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Geophysical characterization of the Etla Valley aquifer, Oaxaca, Mexico

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RESUMEN

La ciudad de Oaxaca ha incrementado considerablemente sus necesidades de agua durante los últimos 20 años. El acuífero que produce casi el 80% del total de agua que se consume en la ciudad proviene del Valle de Etla, localizado al noroeste de la ciudad. La explotación intensiva del acuífero ha reducido su calidad.

La geometría de esta cuenca se estimó a partir de modelos de 2.5 dimensiones obtenidos a partir de datos de gravimetría, a lo largo de cuatro perfiles, tres de ellos orientados en la dirección W-E y otro en la dirección N-S. El grosor sedimentario alcanza 730 m como máximo. La interpretación de la información geológica y de los datos gravimétricos muestran que las milonitas del Mesozoico pertenecientes a la Sierra de Juárez y las rocas metamórficas de la Sierra de Oaxaca subyacen el relleno sedimentario. El patrón de fallas inferido controla el comportamiento tectónico de la región y la circulación de agua subterránea. Se estimó la posición de la falla de Etla a profundidad a partir de los perfiles gravimétricos. Estos estudios indican que el Valle de Etla es un graben de gran pendiente acotado por las fallas de Etla y Oaxaca.

Los principales acuíferos se encuentran dentro de los horizontes Terciario y Cuaternario. Veintitrés Sondeos Eléctricos Verticales (SEV) se realizaron hacia la porción central del valle. Estos permitieron inferir el grosor del primer acuífero (20 m a 50 m). Los pozos en el área se emplearon para establecer una correlación entre los horizontes resistivos y la estratigrafía.

Se llevaron a cabo tres perfiles de tomografía eléctrica en la porción sur del valle. Uno de ellos mostró la base del primer acuífero a 50 m de profundidad. Las capas sedimentarias que pueden contener un alto grado de saturación incrementan su grosor hacia el norte, siguiendo la configuración del basamento. Por otro lado, las mediciones electromagnéticas realizadas con un equipo EM-34 mostraron que la zona vadosa tiene un grosor de 20 m hacia el centro del valle. Estos estudios también sugirieron una posible fuente de contaminación que se encuentra en la parte norte de la ciudad de Oaxaca..

PALABRAS CLAVE: gravimetría, electromagnéticos, tomografía eléctrica, prospección de aguas subterráneas.

ABSTRACT

The water supply needs of the city of Oaxaca have increased considerably over the last twenty years. The aquifer that produces 80% of the total water in the region is located in the Valley of Etla, to the NW of the city. Intensive exploitation of the aquifer has reduced the water quality.

Basin geometry was estimated from 2.5-D models along four profiles, three W-E and one N-W. The sedimentary thickness reaches up to 730 m. Gravity and geologic interpretations suggest that the Mesozoic mylonites of the Sierra de Juárez and the metamorphic rocks of the Sierra de Oaxaca underlie the sedimentary infill. The fault pattern controls the tectonic behavior of the region and groundwater circulation. The Valley of Etla is a steep graben bounded by the Etla and Oaxaca faults.

The main aquifers are in the Tertiary and Quaternary horizons. Twenty-three Vertical Electrical Soundings (VES) across the central part of the valley yield a thickness of the first aquifer of 20 m to 50 m. Wells in the area were used to control the resistive horizons and the stratigraphy.

Electric tomography studies in the southern portion of the valley showed the base of the first aquifer at 50 m depth. The water-bearing sedimentary layers increase in thickness to the north of the valley, following the basement. Electromagnetic measurements reveal a vadose zone of at least 20 m thickness towards the center of the Valley. Zones of low resistivity were found in the northern and southern sections of the Valley. A possible contamination is suggested towards the northern portion of the City of Oaxaca.

KEYWORDS: gravity, electromagnetic, electric tomography, groundwater prospecting

INTRODUCTION

Around 67% of the total water supply for the main cities in Mexico is obtained from arid and semi-arid zones. Over-exploitation, contamination by saline intrusion and domestic wastes, and industrial dumping are threatening the subsurface aquifers. The city of Oaxaca is an example.

The State of Oaxaca is crossed by the Sierra Madre del Sur, which extends from Michoacán to the Isthmus of Tehuantepec, and the Sierra Madre Oriental. Both ranges converge towards the eastern end of the State forming several intermountain valleys with potential aquifers. The city of Oaxaca lies at the junction of the valley of Etla to the north, the valley of Tlacolula-Mitla on the southeast and the valley of Zimatlán to the south (Figure 1). Atoyac River flows southward through the valleys of Etla and Zimatlán; at Oaxaca city it is joined by the Mitla River. The valley of Etla at 17° 03' to 17° 17' N and 96° 44' to 96° 54' W has a mean altitude of 1700 m above mean sea level. More than 100 shallow wells supply water to the city of Oaxaca and to the agricultural lowlands. Sierra de Juárez to the east and Sierra de Oaxaca to the west of the valley are the main recharge zones of the aquifers.

The purpose of this paper is to describe the structural and geological setting of the main aquifers as well as the sedimentary units in Etla Valley by means of gravity measurements, shallow electromagnetic soundings (EM-34) and electrical methods (VES and tomography).

GEOLOGICAL SETTING

The valley of Etla is in the geological province of Sierra Madre del Sur (SMS) that contains different basement terrains with contrasting stratigraphy and tectonic features (Ortega-Gutiérrez, 1981; Campa and Coney, 1983; Morán *et al.,* 1999). The Sierra de Juárez bounds the study area to the east (Figure 1); this mylonitic complex has been interpreted as a thrust zone reactivated in the Jurassic, followed by normal brittle-ductile fault reactivation during Cenozoic uplift of the mylonitic belt (Delgado-Argote, 1988; Centeno-García *et al.,* 1990; Alaniz-Álvarez *et al.,* 1996). Mesozoic sedimentary sequences and volcanic strata are also present (Carfatán, 1986; Barbosa, 1994). The Sierra de Oaxaca to the west consists of Grenvillian granulites covered by Paleozoic and Mesozoic sedimentary sequences (Pantoja-Alor, 1992; Schlaepfer, 1970, Ortega-Gutíerrez *et al.,* 1995) (Figure 1). The Oaxaca Fault trends NW and has a complex history starting in Pre-Jurassic as a NNW trending polygenic mylonitic shear zone, followed by left-lateral displacement in the Jurassic and ending with a reactivation in Tertiary times (Alaniz-Álvarez *et al.,* 1996; Alaniz-Álvarez and Nieto-Samaniego, 1997).

The geological map shown in Figure 1 is based on Carfantán (1986), Ferrusquía-Villafranca (1992) and Barbosa (1994) for the northern part of the Valley above 17° 10' N, and Alaníz-Álvarez and Nieto-Samaniego (1997) for the southern part complemented by satellite images.

The stratigraphy of the Etla Valley can be summarized as follows (Figure 2). Grenvillian metamorphic rocks of the Oaxaca Complex constitute the basement of the region. Mesozoic mylonites of the Sierra de Juárez are related to the Oaxaca complex by the Oaxaca Fault. Tertiary sequences lie unconformable on rocks of Precambrian and Mesozoic ages. These can be divided into two series. The first is made up of conglomerates and early Tertiary volcanic sequences of andesitic-latiandesitic composition (Wilson and Clabaugh, 1970; Ferrusquía-Villafranca, 1992). The second is a Miocene sequence, including the Suchilquitongo formation and the Telixtlahuaca conglomerate. The Suchilquitongo formation contains lake deposits (shale, sandstone and limestone), silicic tuffs, epiclastic tuffs and silicic ignimbrites (Wilson and Clabaugh, 1970; Ferrusquía-Villafranca, 1992). Overlaying the ignimbrite is the Telixtlahuaca unconsolidated conglomerate. The aquifers of the valley lie in the Tertiary sand and gravel sediments, with thicknesses ranging from 10 to 40 m. The base of the aquifers is a clay body with an average thickness of 36 m (INEGI, 1991).

GEOPHYSICAL SURVEY

Gravity measurements were made along main and local roads (Figure 3). A total of 125 gravity observations were reduced to the base station at the Oaxaca International Airport. A Scintrex model CG-3 gravitymeter was used. The geographical locations were obtained with a Garmin Global Position System (GPS).

23 vertical electrical soundings (VES) were carried out in the central part of the Valley of Etla (Figure 3). A Schlumberger array was used with electrode spacing (AB/2) of up to 200 m. 123 electromagnetic soundings using a Geometrics EM-34 were made over an irregular grid of observations (Figure 3). Working frequencies of 6400, 1600 and 400 Hz were used, for spool openings of 10, 20 and 40 m.

GRAVITY INTERPRETATION

The Bouguer anomaly was computed for a standard density of 2.67 g/cm^3. The topographic correction was computed after Herrera (1992). The correction varied from 5 mGal close to the ranges to less than 1 mGal in the lower valley. Figure 4 shows the Bouguer anomaly map; note a

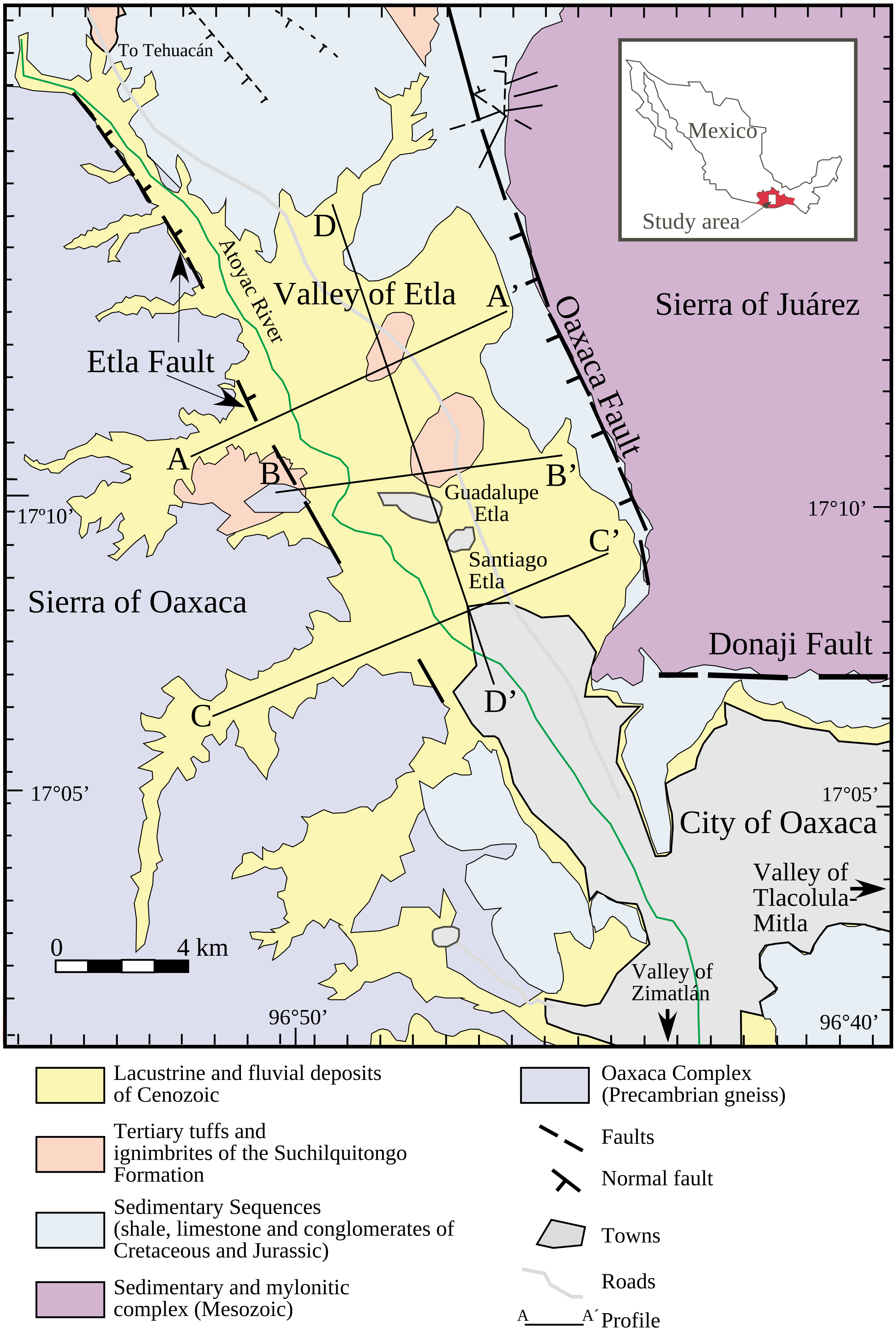

Fig. 1. Geological map of the Valley of Etla bounded by Sierra of Juárez and Sierra of Oaxaca (based on Carfantán (1986); Ferrusquía-Villafranca (1992); Barbosa (1994); Alaníz-Álvarez and Nieto-Samaniego (1997)). The Oaxaca and Donaji faults are schematically depicted. The Etla fault position was inferred from geophysical interpretation.

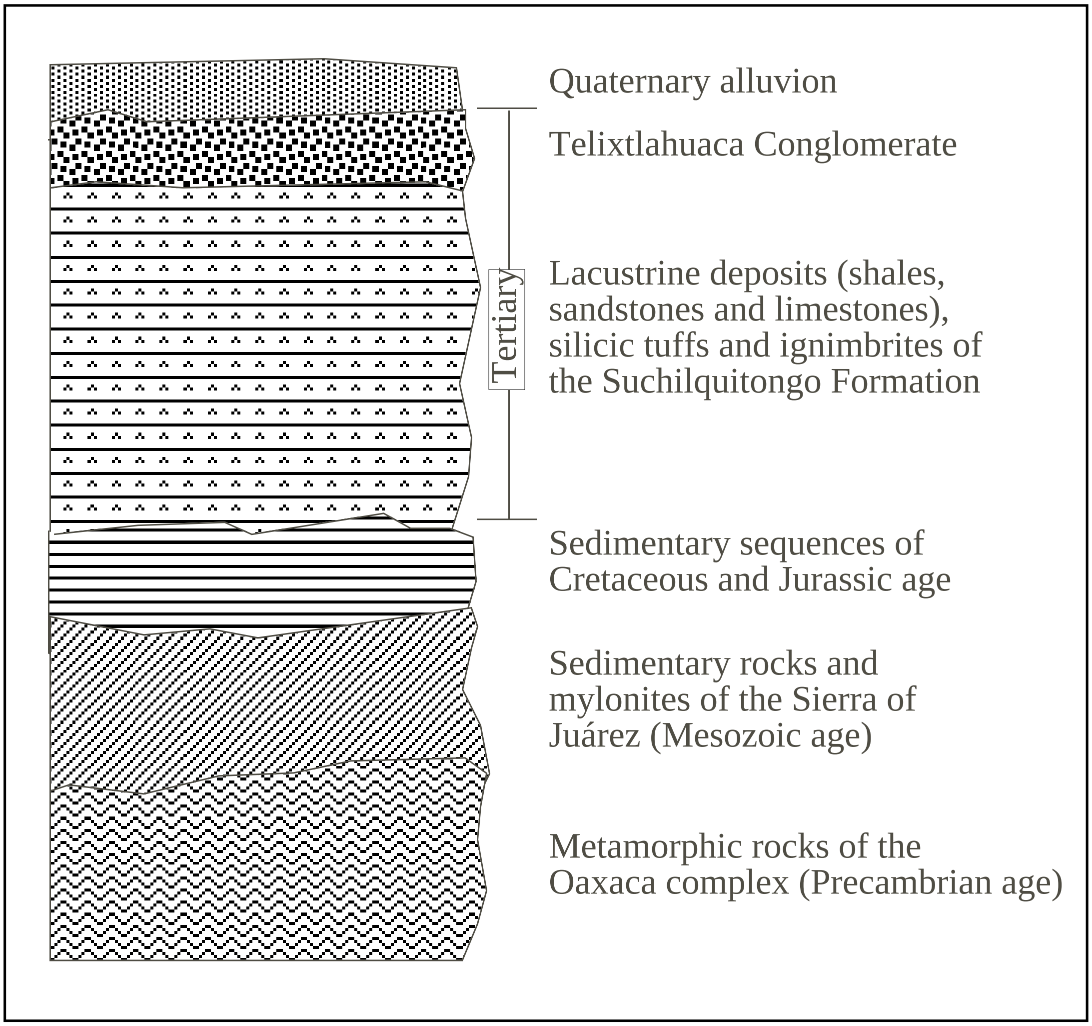

Fig. 2. Composite stratigraphic column for the Valley of Etla region (after Ferrusquía-Villafranca, 1992, Alaníz-Álvarez and Nieto-Samaniego, 1996 and Centeno *et al.*, 1990).

NW-SE elongated gravity low. The sediments appear to reach their maximum thickness north of Guadalupe Etla. A steep gravity gradient can be observed in the western flank of the range, which may be associated with the Etla fault. The eastern boundary is characterized by a smooth gravity gradient. Data towards the Sierra de Juárez is scarce and inadequate. It is important to point out that the Sierra de Juárez is higher than the Sierra de Oaxaca, and that densities are different, 2.65 g/cm^3 against 2.80 g/cm^3 respectively.

Preliminary depth estimation based on the Spector and Grant (1970) approach yielded a mean depth of 500 m for the basement under the valley. We interpreted four gravity profiles (Figures 5 and 6). Three profiles across the valley in a general W-E direction, and one profile in the NW-SE direction along the valley axis. From geology we know that the basement of the valley is composed of Precambrian gneisses of the Sierra de Oaxaca and deformed Mesozoic sedimentary sequences and mylonites of the Sierra de Juárez. Densities were estimated from tables by Telford *et al.* (1990), since measurements *in situ* are not available. An interpretation program developed by Interpex (1998) to model the gravity data was employed. We have used trial and error jointly with inversion to interpret the profiles. A density of 2.80 g/cm^3 was assumed in the Sierra de Oaxaca and 2.65 g/cm^3 in the Sierra de Juárez. Densities of sedimentary units are displayed in Figures 5 and 6. The models suggest a rather complex basin; the faulting pattern resembles a graben. The models proposed for profiles A-A' and B-B' (Figure 5) are very similar. The basement features two blocks of different densities. A gentle slope is observed to the east of the interpreted gravity basement, while the Oaxaca Complex shows a steeper slope.

Cenozoic continental sediments (lacustrine and alluvial deposits) and some volcanic tuffs are emplaced on this

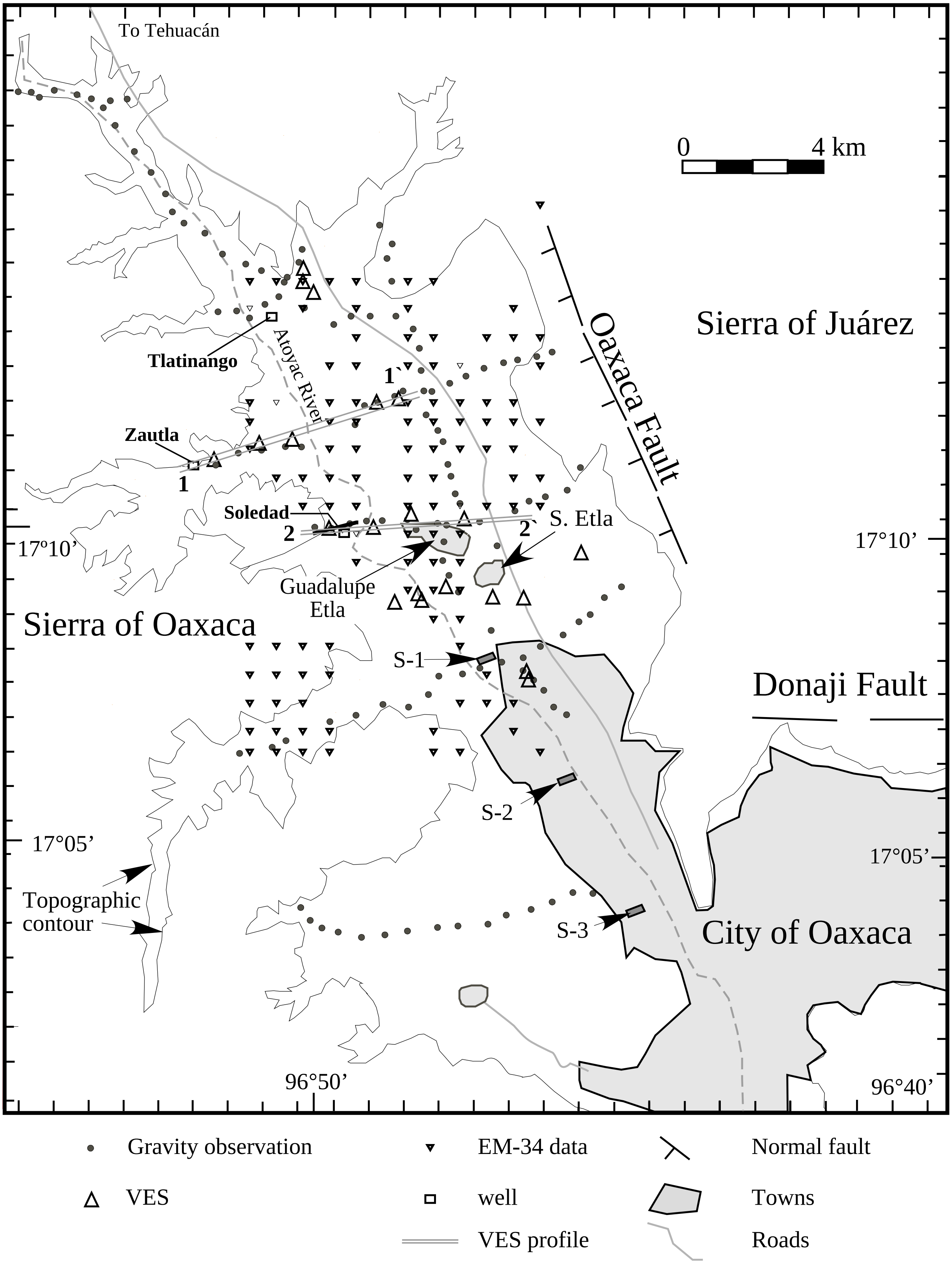

Fig. 3. Gravity, VES and EM-34 survey location. The water exploitation wells Soledad, Zautla and Tlatinango are also shown.

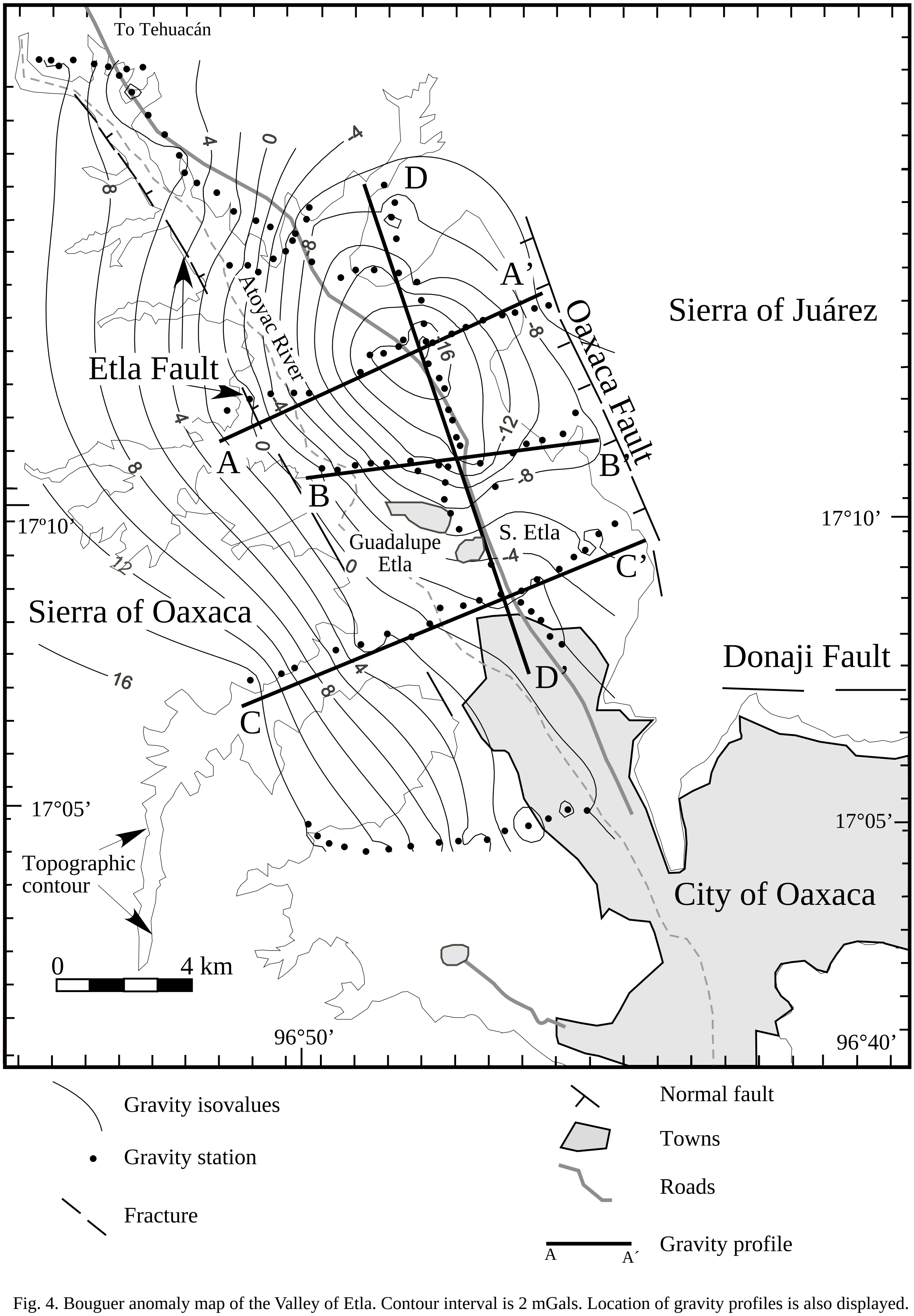

Fig. 4. Bouguer anomaly map of the Valley of Etla. Contour interval is 2 mGals. Location of gravity profiles is also displayed.

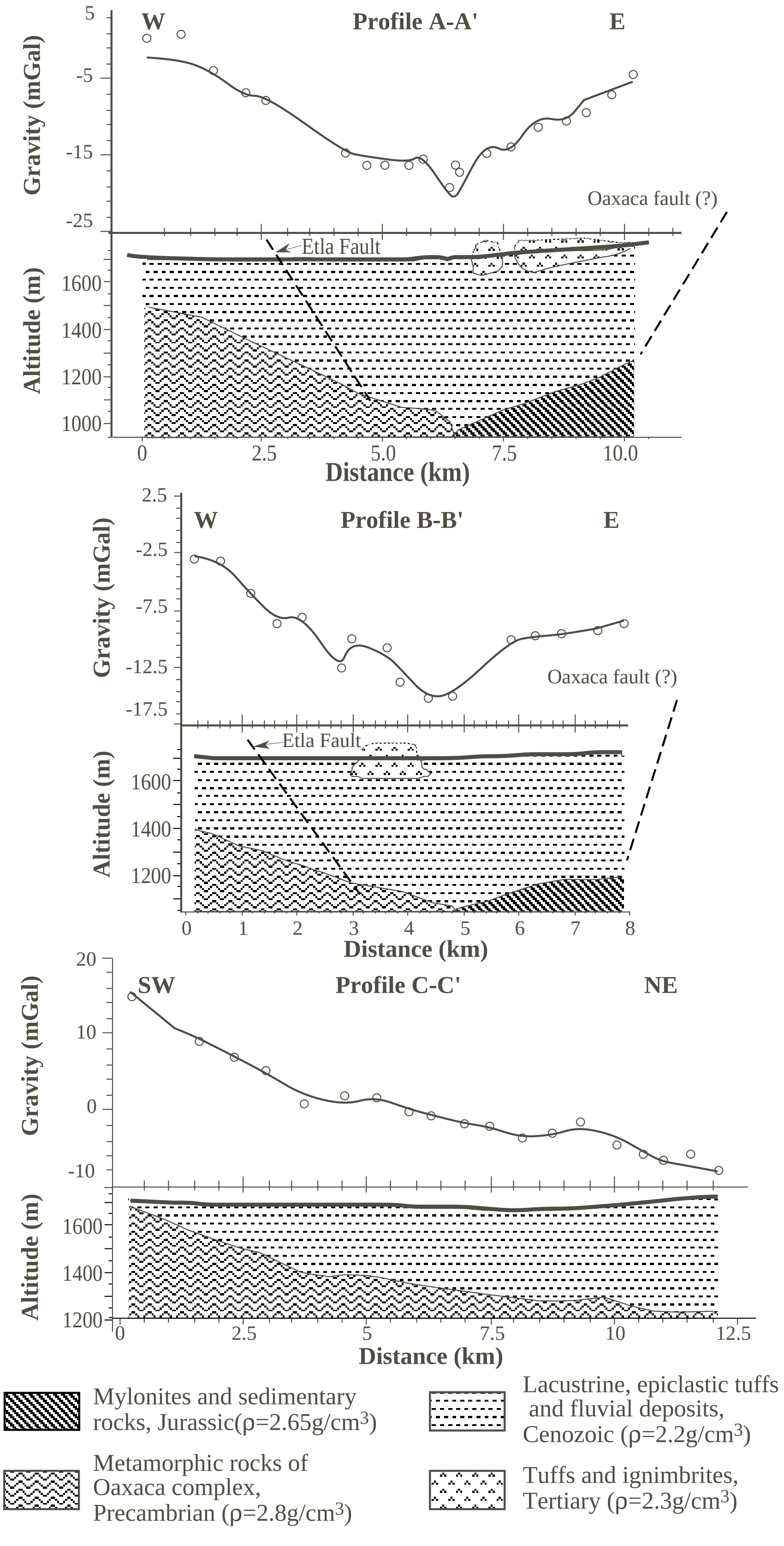

Fig. 5. Gravimetric model along profiles: A-A', B-B' and C-C'. These are set in the E-W direction, approximately. The models in profiles A-A' and B-B' depict two basement blocks revealing the presence of a fault (The Etla fault). However, model in profile C-C' shows a single basement structure.

basement. The maximum thickness of the sedimentary sequence reaches 730 m (Figure 5, profile A-A’). Small outcrops of volcanic rocks did not contribute significantly to the gravity anomaly. The Oaxaca fault is not depicted: it is found further east. However, a fault to the east of the valley has been inferred; we named it the Etla fault. It is observed in the Bouguer gravity anomalies, and may be correlated with a fault reported by Ferrusquía-Villafranca (1992). Profile C-C’ (Figure 5) differs from the other profiles. Metamorphic rocks of the Oaxaca Complex form the basement. It gently slopes to the east. The Cenozoic sediments thicken in that direction. The gravity profiles suggest that mainly two blocks form the basement. However, the mylonitic block ends abruptly at depth near Santiago Etla, towards the southern part of the Valley.

Profile D-D’ (Figure 6) runs perpendicular to the other sections. Our model shows a smooth relief of the basin (the Oaxaca Complex). Location of the other gravity profiles is also shown. Note that the sedimentary thickness increases towards the center of the Valley (see profile A-A’).

GEOELECTRIC RESULTS

Vertical Electrical Soundings (VES) were interpreted by a standard inverse algorithm assuming a one-dimensional stratified earth (Das *et al.*, 1974). Some soundings show evidence of a high resistivity material, interpreted as a clay layer. Figure 7 shows the integration of some VES along two selected W-E profiles. The lithology reported from the Zautla and Soledad wells was used to interpret the resistivity. The readings for each electric horizon were associated to a sedimentary sequence. The values obtained are in good agreement with reported resistivity values (Shara, 1980; MacNeill, 1991). The shallow layer corresponds to alluvium. This layer is 7 m thick (170 ohms-m). We interpreted water-saturated sand (50 ohms-m) beneath some VES. Thickness of this layer ranges from 10 m to 25 m (100 ohms-m). A mixture of sand and clay with resistivities of 200 ohms-m was interpreted below 25 m. The aquifer consists of two resistivity strata (about 100 ohms-m to 200 ohms-m), and basically contains sand and little clay. In most cases, the electrical soundings were spaced less than 200 m (AB/2).

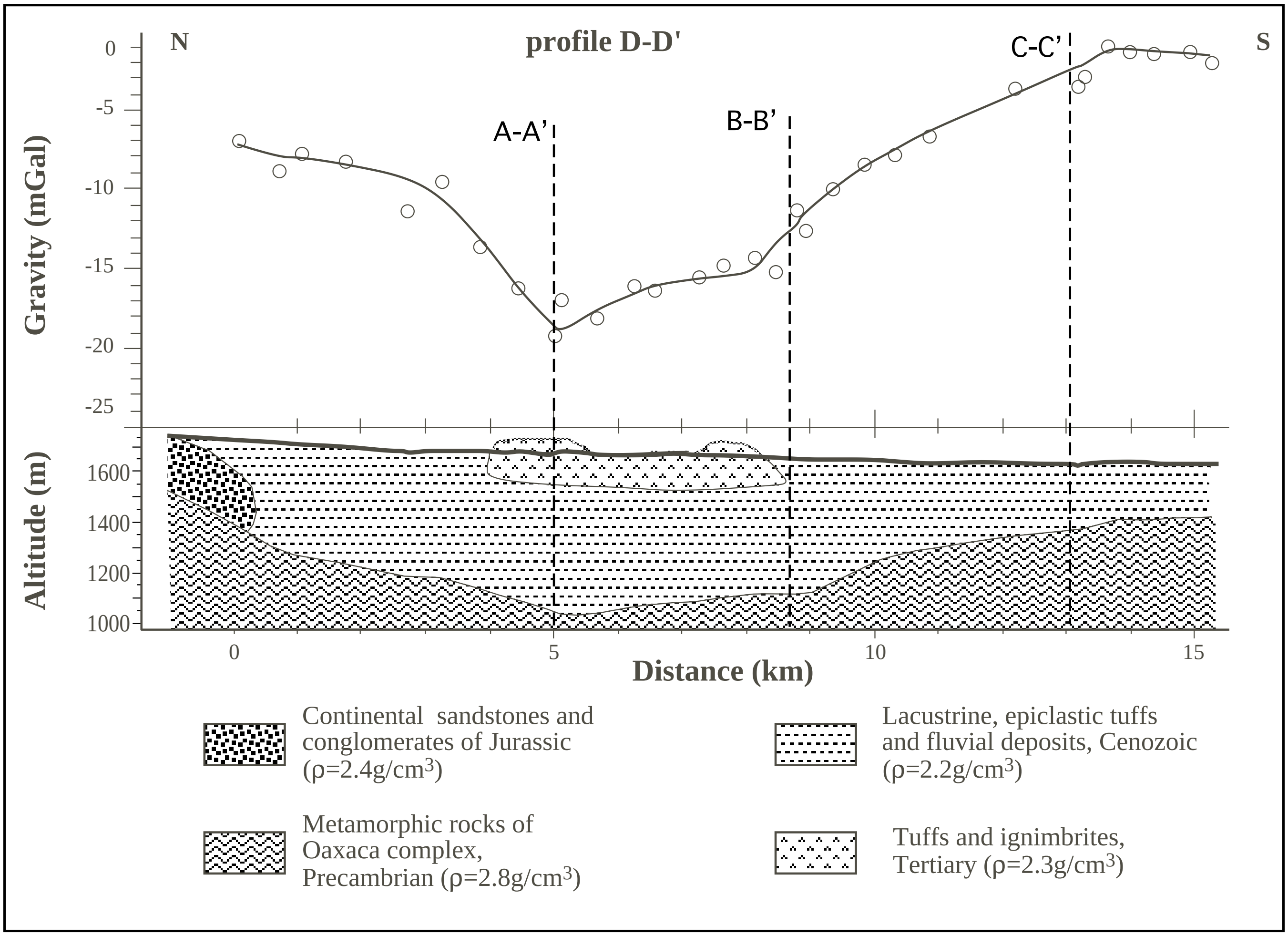

Fig. 6. Gravimetric model along profile D-D’. This trends in a N-S direction. The Oaxaca Complex was proposed as a single causative structure fitting the observed anomaly.

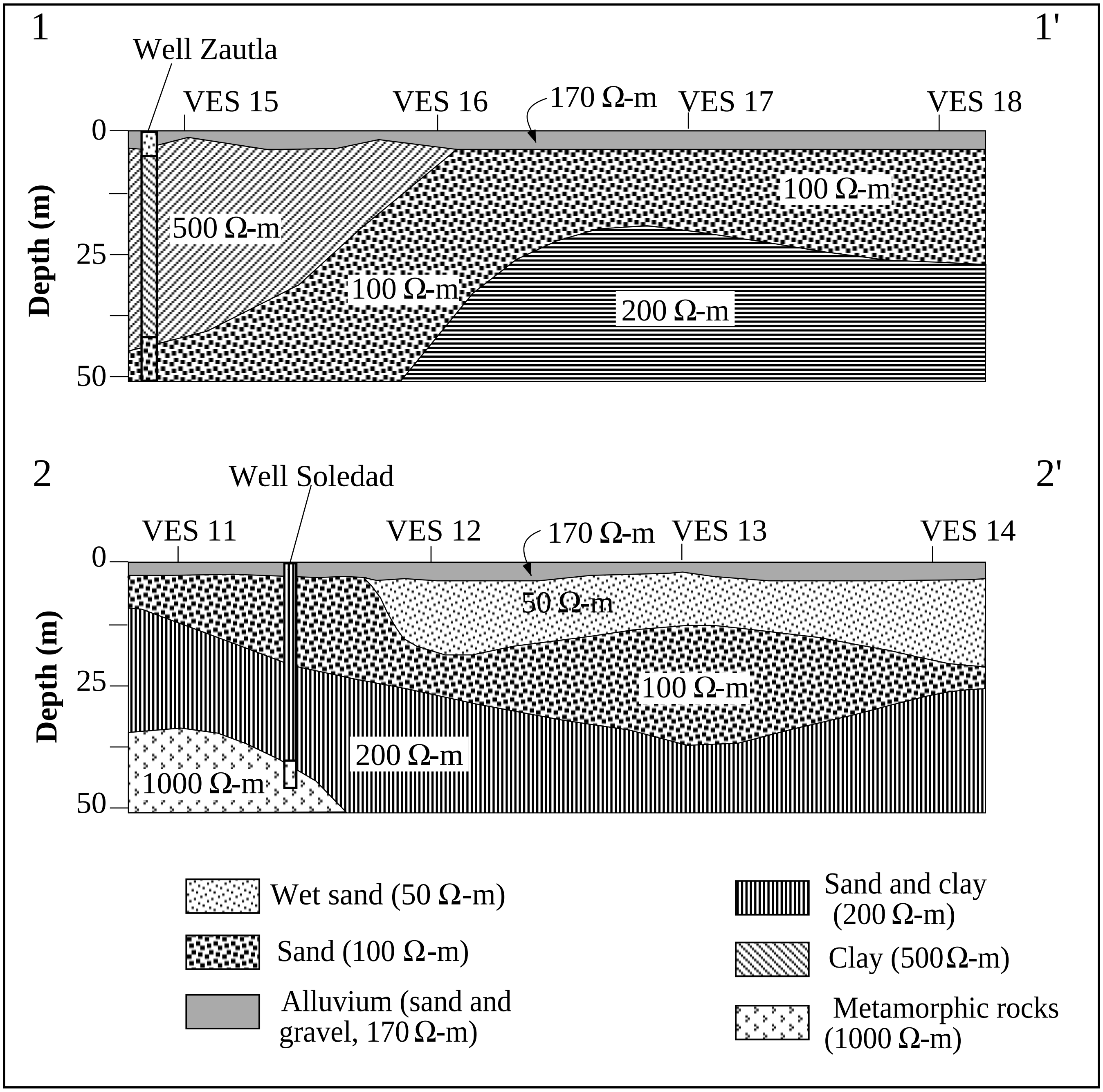

Fig. 7. Two-dimensional profiles based on VES (see Figure 3 for location). Profile 1-1' coincides with gravimetric profile A-A'. Lithology from wells is also shown.

Therefore the base of the first aquifer was not found. This horizon is shallower to the south and increases in depth to the north, following the geometry inferred for the basement from the gravity interpretation.

The Loke and Barker (1995) algorithm was used to invert the apparent resistivities along three profiles. A Wenner-Schlumberger array was used and 21 electrodes were deployed at 15 m intervals. A total length of 300 m was surveyed, corresponding to 8 levels of investigation. A saturated clay layer is clearly seen in Figure 8, with very low resistivities (about 10 ohms-m, blue). The top of the fresh water layer (clay and sand) is observed in Figure 8 (S-3), at depths greater than 55 m. This layer shallows to the south and increases in depth to the north of the valley.

EM-34 data was interpreted by direct and inverse methods for each sounding assuming a three-layer model in

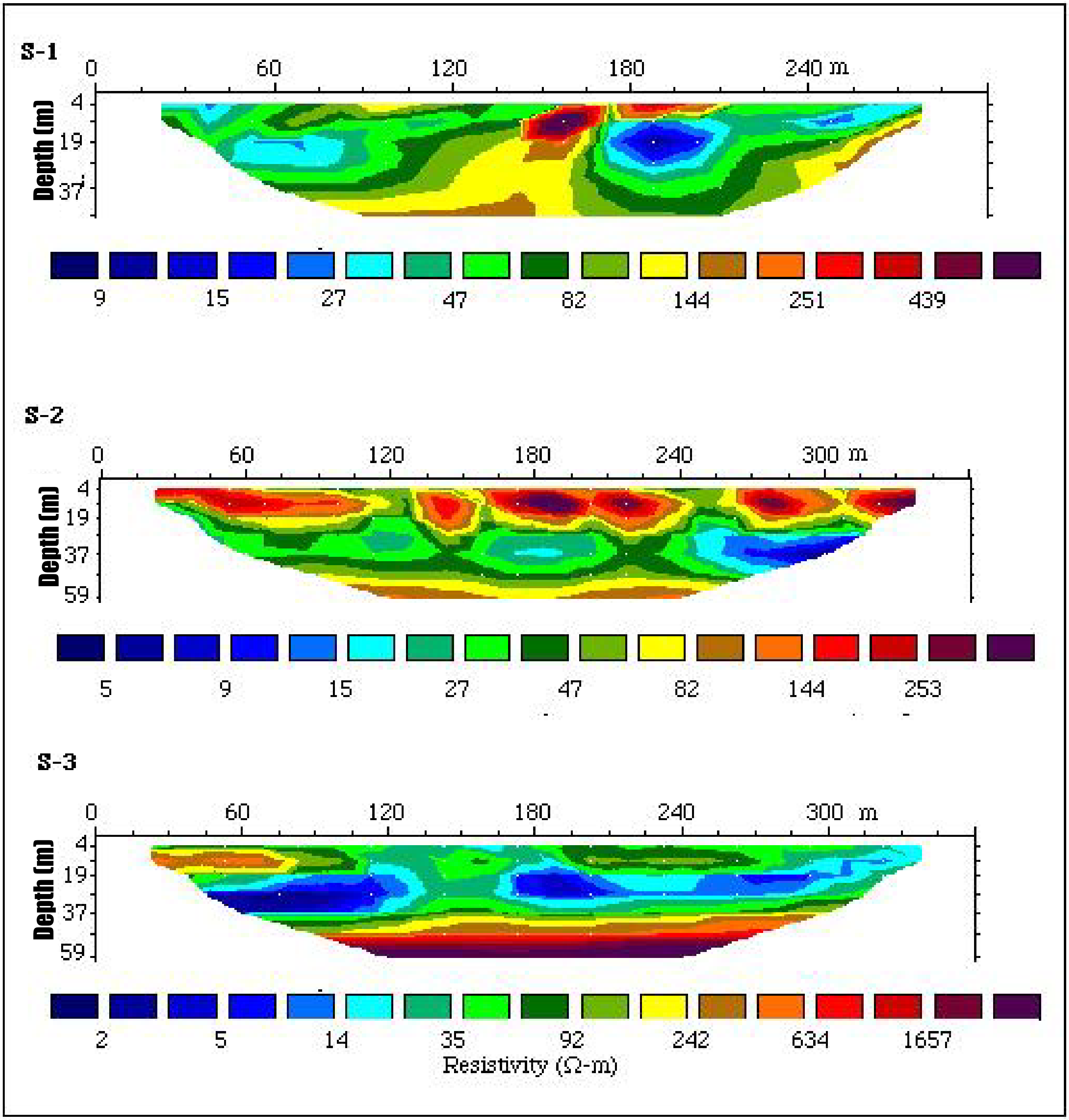

Fig. 8. Electric tomography profiles. These are detailed resistivity studies surveyed perpendicular to the valley axis. They are from north to south: S-1, S-2, S –3 (See Figure 3 for location).

a horizontally stratified earth. Results helped to define the vadose zone (shallow horizon) and the base of the aquifer (Figure 9). The lateral variation of resistivity in the electric horizons is also displayed. Mean resistivity in the vadose zone is around 100 ohms-m, but the deepest horizon shows a higher value (1000 ohms-m), corresponding to the tuffs. This second aquifer is found at 50 m depth, approximately. Figure 9 also displays extremely high resistivities (1800-2200 ohms-m) in the southern part of the area. This may be due to a contamination plume extending to the north; the source might be located within the urban limits of Oaxaca City.

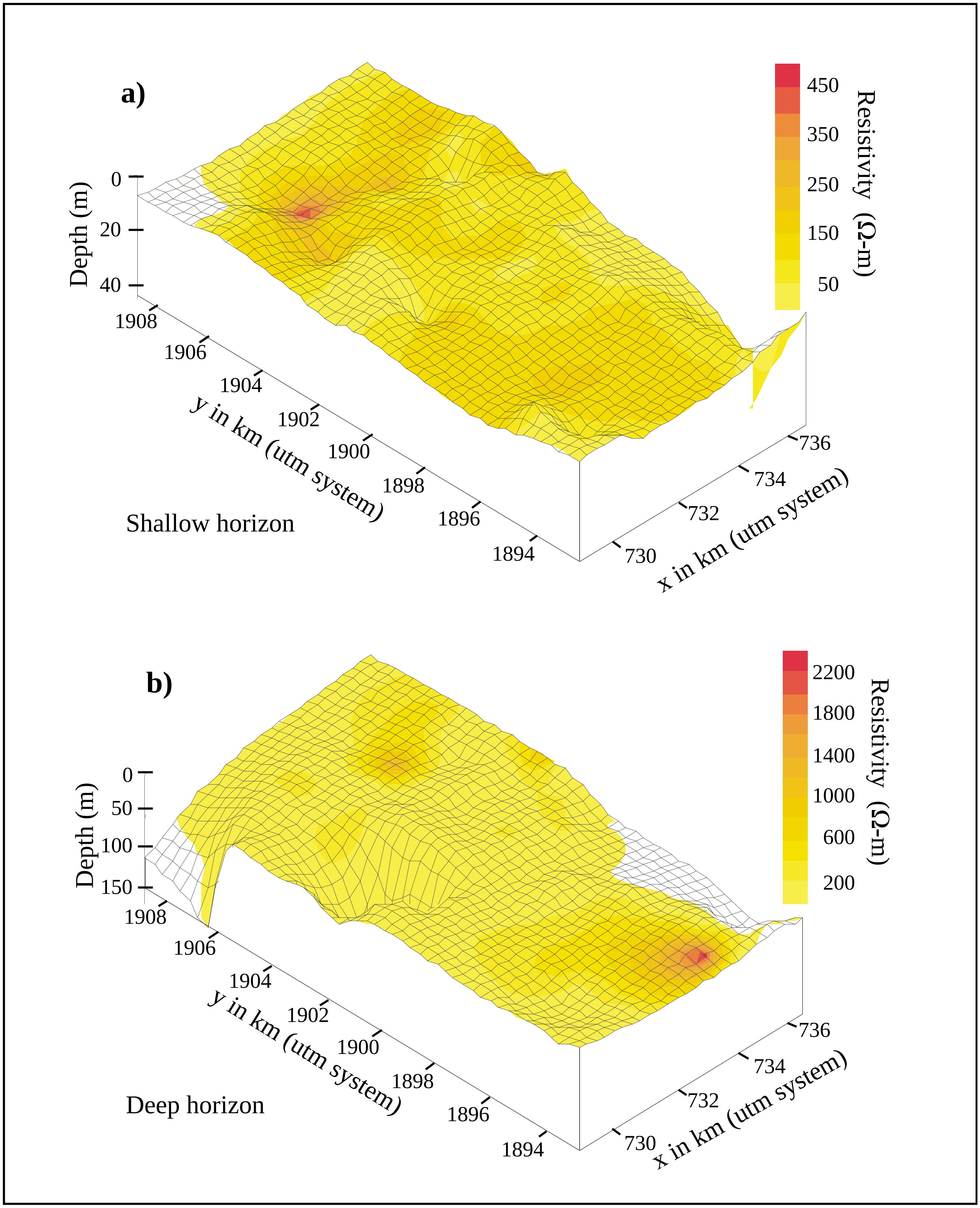

Fig. 9. Interpretation of electromagnetic soundings (EM-34) based on available reported lithology. a) The vadose zone was interpreted at the top with very low resistivities. b) The high resistivity layer was assumed as the bottom of the aquifer. Note the high resistivity values towards the southern section of diagram. This anomaly may be related to a contaminant plume.

CONCLUSIONS

The gravity interpretation suggests a graben with its deepest part under the northern end of the Valley (near the middle of profile A-A'). Gravity interpretation of four 2-D profiles indicates a sedimentary infill 730 m thick at its deepest location. It shallows to the southeast of the valley, near the city of Oaxaca. The Etla and Oaxaca faults are the boundaries of the basement, formed by steep blocks. Profiles A-A' and B-B' show a basement formed by two different high-density materials. Profile C-C' shows the basement sloping to the east with a uniform density. The deep contact between the Mesozoic mylonites of the Sierra de Juárez and the metamorphic rocks of the Oaxaca Complex seems to converge to the east near the Donaji fault. The Etla Valley is due to a graben formation, bounded by Oaxaca and Etla faults. This graben may have been reactivated in the Tertiary, in agreement with Alaniz-Álvarez and Nieto-Samaniego (1997).

The VES profiles show an aquifer basically containing sands, boulders, gravels and alluvium overlaying a clay strata that behaves hydraulically as the seal of the first aquifer (aquitard). The complementary resistivity profiles reveal a high-resistivity horizon that we interpret as a saturated clay layer at a depth greater that 50 m. The water extracted in this area is mainly used for the industrial and domestic needs of Oaxaca City. This layer is shallower south of the valley, near the city of Oaxaca, and increases in depth to the north, following the basement described by the gravity interpretation.

The EM-34 observations show that the vadose zone averages 20 m in thickness, which agrees with VES measurements. Deep and shallow horizons suggest the presence of a second aquifer underlying a saturated-clay layer. It might extend between 18 to 20 km in a NW-SE direction, and may be 8 to 12 km wide. A contamination plume with extremely high resistivity values is found in the southern section of the resistivity map (Figure 9). This feature seems to disperse towards the northern portion of the Valley, where the main water wells are located.

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