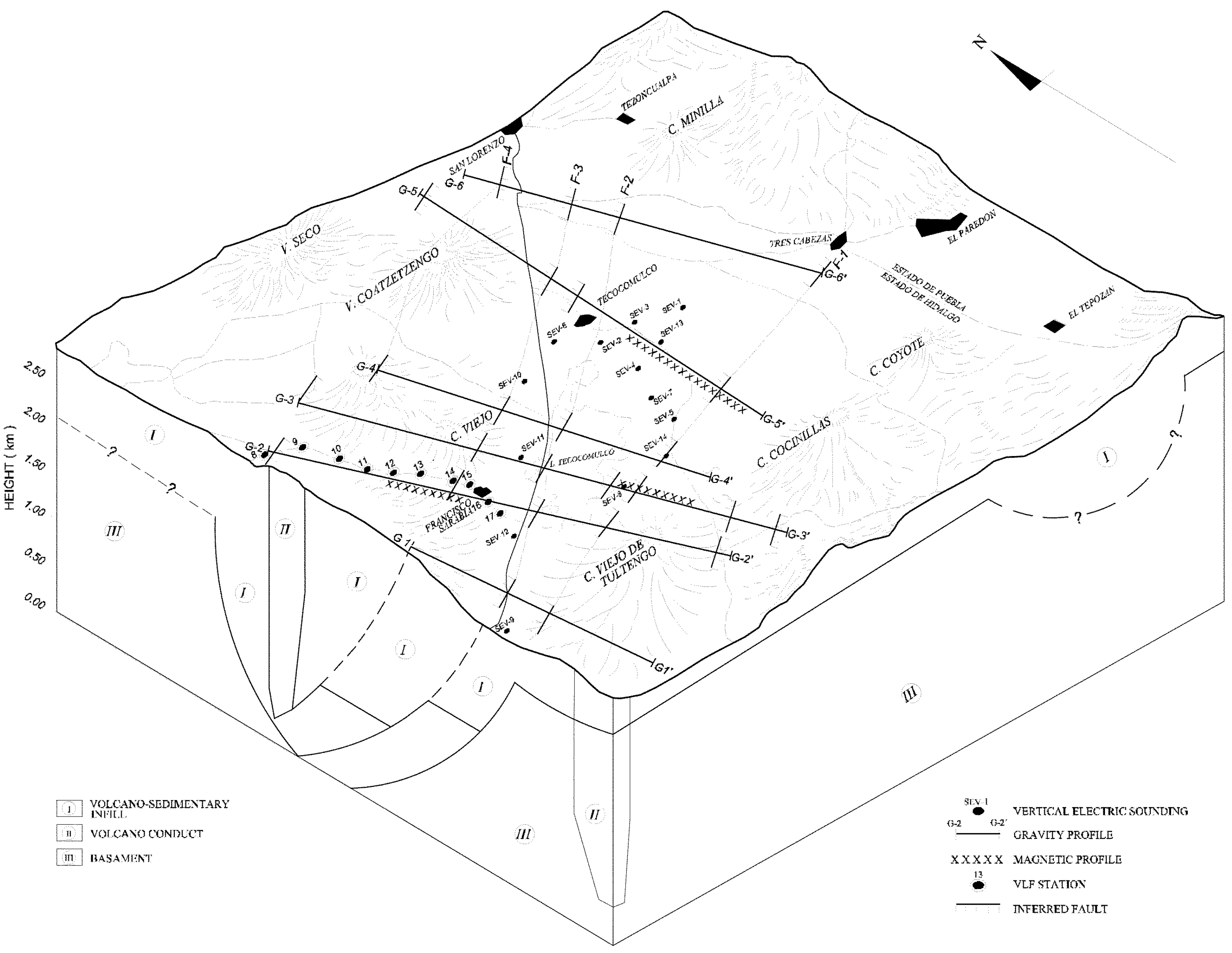
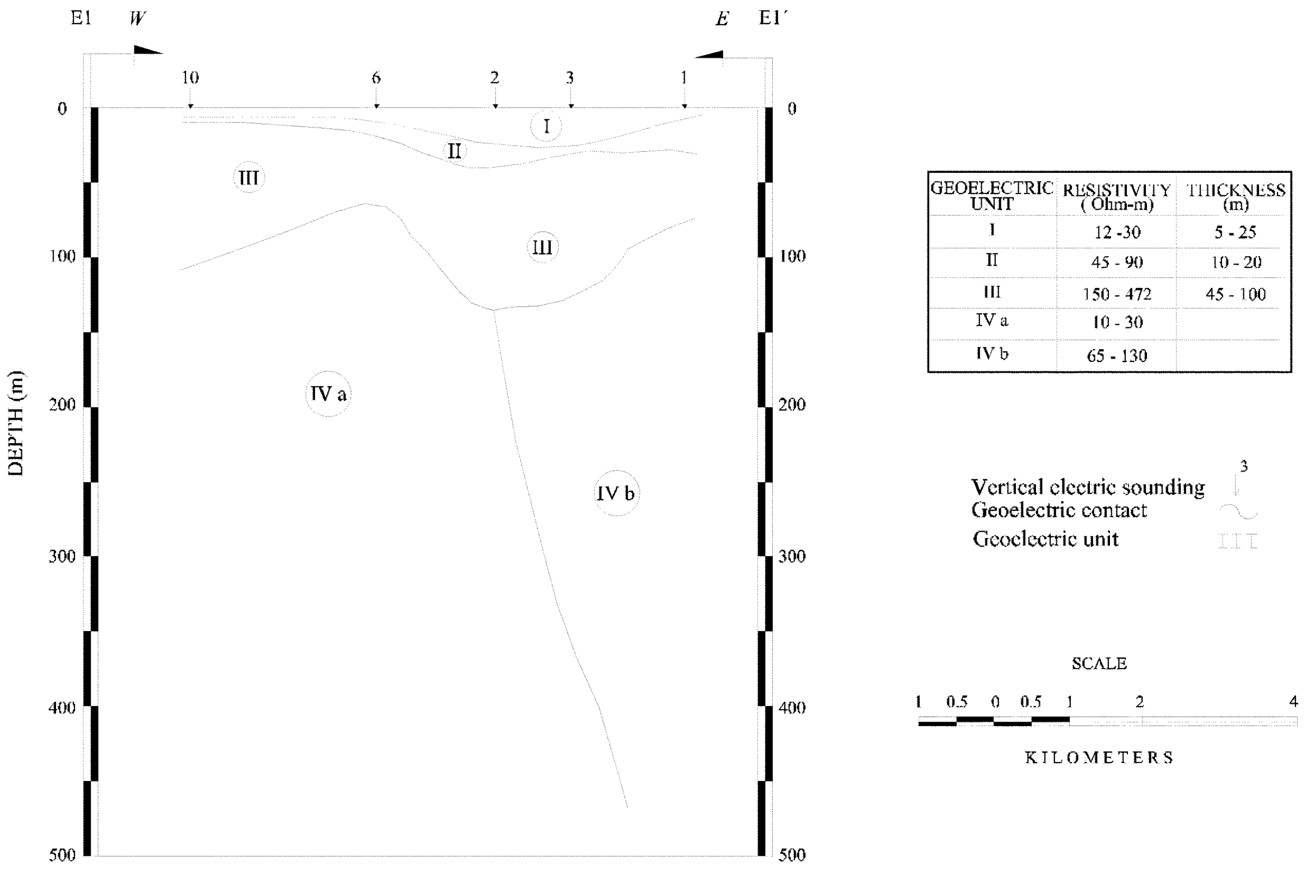


Fig. 14. Schematic block diagram of the sub-basin of Tecocomulco. F1, F2, F3 and F4 represent the inferred faults.



GEOELECTRIC UNIT	RESISTIVITY (Ohm-m)	THICKNESS (m)
I	12 -30	5 - 25
II	45 - 90	10 - 20
III	150 - 472	45 - 100
IV a	10 - 30	
IV b	65 - 130	

Fig. 15. Geoelectric section E1-E1’. See Figure 7 for its location.

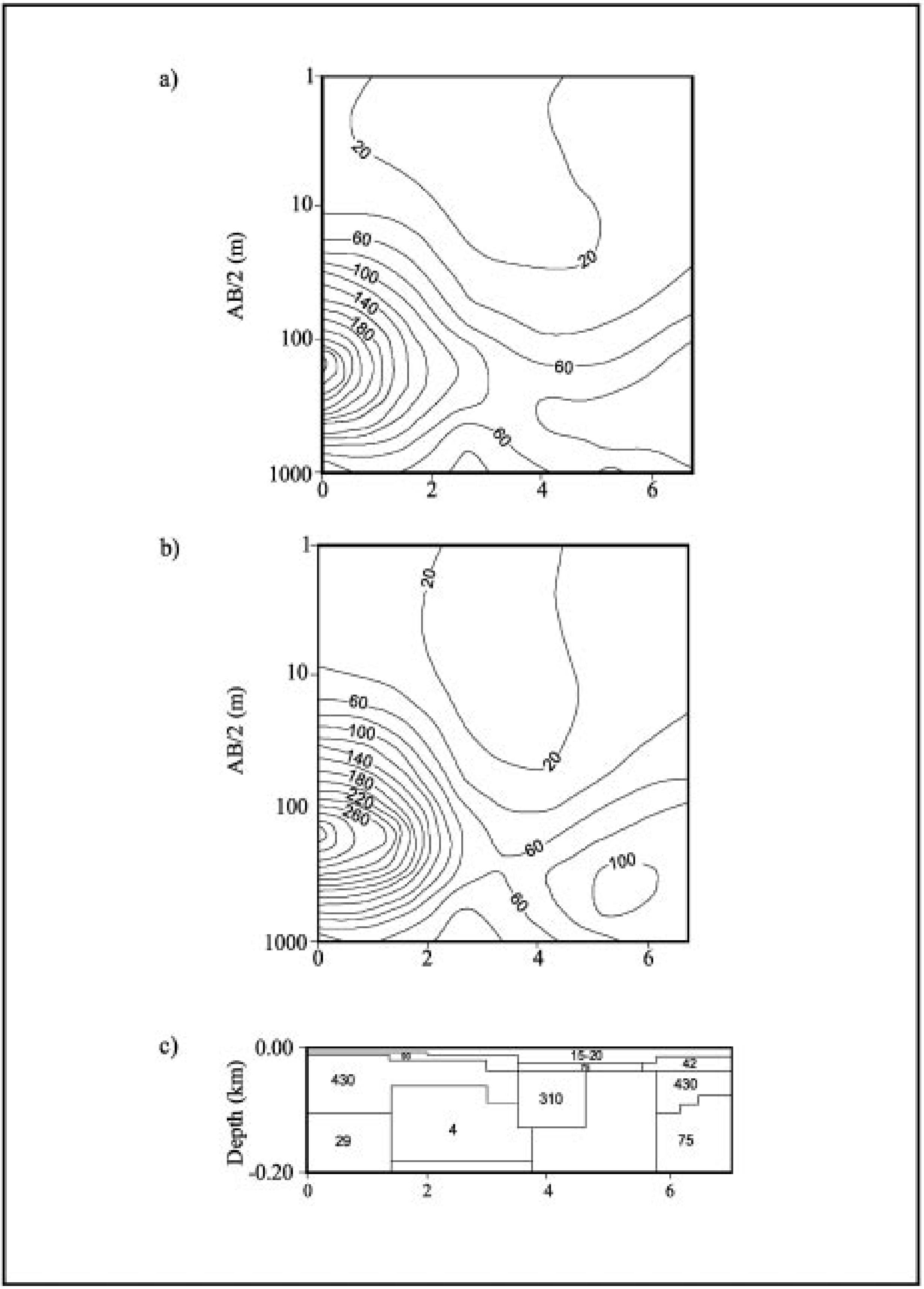


Fig. 16. 2-D interpretation of geoelectric section E1-E1’. See Figure 7 for its location.

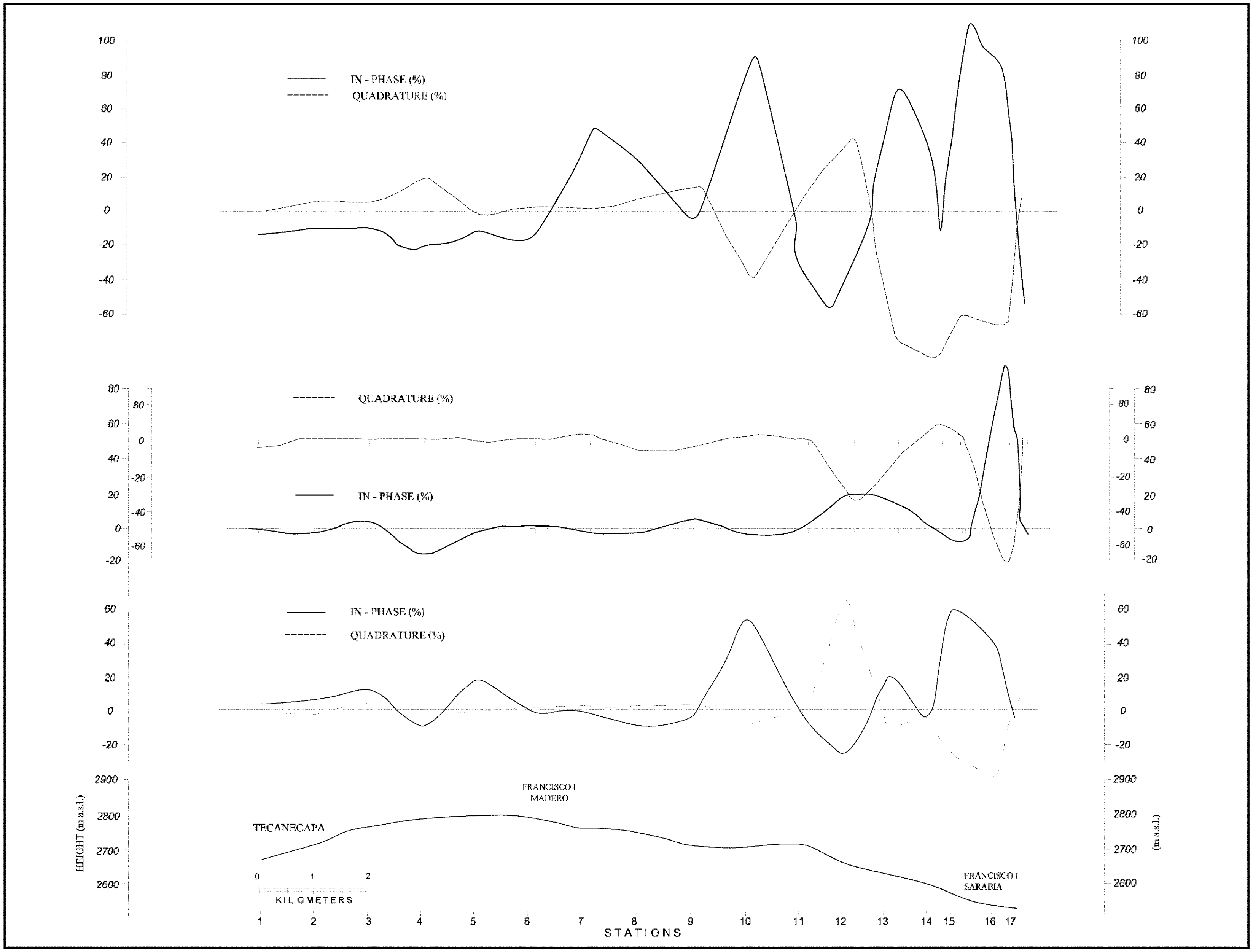


Fig. 17. VLF profile. See Figure 7 for location. a) for signal from transmiting station at Lualualei, Oahh, Hawai (NPM), b) for signal from transmiting station at Cutler, Maine (NAA), c) for signal from transmiting station at Jim Creek, Washington (NLK)

ACKNOWLEDGEMENTS

This study was supported by a research grant from DGAPA-UNAM (IN-167996). Alatriste-Vilchis received a research scholarship from the Instituto Mexicano del Petróleo (IMP). Drawings were made by Salvador Villalbazo Ferra, Hugo de la Rosa Ortega.

BIBLIOGRAPHY

ALATRISTE-VILCHIS, D. R., 1999. Determinación de la estructura subsuperficial de la subcuenca de Tecocomulco, Estado de Hidalgo, empleando técnicas geofísicas, Master´s Degree Thesis, Posgrado en Ciencias de la Tierra, UNAM, 93 pp. 96.

ARELLANO, A. R. V., 1953. Estratigrafía de la Cuenca de México, Memorias del Congreso Científico Mexicano, 3, 172-186.

BELLIA, S., G. CUSIMANI, T. GONZÁLEZ, R. RODRÍGUEZ and G. GIUNTA, 1992. El Valle de México. Consideraciones preliminares sobre los riesgos geológicos y análisis hidrogeológico de la Cuenca de Chalco, Instituto Italo-Latino Americano, Roma, Italia, 96 pp.

BRYAN, K., 1948. Los suelos complejos y fósiles de la Altiplanicie de México con relación a los cambios climáticos, Boletín de la Sociedad Geológica Mexicana, Vol. 13, p. 1-20.

CABALLERO, M., S. LOZANO, B. ORTEGA, J. URRUTIA and J. L. MACÍAS, 1999, Environmental characteristics of Lake Tecocomulco, northern basin of Mexico, for the last 50,000 years. *J. Paleolimnol., 22,* 399-411.

CAMPOS-ENRÍQUEZ, J. O., O. DELGADO-RODRÍGUEZ, R. CHÁVEZ-SEGURA, P. GÓMEZ-CONTRERAS, L. FLORES-MÁRQUES and F. BIRCH, 1997, The subsurface structure of Chalco sub-basin (Mexico City) inferred from geophysical data. *Geophys., 62,* 23-35.

CASTILLO-HERNÁNDEZ, D., 1986. Características geológicas de la zona termal de Chignahuapan-Zacatlán (Acoculco), Pue., Comisión Federal de Electricidad, México, Internal Report 4/86, 8 pp.

CASTRO-GARCÍA, A. and D. CÓRDOBA, 1994. Estratigrafía del área volcánica de Tulancingo, Hidalgo, México, Pancromo 23. *Rev. Invest., Universidad Autónoma del Estado de Hidalgo, 1,* 26-39.

DE LA CRUZ-MARTÍNEZ, V. and D. CASTILLO-HERNÁNDEZ, 1986. Estudio geológico de la zona geotérmica de la Caldera de Acoculco, Pue., Comisión Federal de Electricidad, Mexico, Internal Report 36/86, 23 pp.

DEMANT, A., 1981, Axe Néovolcanique Mexicain. Étude volcanique et pétrographique, signification géodynamique, Thèse Doc. D´Etat, Univ. Aix Marseille, France, 106 pp.

DEY, A., W. H. MEYER, H. F. MORRISON and W. DOLAN, 1975. Electric field response of two-dimensional inhomogeneities to unipolar and bipolar electrode configurations (pole-pole, dipole-dipole). *Geophys., 40,* 630-640.

DEY, A., 1976. Resistivity modelling for arbitrarily shaped two dimensional structures, University of California, Berkeley, 56 pp.

DEY, A. and H. F. MORRISON, 1979. Resistivity modelling for arbitrarily shaped three-dimensional structures (conductivity finite difference dipole-dipole). *Geophys., 44,* 753-780.

GARCÍA PALOMO, A., J. L. MACÍAS, G. TOLSON, G. VALDEZ and J. C. MORA, 2002. Volcanic stratigraphy and geologic evolution of the Apan region, east-central sector of the Trans-Mexican Volcanic Belt. *Geofís. Int., 41,* 133-150.

GONZÁLEZ-POMPOSO, G. J. and C. VALDÉS-GONZÁLEZ, 1995. Seismicity in the state of Puebla, Mexico, 1986-1989. *Geofís. Int., 34,* 221-231.

HERRERA, I., 1989. El Sistema acuífero de la Cuenca de México. Introduction. *Geofís. Int., 28,* 130-132.

HUIDOBRO-GONZÁLEZ, A. and J. LERMO-SAMANIEGO, 1993. Secuencia sísmica en la Cuenca de Apan, Hidalgo del 24 al 29 de febrero de 1992, Reporte Interno, Instituto de Ingeniería, UNAM, pp. 45.

HUIZAR-ÁLVAREZ, R., 1989. Contribution à l‘étude géologique et hydrogéologique de la plaine de Chalco-Amecameca et de son bassin versant (Mexique), Diplôme de Docteur de l‘Université de Besançon, France, 160 pp.

HUIZAR-ÁLVAREZ, R., 1993. Simulación matemática del sistema acuífero de Chalco-Amecameca, México. *Geofís. Int., 32,* 57-79.

HUIZAR-ÁLVAREZ, R., J. O. CAMPOS-ENRÍQUEZ, J. LERMO-SAMANIEGO, O. DELGADO-RODRÍGUEZ and A. HUIDOBRO-GONZÁLEZ, 1997. Geophysical and hydrogeological characterization of the sub-basins of Apan and Tochac (Mexico Basin). *Geofís. Int., 36,* 217-233.

INTERPEX LIMITED, 1992. Resix Plus User manual resistivity data interpretation software, Interpex Limited, Golden, CO, USA, 310 pp.

LEDESMA-GUERRERO, O., 1987. Hoja Calpulalpan 14 Q-H (3). Resumen de la geología de la Hoja Calpulalpan, Estados de México, Tlaxcala e Hidalgo, Universidad Nacional Autónoma de México, Instituto de Geología, Carta geológica de México, Serie 1:100,000.

LÓPEZ-HERNÁNDEZ, A. and D. CASTILLO-HERNÁNDEZ, 1997. Exploratory drilling at Acoculco, Puebla, Mexico: A hydrothermal system with only nonthermal manifestations. *Geoth. Res. Council Trans., 21,* 429-433.

MARÍN, C. S., J. MANDUJANO and R. HUIZAR, 1985. Geología en el Valle de México con fines geohidrológicos, Reporte Técnico, Instituto de Geología, UNAM para la CAVM, No. 85, 405 pp.

MOOSER, F., 1963. Historia Tectónica de la Cuenca de México, Boletín de la Asociación Mexicana de Geólogos Petroleros, 15, 239-245.

MOOSER, F., 1975, Historia Geológica de la Cuenca de México. *En:* Memoria de las obras del sistema de drenaje profundo del Distrito Federal, México, D.F., DDF, T. 1, p. 7-38 y mapa geológico.

ORELLANA, E. and H. M. MOONEY, 1966. Master tables and curves for electrical soundings over layered structures, Editorial Interciencia, Madrid, 150 pp.

ORTEGA-GUERRERO, A., J. CHERRY and D. L. RUDOLPH, 1993. Large-scale aquitard consolidation near Mexico City. *Ground Water, 31,* 708-718.

PÉREZ-CRUZ, G. A., 1988. Estudio sismológico de reflexión del subsuelo de la Ciudad de México, M. Sc. Thesis, Mexico City, DEPFI-UNAM, 83 pp.

SEGERSTROM, K., 1961, Geología del sureste del Estado de Hidalgo y noreste del Estado de México, Boletín de la Asociación Mexicana de Geólogos Mexicanos, 13, 147-168.

SUTER, M. and M. CARRILLO, 1991, Región de Zimapan, Hidalgo. Observaciones de un ejemplo de la tectónica de la Sierra Madre Oriental, *In:* Alcayde, M., De Cserna, Z. (editors), Excursion Geológica, 68 pp.

TALWANI, M., L. WORZEL and M. LANDISMAN, 1959. Rapid gravity computations for two-dimensional bodies with applications to the Mendocino submarine fracture zone. *J. Geophys. Res., 64,* 49-59.

TALWANI, M., 1965. Computations with the help of a digital computer of magnetic anomalies caused of arbitrary shape. *Geophys., 20,* 797-817.

TEJERO-ANDRADE, A., R. SÁNCHEZ-LEÓN and P. GONZÁLEZ-VILLALVASO, 1987. Interpretación iterativa de sondeos. *Geotermia. Rev. Mexicana de Geoenergía, 3,* 155-169.

WALKER, G. P. L., 1984. Downsag calderas, ring faults, calderas sizes, and incremental caldera growth. *J. Geophys. Res., 89B,* 8,407-8,416.

VÁZQUEZ, E. and R. JAIMES, 1989. Geología de la Cuenca de México. *En:* Memorias de Simposio sobre tópicos geológicos de la Cuenca del Valle de México, Sociedad Mexicana de Mecánica de Suelos, A.C., 1-24 pp.

VERMA, S. P, 2001. Geochemical evidence for a lithosphere source for maagmas in the Mexican Volcanic Belt from Acoculco caldera, eastern Mexican Volcanic Belt, *Int. Geol. Rev., 43,* 31-51.

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