Geophysical and hydrogeological characterization of the sub-basins of Apan and Tochac (Mexico basin)

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RESUMEN

A partir de los datos de resistividad, gravimétricos, magnéticos, hidrogeológicos y geoquímicos, se describen las principales características del sistema hidrogeológico de las subcuencas de Apan y Tochac, pertenecientes a la cuenca de México. Ambas subcuencas presentan un relleno volcano-sedimentario de aproximadamente 600 m de espesor, y están separadas por la cordillera de Apan, la cual se extiende a lo largo de una gran falla de orientación NE-SW, definida como una prolongación del lineamiento regional que une a los volcanes de Tlaloc y Telapon. La subcuenca de Apan tiene un bajo nivel de actividad sísmica. La correlación de la información geofísica con los datos de pozos confirma la existencia de un sistema hidrogeológico que incluye acuíferos intergranulares, mixtos y fisurados con transmisibilidad entre 5.7×10^{-3} m^2/s y 1.1×10^{-1} m^2/s, y permeabilidad aproximada de 4.0×10^{-4}. El acuífero fisurado constituye el área de recarga, mientras los otros dos conforman un acuífero semi-confinado cuya única descarga proviene del bombeo de los pozos. La zona no-saturada tiene 60 m de espesor y la superficie potenciométrica fluctúa 0.30 m anualmente. Sin embargo, en algunas zonas del área en estudio no se observaron estas fluctuaciones. De acuerdo con la información litológica de los pozos y la interpretación de los Sondeos Eléctricos Verticales, el mayor espesor del acuífero se encuentra en la porción sur de la subcuenca de Tochac. Los valores de resistencia eléctrica y los estudios hidrogeoquímicos indican la presencia en profundidad de agua de buena calidad ligeramente mineralizada.

PALABRAS CLAVE: Cuenca de México, subcuencas de Apan y Tochac, sistema hidrogeológico, calidad del agua subterránea, caracterización geofísica e hidrogeológica.

ABSTRACT

The main features of the hydrogeologic system in the Apan and Tochac sub-basins of the basin of Mexico are described from gravity, magnetic, resistivity, hydrogeological, and geochemical data. Both sub-basins have about 600 m of volcano-sedimentary infill, and are separated by the NE-SW trending Apan range. Gravity and magnetic data indicate that the Apan range is emplaced along a major NE-SW trending fault along the extension of a regional lineament joining the Tlaloc and Telapon volcanoes. The Apan sub-basin has low-level seismic activity. A correlation with borehole data confirms a model of the hydrogeologic system which includes intergranular, mixed and fissured aquifers with transmissivities between 5.7×10^{-3} m^2/sec and 1.1×10^{-1} m^2/sec, and permeability around 4.0×10^{-4}. The fissured aquifer is the recharge area, while the other two aquifers constitute a semi-confined aquifer whose only discharge comes from well pumping. The unsaturated zone is 60 m thick and the potentiometric surface fluctuates 0.30 m yearly. However, in places no fluctuations were observed. The thickest portion of the aquifer, as delimited by vertical electric soundings and boreholes, is in the southern portion of the Tochac sub-basin. Resistivity values and hydrogeochemical studies indicate the presence at depth of good quality, slightly mineralized water.

KEY WORDS: Mexico basin, sub-basins of Apan and Tochac, hydrogeological system, groundwater quality, geophysical and hydrogeological characterization.

INTRODUCTION

The basin of Mexico City comprises 12 sub-basins. The southern part of the basin comprises the sub-basins of Xochimilco and Chalco. The northeastern portion comprises the sub-basins of Apan, Tochac, and Tecocomulco. Fifty percent of Mexico City's water supply is extracted from aquifers beneath the city itself or from the Chalco sub-basin. Extensive pumping has caused a decline in the potentiometric surface and has induced a subsidence of about 0.4 m per year (Ortega-Guerrero *et al.*, 1993). Numerous studies have focused on the aquifers beneath Mexico City (e.g., Herrera, 1989) and of Chalco (e.g., Huizar-Alvarez, 1981, and Campos-Enríquez *et al.*, 1997). The sub-basins of Apan, Tochan, and Tecocomulco have been less extensively studied.

The purpose of this multi-disciplinary study is to establish the main features of the hydrogeological system in the Apan and Tochac sub-basins. The study area is located in the east-central Trans-Mexican Volcanic Belt (TMVB) (Figure 1). The TMVB is a Pliocene-Quaternary calc-alkaline province that crosses Mexico from west to east between 19° and 21° north latitude. It includes most of the historic and present-day volcanism of Mexico in the form of andesitic-dacitic stratovolcanoes, cinder cone fields, iso–

Fig. 1. The study area in the Trans-Mexican Volcanic Belt, and location of the Apan and Tochac sub-basins in the northeastern portion of the basin of Mexico. Location of the gravity profile is indicated (see also Figures 2 and 3).

lated occurrences of rhyolitic volcanism, and major rhyolitic centers. It is interpreted as a volcanic arc related to the subduction of the Cocos Plate under the North America Plate (Molnar and Sykes, 1969; Demand and Robin, 1975).

The sub-basins of Apan and Tochac occupy the northeastern portion of the basin of Mexico (Figure 1), between the Sierra de Tepozan on the east, the Sierra de Calpulalpan or Sierra de Río Frío on the south, and unnamed ranges on the west and north. The two basins are separated by the Apan range, and have a joint area of 1,480 km^2. Of this area, 35% corresponds to plains, and the remainder is occupied by hills. The plains extend in an east-west direction with a mean elevation of 1,495 m above sea level. Locally the Tochac sub-basin contains several isolated cinder cones (Figure 2).

The main economic activity is agriculture, most of which is seasonal. A few areas are irrigated. The neighboring towns and cities have growing services-based economies. The waste waters from these towns and cities run into streams draining into oxidation ponds. Because of the local geology, residual waters infiltrate into the subsurface and represent a potential source of pollution for the local aquifers.

There is a growing need of water supply for agricultural and domestic uses in the sub-basins of Apan and Tochac. However, little information exists regarding the sub-surface structure of these sub-basins, or on the hydrologic system including the quality and vulnerability of groundwater resources.

Based on gravity and magnetic data, we infer the major structural features of the sub-basins and the thickness of the volcano-sedimentary fill. Vertical electric soundings together with information from boreholes enable us to establish the stratigraphy of the volcano-sedimentary fill. We identify the types of aquifers comprising the hydrogeological system, and their hydraulic transmissivities. We measure climatological variables such as precipitation, evapo–

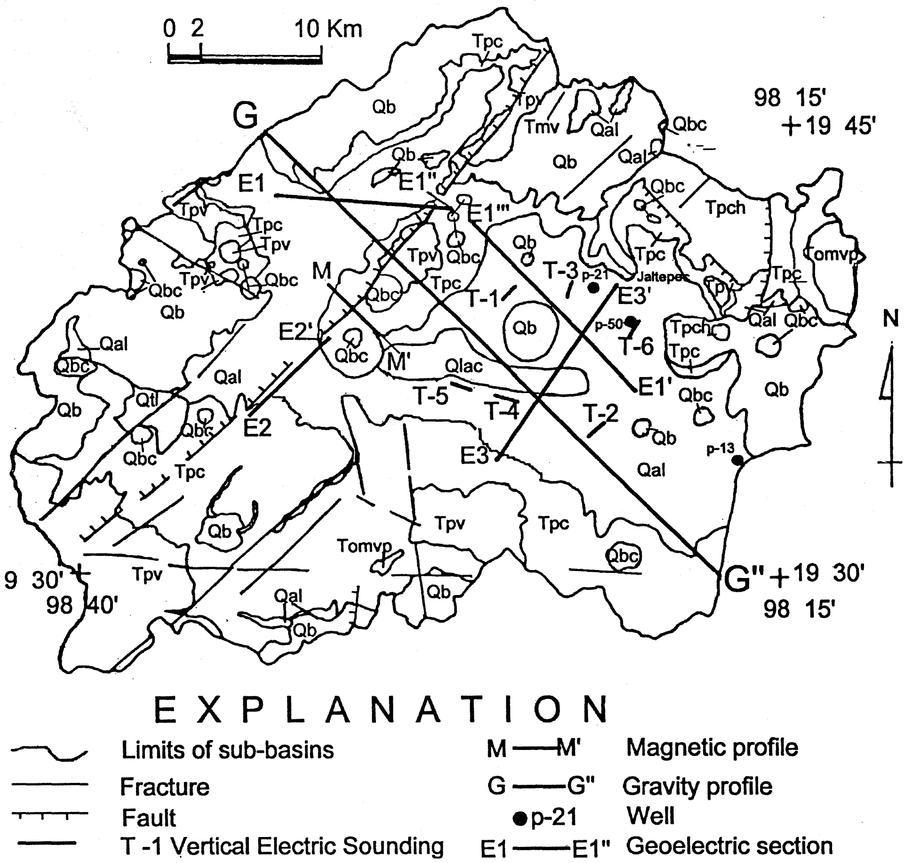

Fig. 2. Geologic setting of the Apan and Tochac sub-basins (after Mooser, 1975, and Ledesma-Guerrero, 1987). The Tertiary units comprise: El Peñon andesite (Tomvp), the Chignahuapan formation (Tpch), the group of undifferentiated Tertiary volcanic rocks (Tpv), the Calpulalpan formation (Tpc). The Quaternary products are basaltic and include lava flows, breccias, volcanic ash (Qb), and cinder cones (Qbc). The volcano-sedimentary deposits include fine and coarse clasts (Qal), pyroclasts and tuffs deposited in water (Qtl), and lacustrine deposits (Qlac).

transpiration, and mean annual temperatures, which enable us to analyze the recharge and discharge regimes. The ground water quality is established based on chemical analysis of extensive water sampling during a 3-year period.

GEOLOGICAL SETTING

The local basement of upper Mesozoic to lower Tertiary sedimentary rocks is covered by a thick sequence of volcanic rocks, pyroclastic products, and fluvial sediments (Figure 2). We assume that this basement overlies metamorphic rocks (Paleozoic ?). The basement is comprised of continental conglomerates of the El Morro formation, of upper Eocene to lower Oligocene age, or Cretaceous limestones. The age of the volcano-sedimentary cover ranges from Tertiary to Quaternary. The lower unit of the volcanic sequence is composed of andesitic and rhyolitic flows. It forms hills with heights of about 3,000 m above sea level (up to 500 m above the basin floor). This unit, named El Peñon by Ledesma-Guerrero (1987), has been correlated with the Oligocene-Miocene Pachuca Group of Segerstrom (1961). There are no radiometric dates for these andesitic rocks, but similar rocks in the Actopan range to the northwest of the study area suggest an age of 2.38 Ma (Cantagrel and Robin, 1979).

The 200 to 250 m thick Chignahuapan formation overlies the El Peñon andesitic sequence. It is 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), Overlying the Chignahuapan formation is a group of undifferentiated Tertiary volcanics (andesites, latites, rhyolites and rhyolitic tuffs) which outcrop in different parts of the study area. The Sierra de Río Frío, (locally known as Sierra de Calpulalpan) has heights of 4,000 m a.s.l. and is composed of andesites and dacites. These rocks underlie the Calpulalpan formation and unconformably the Quaternary flows. Mooser (1972) assigned this formation a Pliocene age. The Calpulalpan formation has a thickness of 300 m according to Ledesma-Guerrero (1987). It is composed of mud, sands and conglomerates, all of andesitic clasts. At its base we have alternating layers of mud, sands, and gravels containing pebbles derived from andesites and dacites. It also contains some horizons of pumice. At the top are volcanic ash, pumice, and fluvial deposits constituting a piedmont plain. This formation is similar to the Tertiary Tarango formation of the basin of Mexico (Bryan, 1948; Fries, 1962).

The Quaternary products are mainly volcanic rocks (basalts and basaltic andesites that cover a great portion of the sub-basins), and alluvium. The volcanics occur in elongated hills or isolated volcanoes. The alluvium includes deposits of fluvial and lacustrine origin, as well as aerial pyroclastics. They are found in the low-lying parts of the valleys.

The distribution of the volcanics suggests three main fracture systems striking NE-SW, NW-SE, and E-W. According to Mooser (1975), the oldest is the NE-SW fracture system which together with the NW-SE system, delimits horsts and tectonic depressions, as may be seen in the nearby sub-basin of Tecocomulco. A tectonic lineament joining the Tlaloc and Telapon volcanoes continues further northeastwards. In the sediments of the Calculalpan formation we can follow this linear feature. Its prolongation coincides with the NE-SW trending Apan range (Figures 1 and 2), and if further extended to the northeast, with the eastern limits of the Tecocomulco sub-basin. We suggest that the Tecocomulco sub-basin may extend into the northwestern portion of our study area.

MAJOR SUB-SURFACE STRUCTURAL FEATURES INFERRED FROM GEOPHYSICAL DATA

To infer the major sub-surface structural features of the Apan and Tochac sub-basins we measured gravity on a profile normal to the Apan range (Figures 1, 2 and 3). This profile is 98 km long, and trends NW-SE. We used a Worden Master gravitymeter with stations every 500 m. A reference density of 2,670 kg/m^3 was used and the complete Bouguer anomaly (e.g. including drift, free-air, latitude, Bouguer, and terrain corrections out to 20 km) was obtained. A regional-residual separation was done. The regional is assumed to be the low-frequency portion of the spectrum as obtained digitally in the wavenumber domain by low-pass filtering (e.g., Hildenbrand, 1983). We obtained the residual anomaly as the difference between the Bouguer and regional anomalies.

We used a 2-D gravity modeling algorithm (Talwani *et al.*, 1959) modified to take into account topography effects. Available surface geology and bore-hole data was used to constrain the gravity model. The densities for the different geologic units were obtained from rock samples, and are similar to those obtained by Pérez-Cruz (1988) in cores from wells in Mexico City. The model (Figure 3) includes: (1) a limestone basement (2,800 kg/m^3); (2) a limestone sub-basement (2,700 kg/m^3); (3) an undifferentiated Tertiary to Quaternary unit comprising rhyolites and basalts (2,500 kg/m^3); and (4) a volcano-sedimentary infill, to which we assigned a density between 2,000 to 2,200 kg/m^3.

In our model the Apan and Tochac sub-basins have infill thicknesses between 300 and 600 m (Figure 3). The basement under the Tochac sub-basin is approximately 1,500 m deep. Towards the Apan basin, the basement drops about 500 m at a steep fault along the NW-SE trending Apan volcanic range. The Apan range coincides with

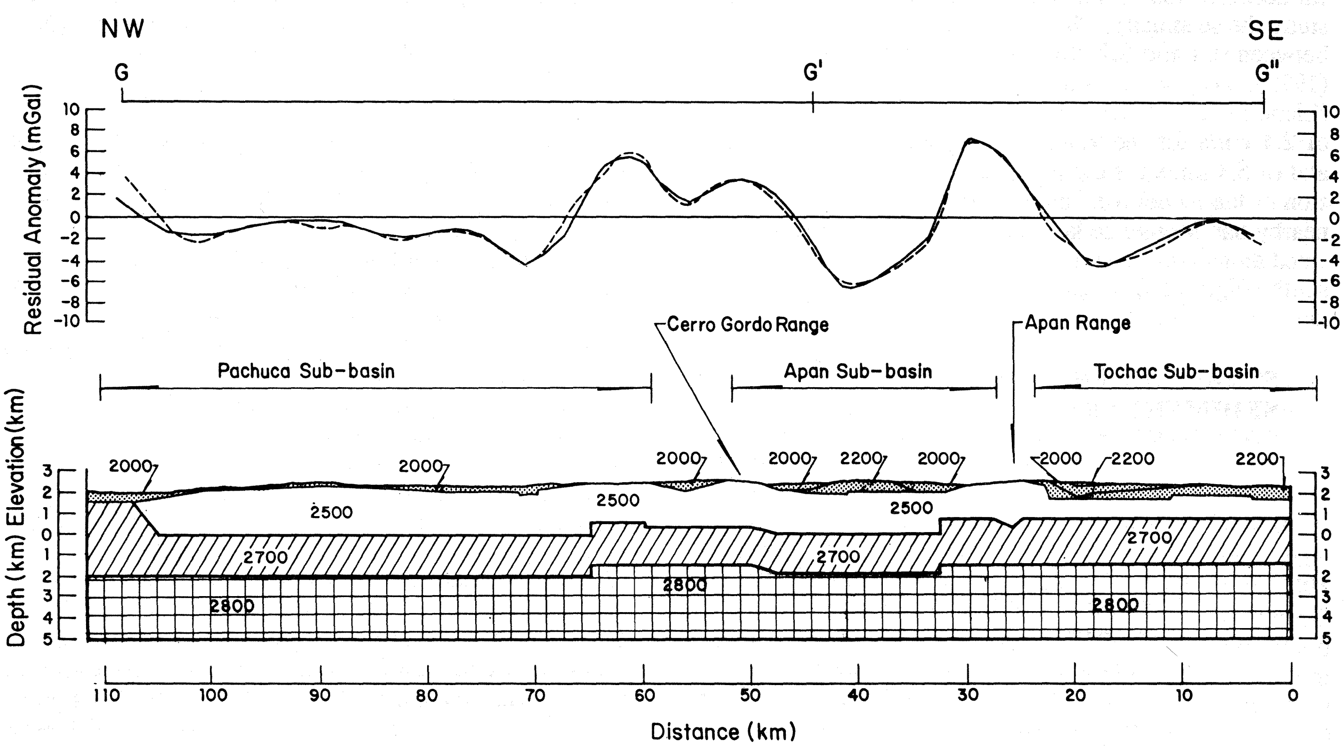

Fig. 3. Gravity profile G-G'-G" and corresponding density model. Figures indicate densities in kg/m^3. See Figures 1 and 2 for profile location.

the Tlaloc-Telapon lineament. Under the NE-SW trending Cerro Gordo, also known as Teotihuacán range, between the sub-basins of Pachuca and Apan, the basement has a structural high about 2,200 m below the surface and bounded to the north-west by a steep fault.

We conducted magnetic measurements along an E-W profile (Figures 2 and 4). The magnetic section covers the Apan volcanic range and extends into the Apan plain. Measurements were done with an EG & G Geometrics proton precession magnetometer (model 856A), every 100 m. Diurnal corrections and removal of the regional geomagnetic field according to the IGRF yield the total field anomaly in Figure 4. Note a peak-to-peak anomaly of about 700 nT across the transition between the volcanic range and the plain. A Talwani type 2-D computer program was used in its interpretation (Talwani, 1965). Only induced magnetization was considered. Our magnetic model confirms the presence of a fault, or fault zone, along the western edge of the Apan volcanic range. According to the model the fault affects the limestone basement as well as the overlying Tertiary to Quaternary volcanic sequence.

Recent seismicity suggests that the area to the west of this fault (the Apan sub-basin) has a low level seismicity of the swarm-type. After 1976 the seismological network in the Mexico basin (SISMEX) has recorded seismic activity in this area. In May, 1986, and more recently during February 24 to 29, 1992, seismic activity was also recorded. On the first day 18 events were recorded on SISMEX at the IIO station located near Pachuca about 38 km to the west of our study area. Two of these events had magnitudes (Mc) of 3.1 and 3.2. A temporary seismological network was operated from February 25 to March 2 to study the seismicity. The events had coda magnitudes Mc between 0.8 and 3.2 from the relationship of Lee *et al.* (1972). They were located by the HYPOCENTER code (Lienert *et al.*, 1986), using compressional wave velocities of 2.4 km/s for the volcano-sedimentary infill (0.5 km), and of 5.8 km/s for the basement. This is a modified version of the model used by Escamilla-Hernández (1997) in nearby San Miguel de la Cal region. The epicenters are located along two linear trends striking east-west and north-south (Figure 5a). Focal depths are between 0.1 and 8.0 km (Figure 5b).

STRATIGRAPHY OF THE VOLCANO-SEDIMENTARY INFILL BASED ON RESISTIVITY MEASUREMENTS AND WELL LOGGING

Vertical electric soundings (VES) can be very useful to characterize the infill of the sub-basins. Between 1982 and 1983 two geoelectric studies were conducted for the Gerencia de Aguas del Valle de México, which is responsible for the exploration and exploitation of water resources in the basin of Mexico. A Wenner configuration with electrode spacings of up to 3,000 m was used (Estudios y Construcciones Alas, S.A., 1983). Three geoelectric sections were obtained from 1-D inversions (E1-E1', E2-E2', E3-E3' in Figure 2). Rodríguez and Ochoa (1989) resurveyed section E1-E1' and obtained similar results. Six complementary Schlumberger vertical electric soundings were made near the center of the Tochac plain (T1, T2, T3, T4, T5, and T6 in Figure 2). Master curves (Orellana and Mooney, 1966), a constrained least-squares iterative procedure (Tejero-Andrade *et al.*, 1987) and the Resix Plus™ resistivity software (Interpex Limited, 1992) were used to interpret the resistivity soundings.

Soundings T-1 and T-3 are at the foot of an isolated volcano. The corresponding geoelectric sections are very similar (Figure 6). Near the surface we have a high-resistivity shallow thin layer overlying a conducting stratum (resistivities between 10 and 20 Ω-m, and thicknesses between 5 and 20 m). At greater depths the resistivity increases monotonically down to around 100 m. In the soundings T-2, T-4, and T-5, located in the southern half of the plain, a deeper penetration was obtained. These geoelectric sections are also similar to each other. We have a conductive-resistive-conductive-resistive sequence. The shallow conducting layer has thicknesses varying between 5 and 20 m, with resistivities between 10 and 20 Ω-m. The thickness of the underlying resistive layer ranges from 10 to 100 m, and the resistivities are above 100 Ω-m. Below these are 200 to 300 m of resistivity around 20 Ω-m. At the base we have a resistive substratum (50 to 100 Ω-m) with an undetermined thickness. In sounding T-4 we were unable to resolve the thickness of the thick conductor. In sounding T-6, located in the northern sub-basin's half, we penetrate only 10 m. However, the sounding provides details of the shallow lithology.

The depth distribution of the electric resistivity (Figure 6) may be correlated with the lithological column of existing wells and nearby VES (for example well 50 and VES 920 of line E1-E1'). This correlation yields the section of the volcano-sedimentary fill (Figure 7). Resistivity values between 40 and 70 Ω-m correspond to fractured basalts or medium-grained, medium-consolidated material. Resistivities of less than 20 Ω-m are associated with fluvial materials including sands, gravels, muds, and clays. In general we find: (1) fractured basalts and medium consolidated materials near the basin margins and sands, gravels, mud, and clays near the center; (2) In the southern portion of the Tochac plain, the aquifer has thicknesses between 200 and 300 m. In the northern portion of Tochac sub-basin the base of the aquifer was not encountered because of insufficient penetration. However, in the NW portion, the fractured basalts from the Apan range and from the Cerro Jaltepec can be observed (see Figure 2). (3) North of the Apan sub-basin the geoelectric units dip to the west in agreement with the fault inferred from gravity and magnetics (at VES 910 in Figure 7). South of the Apan sub-basin the aquifer correlated with sands and gravel, fractured basalts and medium-grain, medium-consolidated material, more than 150 m deep, deeper than elsewhere. It is covered by nonfractured igneous flows. The final model (Figure 9b) will be discussed below.

The thick conductor observed at soundings T-2, T-4, and T-5 can be correlated with clay layers intercalated with

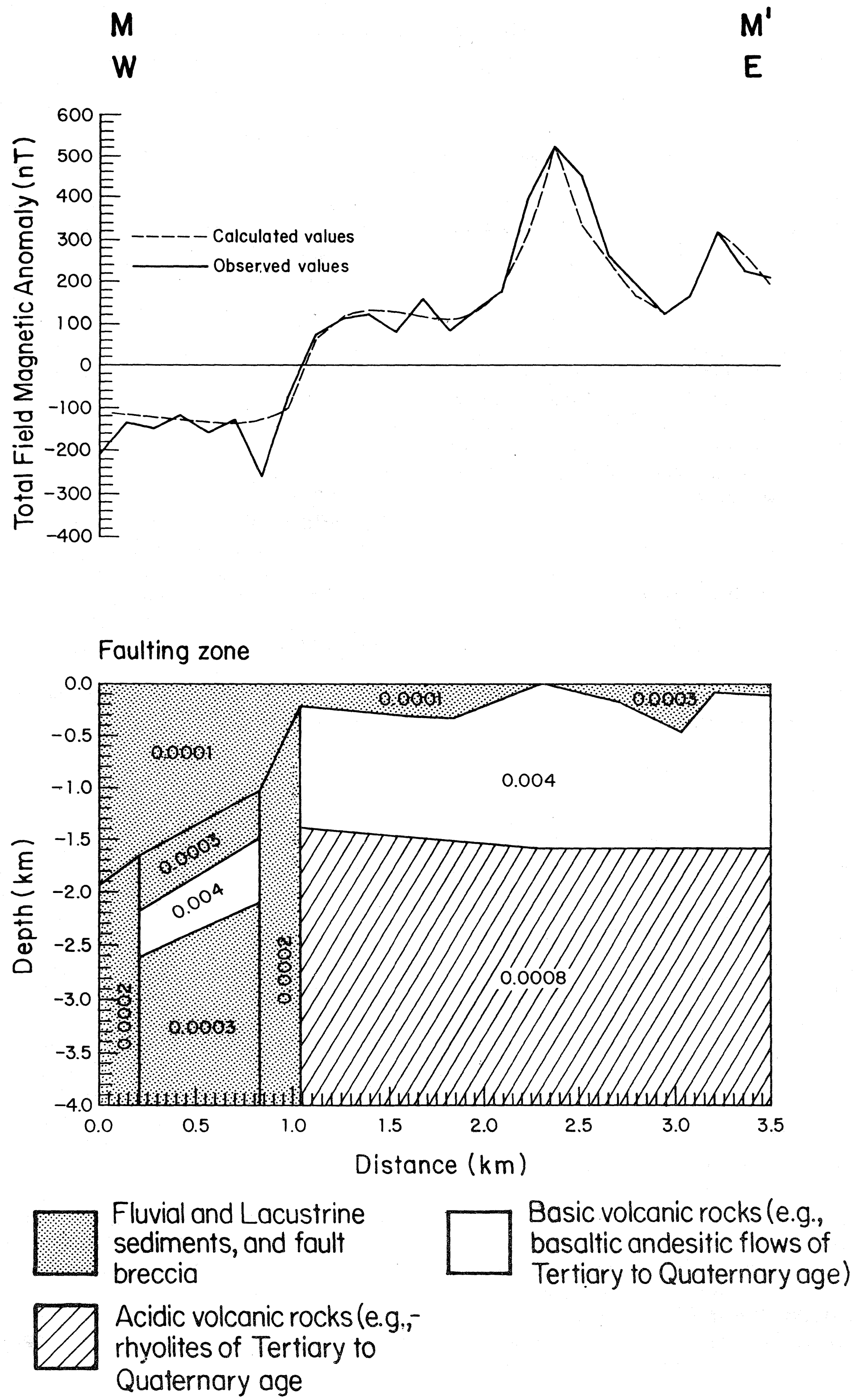

Fig. 4. Magnetic profile M-M' and corresponding magnetic model. Figures indicate magnetic susceptibilities given in SI. See Figure 2 for profile location.

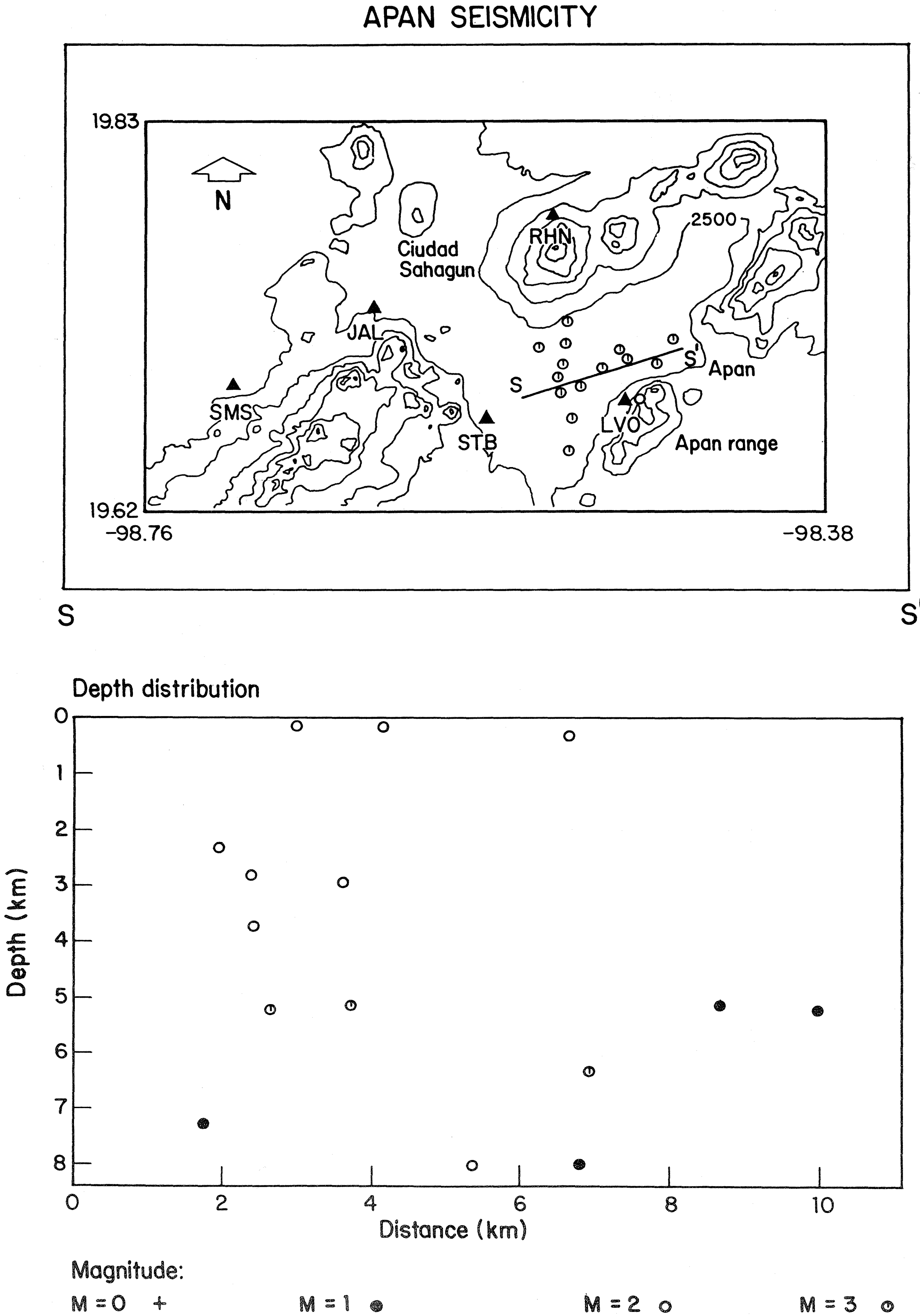

Fig. 5. Seismic activity in the Apan sub-basin. a) Distribution of epicentres of seismic events. Triangles indicate seismic stations. Circles represent the epicenters. Topographic contours are given in meters; b) Profile S-S' indicating the depth distribution of seismic events. See location in a).

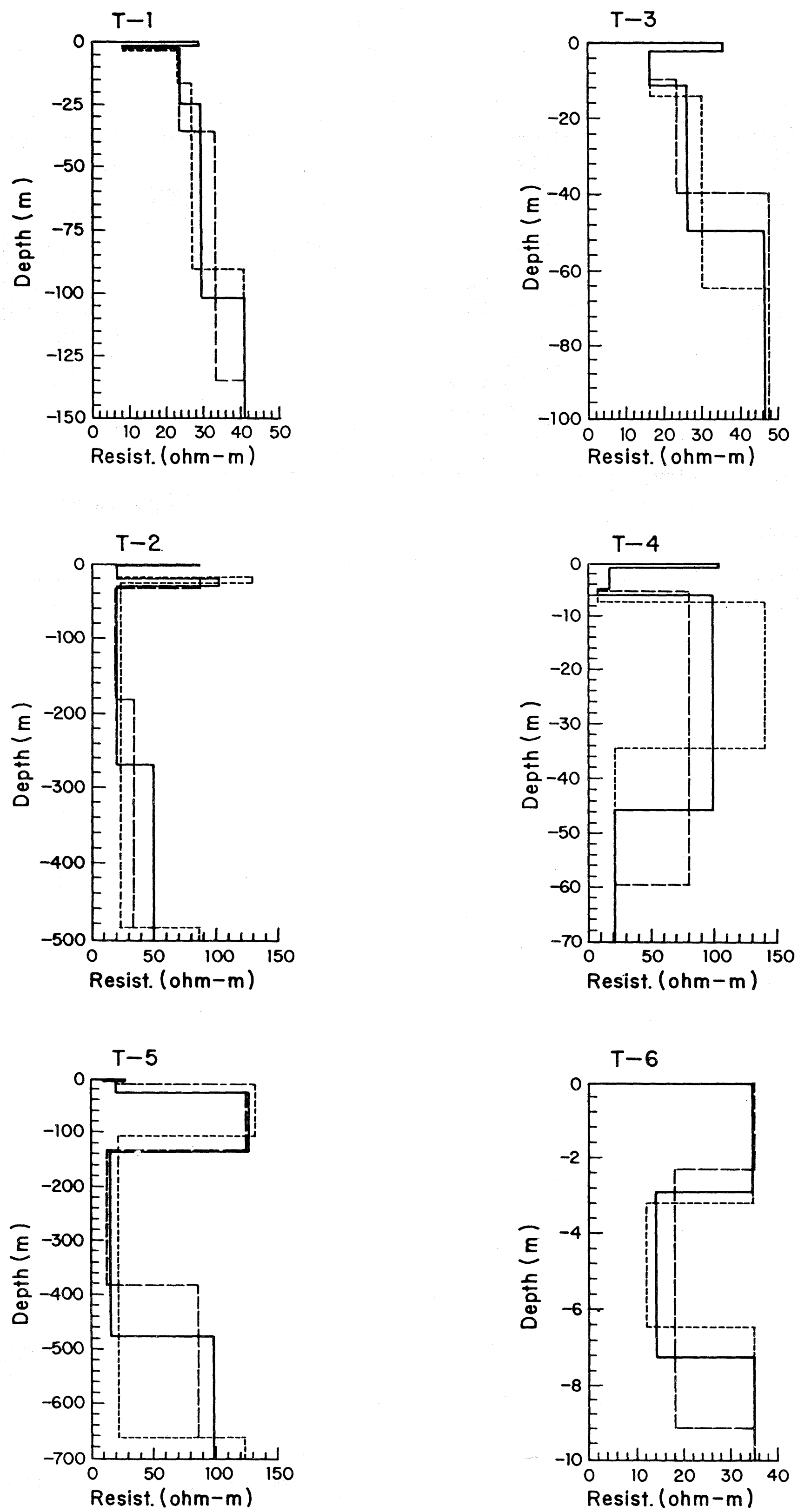

Fig. 6. Geoelectric models obtained for vertical electric soundings T-1, T-2, T-3, T-4, T-5, and T-6 (see figure 2 for their location). Equivalent models are also given (dashed and dotted lines).

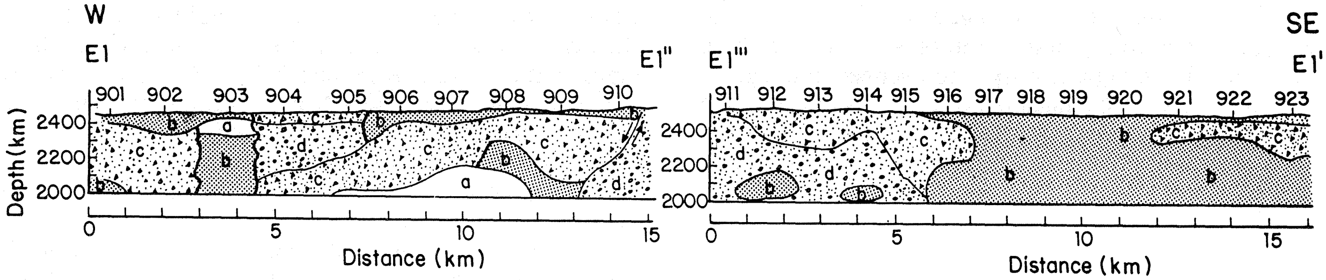

Fig. 7. Geoelectric section E1-E1' (modified after Estudios y Construcciones Alas, S.A., 1983). See Figure 2 for its location. Figures indicate number and location of vertical electric soundings. a: $\rho < 20$ ohm-m and is correlated with fluvial material (sands, gravels, clay and mud); b: 20 ohm-m $< \rho <$ 40 ohm-m, and correlated with sands, and gravel; c: 40 ohm-m $< \rho <$ 70 ohm-m, correlated with fractured basalts and medium-grained, medium-consolidated material; d: $\rho > 70$ ohm-m, correlated with fractured basaltic flows. Vertical scale is height (m) above sea level.

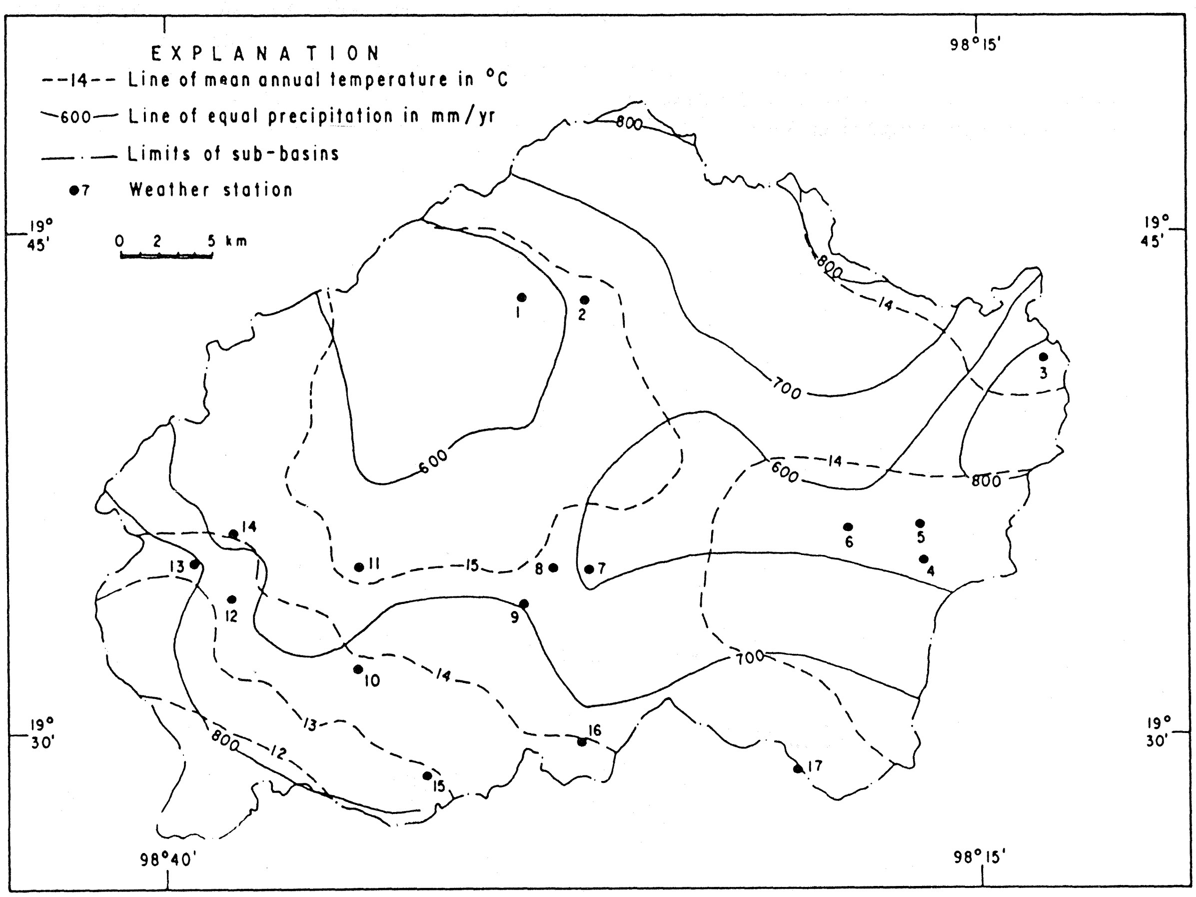

Fig. 8. Location of stations from the Metereological Service. Precipitation (continuous lines) and mean annual temperature (discontinuous lines) are also indicated. The temperatures are given in Celsius degrees, and the precipitation in mm.

sands. The soundings indicate a greater thickness for the fluvial sediments in the southern half of the Tochac plain than in its northern portion. Soundings T-1 and T-3 suggest the presence of a thick stratum of volcanic material (compacted tuff or basaltic flows) from a volcano in the middle of the sub-basin. The resistive substratum is located at a depth of 265 m in sounding T-2.

HYDROCLIMATOLOGY

The precipitation was calculated after Thiessen (1911) and by the isohyetal method (e.g., Custodio and Llamas, 1983). A mean yearly rainfall of 657.9 mm was obtained. We observed variations from 500 mm in the plain to 900 mm in the hills. Table 1 shows the rainfall distribution throughout the year. The mean yearly temperature ranges from 10° to 16°C. The transpiration was estimated by methods of Thornthwait (1944) and Turc (1954). The mean estimated evapo-transpiration, 568 mm, amounts to 85% of the rainfall; the highest values are obtained in the plain. The input data were obtained between 1970 and 1988 from 15 stations of the Meteorological Service (Figure 8). Only the upper hills are forested. The plain is mainly dedicated to seasonal agriculture.

Table 1

Seasonal precipitation in the Apan and Tochac sub-basins

Period	Season	% of anual precipitation
June-September	Wet	66
November-March	Dry	29
October and April-May	Transitional	10

The Apan and Tochac sub-basins were previously communicated, but in the late Pliocene they were separated by the emplacement of the Apan range (Blázquez, 1956). Today the drainage between these two sub-basins is through artificial channels from Tochac to Apan. During the rainy season (June-October), minor streams drain towards the Río de Las Avenidas sub-basin (to the northwest of our study area) in the amount of around 7.5 x 10^6 m^3. This runoff was calculated from data from 3 gaging stations. The output of springs measured in the field amounts to 1.115 x 10^6 m^3. Huizar-Alvarez (1995) estimated a recharge of 2.62 x 10^5 m^3/year and a discharge of 2.61 x 10^8 m^3/year. This balance takes into account all the surface water and groundwater in the basin with the exception of the groundwater output. The difference is probably accounted for by underground flow. The recharge infiltrates through fissured volcanic rocks at the foot of the volcanic ranges.

HYDROGEOLOGY

Three types of aquifer are identified (Huizar-Alvarez, 1995): (1) intergranular; (2) fissured; and (3) stratified (Figure 9b). The plain constitutes an intergranular aquifer extending from Apizaco to Ciudad Sahagún. This aquifer is of a semi-confined type, but towards the edge of the plain it becomes unconfined. It has a thickness of more than 200 m and is bounded by volcanic ranges. The water pumped

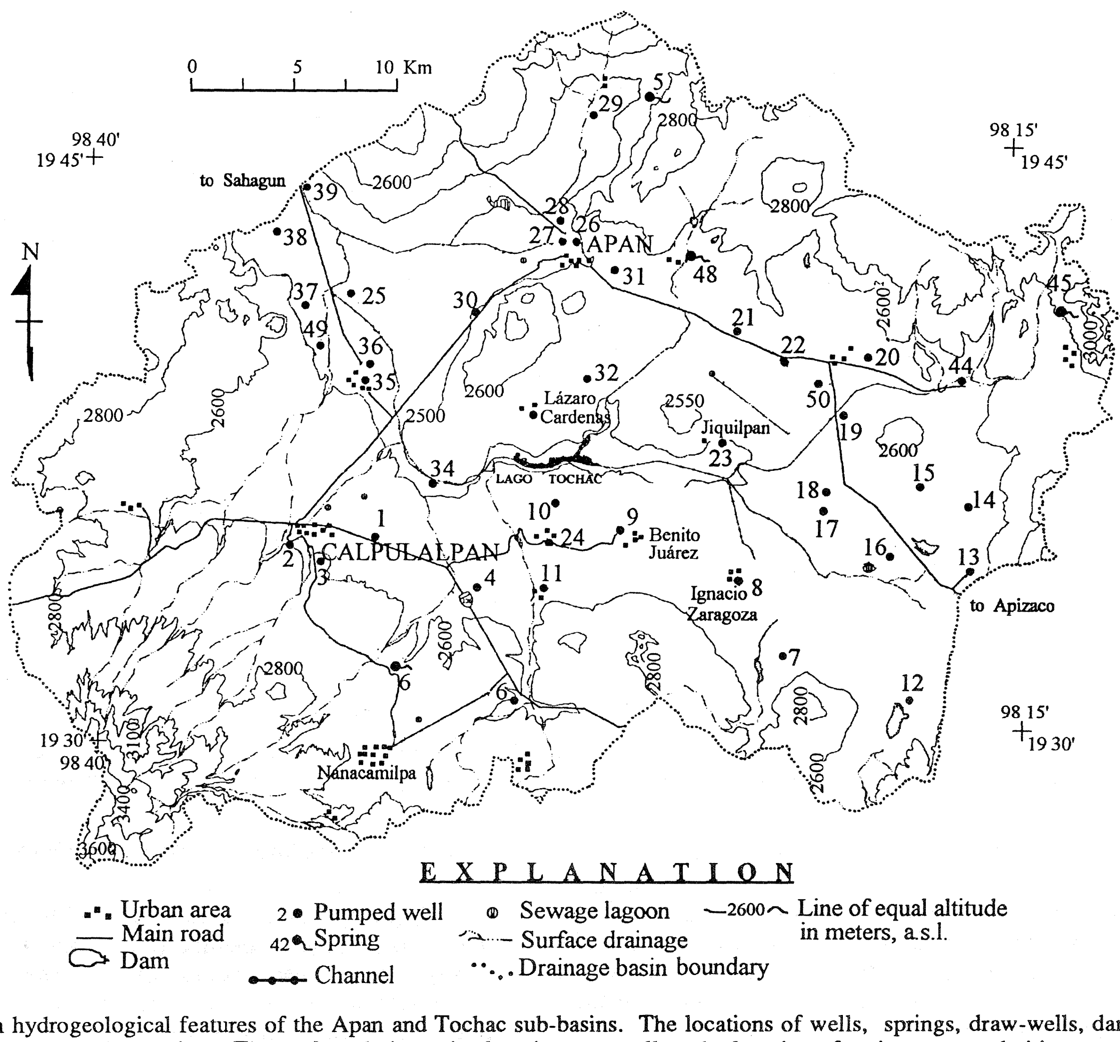

Fig. 9a. Main hydrogeological features of the Apan and Tochac sub-basins. The locations of wells, springs, draw-wells, dams, and sewage ponds are given. The surface drainage is also given, as well as the location of main towns and cities.

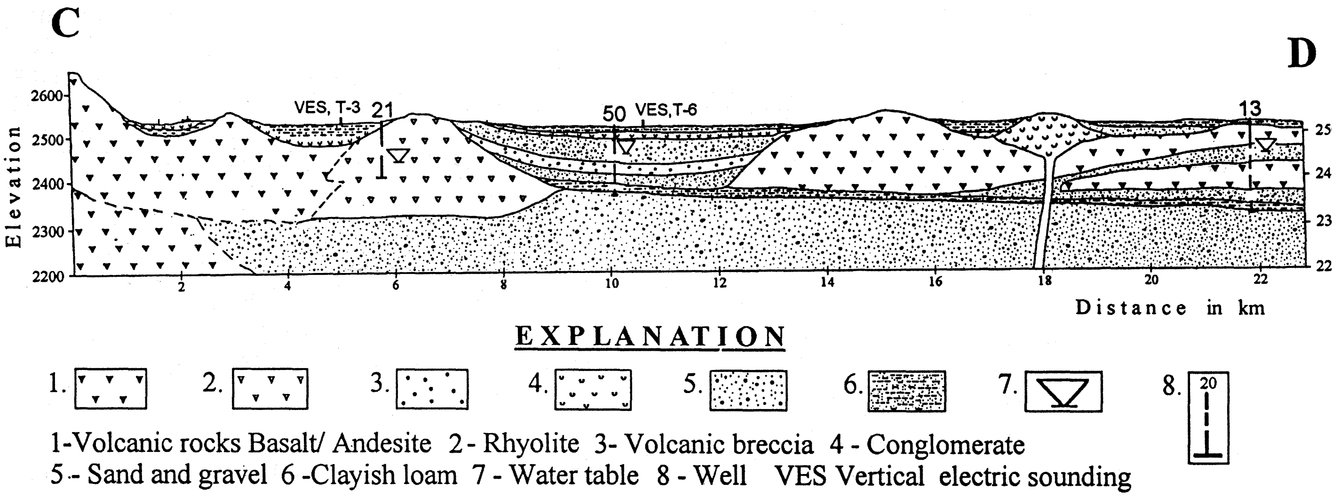

Fig. 9b. Hydrogeological model along the profile C-D (see Figure 9a for its location).

from wells represents its only discharge. Pump test data enable us to establish transmissivity values of 5.7×10^{-3} to 1.7×10^{-2} m^2/s. In the semi-confined portion of the aquifer (i.e., the northern portion of the Tochac basin) the unsaturated zone is 60 m thick.

At the foot of the volcanic ranges the fissured volcanic rocks are interbedded with the sediments of the plain and constitute a recharge aquifer. To the north, there are several springs with an outflow of 1.0×10^{-3} to 1.1×10^{-2} m^3/s, indicating a zone of local discharge. For the wells in the recharge area we estimate a transmissivity of 1.1×10^{-1} m^2/s. In the infill of the basin, lava flows interdigitating with sediments and pyroclastic products constitute a stratified aquifer with continuous hydraulic connection. The only discharge from this aquifer is through pumping. The normal permeability of the materials constituting the volcano-sedimentary infill suggests a flow with medium-to-low values of 2.85×10^{-5} to 4×10^{-4} m/s.

GROUNDWATER QUALITY

We conducted chemical analyses of water samples from 48 random sites in the Apan and Tochac sub-basins, representing 70% of the groundwater withdrawal of the hydrogeological system. The sites correspond to 39 wells, 4 springs, and 5 draw-wells. We sampled the water every three months from November 1993 to November 1995. Temperature, electric conductivity, and pH were determined in situ.

We determined concentrations of total dissolved solids of anions (CO_3^{2-}, HCO^-_3, and SO_4^{2-}), and of cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) in accordance with the standards of the American Public Health Association (APHA-WWA-WPCF, 1994). We also measured electrical conductivity and the pH. The trace elements Fe, Mn, Cu, Ni, Cr, Co, Pb, Zn, and Cd were determined by atomic absorption, as recommended by the United States Environmental Protection Association (U.S.-EPA, 1984). Values of pH determined in the laboratory are basically equal to those measured in situ.

The water temperature in the wells varies between 19° and 24°C. Temperature of springs ranges between 10° and 20°C. In shallow wells the groundwater temperature is about the average annual air temperature (Figure 8). However, in wells deeper than 100 m the groundwater temperature is about 4°C higher than the air temperatures.

The electric conductivity ranges between 230 and 400 µS/cm (with punctual values of 40 and 670 µS/cm) (Figure 10a). The lowest values were measured in the recharge area. In the plain the values are higher and in general quite similar, suggesting a certain homogeneity in the mineralization of the groundwater.

Total dissolved solids range between 200 and 370 ppm (Figure 10b). Samples 42 and 52 had concentrations above 650 ppm. Thus the groundwater mineralization is low. The spatial distribution of dissolved solid concentrations is very similar to the electrical conductivity, which confirms very low mineralization.

The geochemical indexes agree with these interpretations. The ratio Cl/HCO_3 decreases from 0.8 in the plain rim to 0.3 in the center of the plain: hence flow direction is towards the plain. The $SO_4 + HCO_3/Cl$ index increases towards the plain.

The Na/Cl ratio in the rain water typically has values between 0.7 and 1.0. Surface water may present values greater than 1.5. Thus an important contribution to the values of Na/Cl ratio in groundwater may derive from the surface. High values may imply the presence of surface waters in the subsoil, when there are no other sources of Na and Cl in the subsoil. In all the wells located in the plain, the Na/Cl index varies between 0.7 to 2.0 (mostly above 1.0), suggesting direct contact with surface water. The ratio SO_4/Cl increases towards the plain (wells 17, 19, 20, 32,

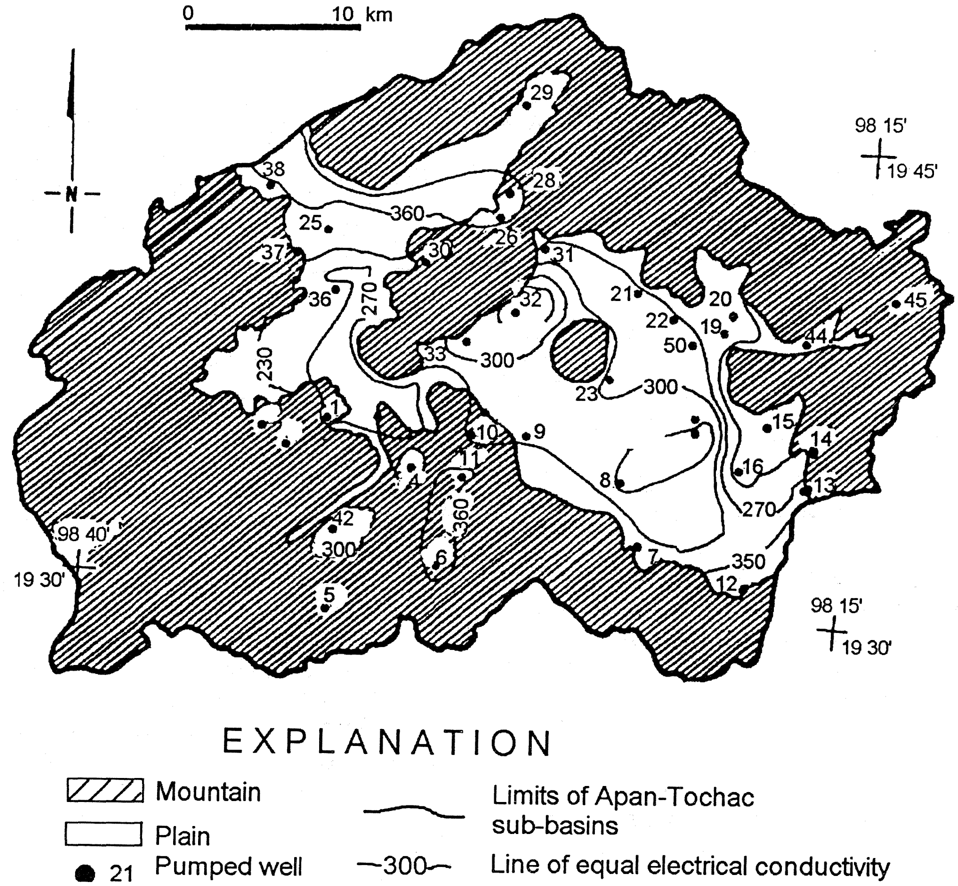

Fig. 10a. Distribution of electric conductivity of well water. Values are given in µS/cm.

and 39) indicating the direction in which the water is being mineralized. In volcanic environments the contents of SO_4^{2-} and Cl^- in water are normally low except under geothermal conditions (Freeze and Cherry, 1979; Appelo and Postma, 1993). In our study area the high concentration of these anions must be due to contamination and not to interaction with subsurface sediments.

The Piper-Hill diagrams (Piper, 1944) enable one to identify temporal variations of a calcium/magnesium bicarbonated hydrochemical facies towards a sodium/calcium bicarbonated facies (Figure 11). From the Schoeller (1955) diagram (Figure 12), there is a predominance of sodium and magnesium influencing the composition of the water towards sodium/calcium bicarbonated and calcium/magnesium chlorided facies. These facies correspond to a volcanic environment with a mafic to intermediate composition in which the calcium comes from pyroxene and biotite (Freeze and Cherry, 1979; Appelo and Postma, 1993; Owen *et al.*, 1995). The anions and cations fluctuate between dry seasons.

The trace elements in decreasing order of importance are: Fe, Pb, Ni, Co, Mn, Cu, and Cr. Their concentrations vary from well to well. According to Secretaría de Salud (SS, 1996), World Health Organization (WHO, 1984), and Economic European Communities (EEC, 1984) guidelines, the relative low concentrations of Cu, Zn, and Co represent no problem in the Apan and Tochac sub-basins. Heavy metals contents, coliform bacteria counts, mesophiles and substances that react to methyl blue (SAAM) indicate, on the other hand, pollution of anthropogenic origin. Their relatively low concentrations indicates that this contamination is controlled by the soil as a fixating agent, and by the 60 m thick unsaturated zone with medium-to-low permeability.

DISCUSSION

In the Apan and Tochac sub-basins, the aquifer is predominantly intergranular as in the sub-basin of Chalco. The aquifer bedrock is also volcanic (basalts, andesites, etc.). The difference between these two aquifers lies in the absence of an aquitard at Apan and Tochac. There once was a lake in the Tochac sub-basin too, but the fine-grained lake sedimentation was less important, and does not constitute an aquitard. Unlike Chalco sub-basin, the Apan and Tochac sub-basins have a 60-m thick unsaturated zone.

The Apan and Tochac sub-basins have a total area of 1,000 km^2. Assuming a mean thickness of 300 m for the

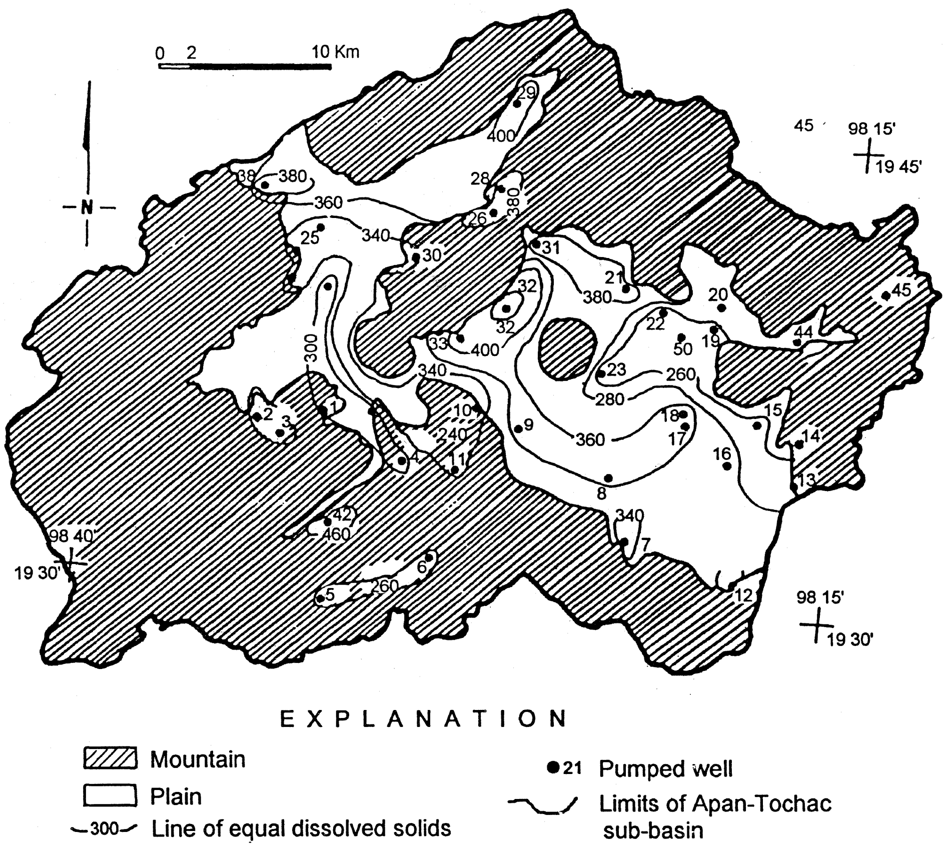

Fig. 10b. Total solid concentration in ppm.

aquifer the volume of water in these sub-basins would range between 30 and 75 km^3 if the porosity is 10-25%. This is a very important groundwater resource. For comparison, the estimated volume of water in the sub-basin of Chalco, which is heavily pumped, attains only 2 to 5 km^3 (Campos-Enríquez *et al.*, 1997). In contrast to the Chalco sub-basin, the regional aquifers from Apan and Tochac are not overexploited. The potentiometric surface declines 0.30 m per year which suggests that the aquifer approaches its equilibrium state. The decline at Chalco amounts to 1.4 m per year (Huizar-Alvarez, 1989; Ortega-Guerrero *et al.*, 1993). No related subsidence is observed in our study area.

In conclusion the Apan and Tochac aquifers can be used to support the development of agriculture in that area.

CONCLUSIONS

The Apan and Tochac sub-basins occupy the northeastern portion of the basin of Mexico. Geologic, hydrogeologic, and geophysical studies enable us to obtain information on: (1) the sub-surface structure, (2) the nature of the hydrogeological system, and (3) quality and vulnerability of groundwater resources.

The Apan range between the Apan and Tochac sub-basins is bounded to the west by a major NE-SW trending fault on the extension of a regional lineament joining the volcanoes of Tlaloc and Telapon. The volcano-sedimentary infill has a mean thickness of 600 m. Low-level swarm type seismicity occurring in the Apan sub-basin indicates that the area is tectonically active. During February and March 1992, seismic activity was studied with a local seismological network. Events with coda magnitudes between 0.80 and 3.2 were recorded. The epicenters are distributed roughly along two intersecting E-W and N-S features. Focal depths are between 0.1 and 8.0 km.

The hydrogeologic system includes intergranular, interstratified, and fissured aquifers. The fissured aquifer constitutes the recharge area and has a transmissivity of 1.1 x 10^{-1} m^2/s. North of the recharge area there are several springs with a yield of 1.0 x 10^{-3} to 1.1 x 10^{-2} m^3/s. In the center of the plain the interstratified and fissured aquifers are semiconfined, but become free towards the edges. The transmissivity of the semi-confined aquifer from well pumpingtests ranges between 5.7 x 10^{-3} to 1.7 x 10^{-2} m^2/s. The only discharge for this hydrogeological system comes from well pumping. The estimated recharge and discharge indicates that the aquifers are nearly balanced. The unsaturated zone is 60 m thick. The observed potentiometric surface falls 0.30 m per year; however, in some locations no decline was observed. From vertical electric soundings and well stratigraphy the thickness of the aquifer in the southern portion of the Tochac sub-basin is about 200 m.

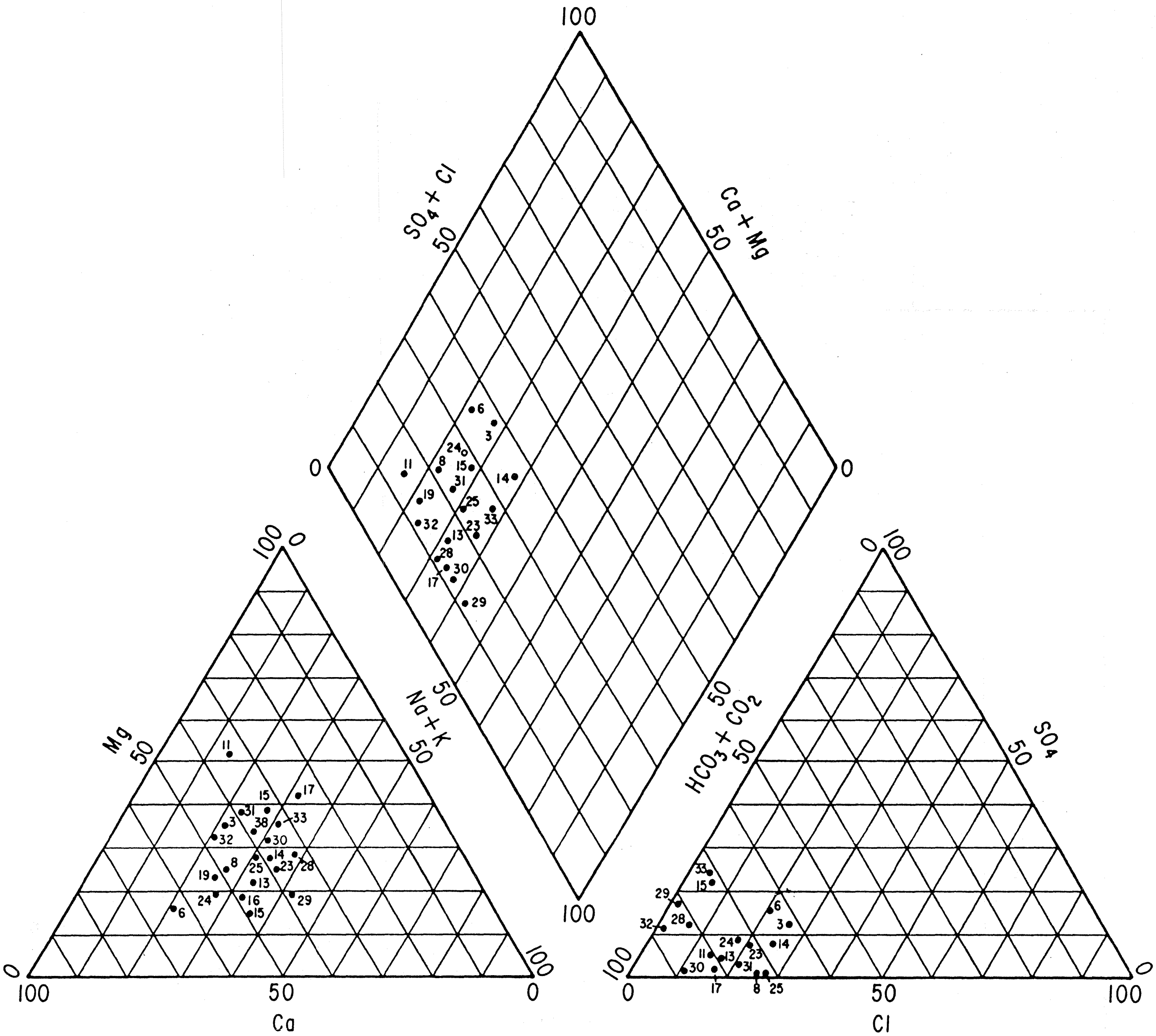

Fig. 11. Piper-Hill diagram for the chemical composition of groundwater of the Apan and Tochac sub-basins. Well numbers are indicated in the plot.

Pollution of the groundwater resources in this area is still at an early stage. This may be due to the existence of materials with low or medium permeability at the top part of the infill, or to the thick unsaturated zone. With the exception of the Pb content, the groundwater is of good quality.

However, the absence of an aquitard makes the groundwater vulnerable to contamination. Sewage from towns and cities is disposed into streams draining into oxidation ponds. Part of these residual waters infiltrates into the subsoil. Caution must be taken in the short term to protect the groundwater resources from contamination. Because of the presence of Pb, Ni, and Mn in relatively significant amounts it is necessary to stop the contamination of the aquifer. Because of the presence of coliforms bacteria, it is recommended to continue chlorinating the water from wells.

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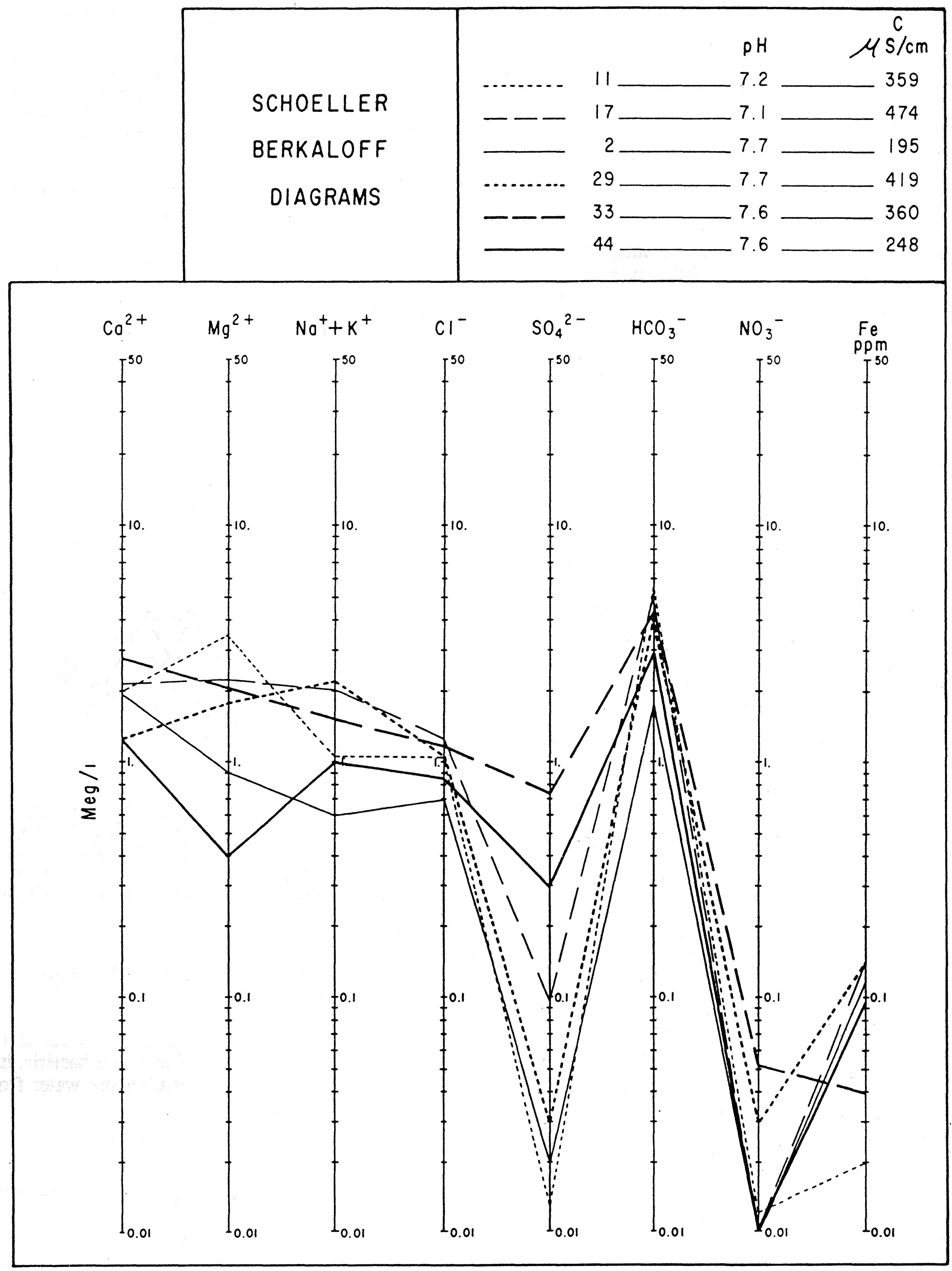

Fig. 12. Schoeller-Berkaloff diagram of the chemical composition of the groundwater from the Apan and Tochac sub-basins. Concentration of principal anions and cations for wells 11, 17,2, 29, 33, and 44 (see Figure 9 for location).

BIBLIOGRAPHY

APHA-WWA-WPCF (a joint publication of), 1994. Standard methods for the examination of water and wastewater, Amer. Pub. Health, HALTH Assoc, Washington, D.C., USA.

APPELO, C. A. J. and D. POSTMA, 1993. Geochemistry, groundwater and pollution, A.A. Balkema, Rotterdam, Brookfield, 537 pp.

ASTIZ, L. M., 1980. Sismicidad en Acambay, Estado de México. El temblor del 22 de Febrero de 1979, B.S. thesis, Universidad Nacional Autónoma de México, Mexico, 130 pp.

BLAZQUEZ, L., 1956. Geohidrología de la Cuenca de México, Instituto Geológico, México, Internal report, 77 pp.

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

CAMPOS-ENRIQUEZ, J. O., O. DELGADO-RODRIGUEZ, R. CHAVEZ-SEGURA, P. GOMEZ-CONTRERAS, L. FLORES-MARQUEZ and F. S. BIRCH, 1997. The subsurface structure of Chalco sub-basin (Mexico City) inferred from geophysical data. *Geophysics, 62*, 23-35.

CANTAGREL, M. and C. ROBIN, 1979. K-Ar dating on eastern mexican volcanic rocks.- Relations between the andesitic and alkaline province. *J. Volcanol. Geoth. Res., 5*, 99-114.

CUSTODIO and M. R. LLAMAS, 1983. Hidrología subterránea, T. I, Editorial Omega.

DEMANT, A. and C. ROBIN, 1975. Las fases del vulcanismo en México, una síntesis en relación con la evolución geodinámica desde el Cretácico. *Revista Instituto de Geología, UNAM*, 71-85.

Economic European Communities (EEC), 1984. Guideline concerned with the quality of water for human consumption. *In:* Rump and Krist, 1989, Laboratory manuals for the examination of water, waste water and soil, VCH Verlagsgesellschaft, Germany, 189 pp.

ESCAMILLA-HERNANDEZ, A., 1977. Sismicidad reciente en el graben del Mezquital, B. Sc. Thesis, ESIA-Ticoman, IPN, 61 p.

Estudios y Construcciones Alas, S.A., 1983. Perfiles geofísicos en diferentes zonas de la Cuenca del Valle de México, SARH, Comisión de Aguas del Valle de México, Contract CAVM 83-418.

FREEZE, R. A. and J. A. CHERRY, 1979. Groundwater, Englewood Cliffs, NJ: Prentice-Hall.

FRIES, C., Jr., 1962. Hoja Pachuca 14 Q-e(11) estados de Hidalgo y México, Universidad Nacional Autónoma de México, Instituto de Geología, Carta Geológica de México, Serie 1 : 100,000 mapa con texto.

HERRERA, I., 1989. El sistema acuífero de la Cuenca de México. Introduction. *Geofís. Int., 28*, 2, 130-132.

HILDENBRAND, T.G., 1983. FFTFIL: a filtering program based on a two-dimensional Fourier analysis of geophysical data, Open-File Rep., 83-237, U.S. Geological Survey.

HUIZAR-ALVAREZ, 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 Beçancon, France, 160 pp.

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

HUIZAR-ALVAREZ, A. R., 1995. Hidrología de la subcuenca de Apan-Tochac. Submitted to Revista Mexicana de Ciencias Geológicas, UNAM, México.

INTERPEX LIMITED, 1992. Resix Plus™ User Manual Resistivity Data Interpretation Software, Interpex Limited, Golden, CO, USA.

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.

LEE, W.H.K., R.E. BENNETT and K.L. MEAGHER, 1972. A method of estimating magnitude of local earthquakes from signal duration, U. S. Geologic Survey. Open-File Rep., 28 pp.

LIENERT, B.R.E., E. BERG, and L.N. FRAZER, 1986. HYPOCENTER, an earthquake location method using centered, scaled, and adaptively damped least squares. *Bull. Seism. Soc. Am., 76*, 771-783.

MOLNAR, P. and L. R. SYKES, 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. *Geological Society of America Bulletin, 80*, 1639-1684.

MOOSER, F., 1956, 1962. Bosquejo geológico del extremo sur de la Cuenca de México, México, D.F., Congreso Geológico Inernacional, 20, Libro-Guía Excursión C-9, 9-16.

MOOSER, F., 1972. The Mexican volcanic belt: structure and tectonics. *Geofís. Int., 12,* 2, 55-70.

MOOSER, F., 1975. Historia Geológica de la Cuenca de México. *In:* Memoria de las obras del sistema de drenaje profundo del Distrito Federal, México, D.F., DDF, T. 1, 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.

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

OWEN, P., B. BRICKER and F. JONES, 1995. Main factors affecting the composition of natural waters. *In:* Trace elements in naturals waters, Ed. Brit Salbu, Eiliv Steinnes, CRC Press, Boca Raton, London, 1, 1-20.

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

PIPER, A. M., 1944. A graphic procedure in the geochemical interpretation of water analysis. *Am. Geophys. Union Trans., 25,* 914-923.

RODRIGUEZ, C. R. and A. C. OCHOA, 1989. Estudio geoeléctrico del sistema acuífero de la cuenca de México. *Geofís. Int., 28,* 2, 191-205.

SEGERSTROM, K., 1961. Geología del suroeste del Estado de Hidalgo y del noreste del Estado de México. Boletín de la Asociación Mexicana de Geología y Petrología, 13, 3-4, 147-168.

SCHOELLER, H., 1955. Géochemie des eaux souterraines. Applications aux eaux de gîsements de pétrole. Institut Français du Pétrole, France.

SECRETARIA DE SALUD (SS), 1996. Norma oficial mexicana, NOM. 127, SSA, Salud Ambiental, Agua para uso y consumo humano, Diario Oficial, Enero, Primera sección, México, D.F., p. 40-50.

STIFF, H. A., Jr., 1951. The interpretation of chemical water analysis by means of patterns. *J. Petrol. Tech, 3,* 10, 15-17.

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. *Geophysics, 20,* 797-817.

TEJERO-ANDRADE, A., R. SANCHEZ-LEON and P. GONZALEZ-VILLALVASO, 1987. Interpretación iterativa de sondeos. *Geotermia, Revista Mexicana de Geoenergía, 3,* 155-169.

THIESSEN, A. H., 1911. Precipitation for large areas. *Monthly Weather Review, 39,* 1082-1084.

THORNTHWAIT, O. W., 1944. 1943-1944 Report of the Community on Transpiration and Evaporation. *Trans. Am. Geophys. Union, 25,* 687.

TURC, L., 1954. Le bilan d'eau des sols: Relations entre la précipitation, l'évaporation et l'écoulement, La Houille Blanche, 3, Journées de l'Hydraulique de la Societé Hydrotechnique, France, p. 36-44.

US-EPA, 1984. Methods for chemical analysis of water and wastewater, EPA, 16-74000, U.S. Environ. Prot. Assoc., Washington, D.C., USA.

WILLIAM, H., 1980. Official methods of analysis, Association Official Analytical Chemist, AOAC, Washington, D.C., USA:

WORLD HEALTH ORGANIZATION (WHO), 1984. Guidelines for drinking water quality recommendation I, WHO, Genève.

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