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 x 10-3 m2/s y 1.1 x 10-1 m2/s, y permeabilidad aproximada de 4.0 x 10-4. El acuífero fisurado constituye el área de recarga, mientras los otros dos conforman un acu'fero 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 x 10-3 m2/sec and 1.1 x 10-1 m2/sec, and permeability around 4.0 x 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, isolated 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).

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).

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 R'o Fr'o 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 km2. 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). activity is agriculture, most of which is seasonal. A few areas are irrigated. The neighboring towns and cities have growing .

The main economic 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 sub-surface 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, evapotranspiration, 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.

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).

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 Creta-ceous 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 Pe-on 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 Pe-on 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 R'o Fr'o, (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/m3 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/m3); (2) a limestone sub-basement (2,700 kg/m3); (3) an undifferentiated Tertiary to Quaternary unit comprising rhyolites and basalts (2,500 kg/m3); and (4) a volcano-sedimentary infill, to which we assigned a density between 2,000 to 2,200 kg/m3.

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/m3. 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) re-surveyed 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[a] 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 W-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 W-m. The thickness of the underlying resistive layer ranges from 10 to 100 m, and the resistivities are above 100 W-m. Below these are 200 to 300 m of resistivity around 20 W-m. At the base we have a resistive substratum (50 to 100 W-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 W-m correspond to fractured basalts or medium-grained, medium-consolidated material. Resistivities of less than 20 W-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 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.

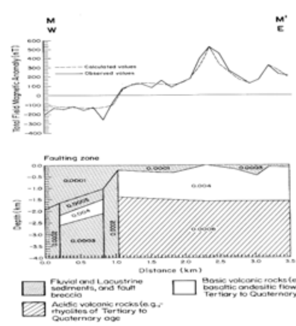

Fig. 4. Magnetic profile M-M' and corresponding magnetic model. Figures indicate magnetic susceptibilities given in SI. See Figure 2 for profile location.

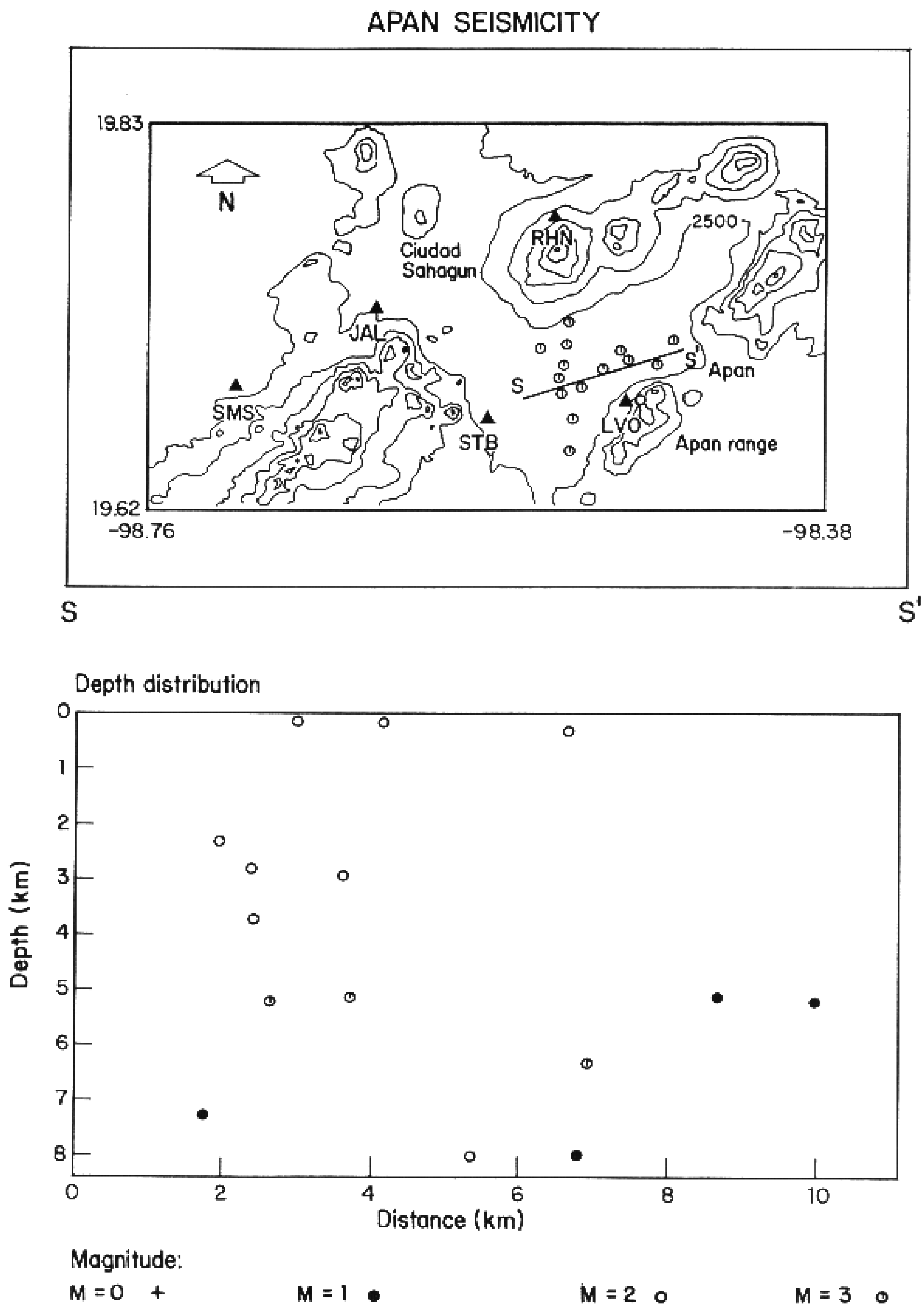

Fig. 5. Seismic activity in the Apan sub-basin. a) Distribution of epicentres of seismic events. Triangles indicate seismic stations. Circles represent the epicenters. Topographic contours are given in meters; b) Profile S-S' indicating the depth