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Influence of faulting on groundwater quality in Valle del Mezquital, Mexico

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RESUMEN

La hidrogeología y la estructura geológica se proponen como causas que influyen en la calidad del agua subterránea en el valle del Mezquital. Se integró la información obtenida de un reconocimiento geológico, análisis de agua subterránea y estratigrafía, para explicar las tendencias espaciales y temporales en la calidad del agua subterránea. Se encontraron mayores concentraciones de nitratos cerca de las fallas y fracturas, que actúan como sitios de recarga del agua residual en un acuífero somero. Las fallas permiten la descarga del acuífero principal en sitios específicos. El flujo subterráneo profundo de las calizas recarga al acuífero volcánico.

PALABRAS CLAVE: Mezquital, nitratos, agua residual, calidad del agua subterránea, fallas, México.

ABSTRACT

The hydrogeology and geological structure of the Mezquital basin are proposed as causes influencing groundwater quality. The integration of a geological survey with groundwater analyses and subsurface stratigraphy explains the spatial and temporal trends of groundwater quality. Higher concentrations of nitrates were measured near faults and fractures acting as recharge sites of wastewater into a shallow aquifer. The faults allow the main aquifer to discharge at specific sites. Deep groundwater flow from limestones recharges the main volcanic aquifer.

KEY WORDS: Mezquital, nitrates, wastewater, groundwater quality, faults, Mexico.

INTRODUCTION

Irrigation with wastewater is a common practice in Mexico. The lack of sewerage systems and urban population growth have led to an increase of irrigated areas. Valle del Mezquital is close to Mexico City (about 20 000 000 inhabitants), and its climate is semiarid to dry, with short periods of rain. This has favored wastewater irrigation of crops since 1896. Initially wastewater was used only in the center of the valley around Tlaxcoapan and Tlahuelilpan. In 1926 Requena dam with a capacity of 71 X 10^6 m^3 was built. In 1934, Taximay and Endho wastewater dams with capacities of 50 X 10^6 m^3 and 182 X 10^6 m^3, respectively, were constructed. Currently, the three dams receive waste and storm run-off. Wastewater from Mexico City now flows through the Gran Canal and Emisor Central drains into Valle del Mezquital. About 75 m^3/s (including storm run-off) in the rainy season and 40 m^3/s in the dry season irrigate more than 45 000 ha in Valle del Mezquital (BGS and CNA, 1995; Jiménez and Homero, 1998; Bahri, 1999). High concentrations of nitrates (up to 19.6 mg/l) and total coliforms (more than 2400 cfu/100 ml in some boreholes) have been found in groundwater resulting from irrigation with sewage in Valle del Mezquital (Gallegos *et al*., 1999).

Valle del Mezquital is located about 50 km north of Mexico City in the northern part of the Trans-Mexican Volcanic Belt. The study area is in the central part of Valle del Mezquital; it comprises about 670 km^2 between El Llano to the SW and Mixquiahuala to the north, between 20º 00' and 20º 15' N and 99º 05' and 99º 20' W (Figure 1). Different types of volcanic rocks were emplaced in various volcanic episodes since middle Tertiary through the Quaternary. Two main fracture systems have been described (INEGI, Instituto Nacional de Geografía y Estadística, 1992). The structural pattern of the Sierra Madre Oriental, about 15 km east of the study area, is associated with a fracture system in the Mesozoic rocks with a northwest-southeast direction. A second fracture pattern, northeast-southwest, is associated with tension in Miocene volcanic rocks.

Extensive volcanic ranges, lava flows, isolated volcanoes, lapilli and lahar deposits, and wide basins containing lakes or lake deposits, constitute the physiography of the area (INEGI, 1992).

A sequence of clay (between 10 and 50 m thick), sand and conglomerate layers, interbedded with some lake limestone, travertine and lava flow layers, form the lake deposits

Fig. 1. Location of study area, central part of Mexico.

in the study area. This unit overlies the volcanic rocks at an angular unconformity.

Tula and Actopan rivers are the main surface streams. Salado river acts as a secondary drainage in the center of the watershed.

The climate is semiarid to dry, with summer rains and an average temperature of 18.3°C. Average annual precipitation is 435-536 mm/y in the lower parts of the watershed and 750 mm/y in the ravines that surround the watershed.

In spite of the wastewater irrigation for more than 100 years, groundwater quality has not been heavily impacted. This has been explained by the action of soils and channels which act as sand filter and stabilization systems (Downs *et al*., 2000; Jiménez *et al*., 2000). In this paper we suggest that the geology and structural features of Valle del Mezquital may also play an important role in the groundwater quality. We define the geological and structural characteristics influencing the groundwater pollution, and we describe the results of a geologic and hydrogeologic survey of the basin.

PROCEDURES AND METHODS

The geologic, hydrogeologic and stratigraphic information reported by CFE (Comisión Federal de Electricidad) in 1985, along with the lithology reported in logs from 29 boreholes drilled by CFE, besides 15 boreholes drilled by PEMEX Oil Corporation, were reinterpreted. This reinterpretation consisted of testing each log reported information against the boreholes' samples to define rock type and structural features, granulometric analysis (using standard dry sieving procedures), and studies of selected samples by petrography. Based on that information, a geologic and hydrogeologic survey of the study area was performed. The underground geologic description also took into account the technical reports from a core sampling program developed by SARH, (Hydraulic and Agriculture Secretary) in 1984. Various reports on the wastewater and groundwater quality were reviewed to study the evolution of groundwater quality.

Sampling and analysis:

Four sampling periods were performed from July 1997 to February 2000. Water samples were collected from springs, piezometers and wells with depths varying from 5.40 m to 205 m (Figure 2). Three samples were taken at each site in plastic containers of 1000, 500 and 125 ml; no chemicals were added to the 1000 ml and 125 ml samples; 50 ml HNO_3 were added to the 500 ml sample. The samples were preserved at 4ºC until analyses within 48 hours at the Geophysics Institute, UNAM, Mexico. Concentration of the major anions: HCO_3^-, Cl^-, SO_4^{2-} was measured in the 1000 ml sample, metals were analyzed in the acidified sample and nitrates were measured in de 125 ml sample. Major anions and cations were determined by titration, turbidimetry, potentiometry with selective electrodes, and emission espectroscopy following standard methods (APHA, 1995). Nitrate was measured by ion cromatography using a WATERS 510 with conductivity detector and eluent prepared with borate/gluconate concentrate and acetonitrile. A blank and standards of 1, 5, 10, 15 and 20 mg/l were used to construct a calibration curve with each batch of samples. Each sample was measured by duplicate. The ionic balance checked the quality of the major species analyses.

At each sampled point, temperature, pH and conductivity were measured *in situ* with a conductimeter Conductronic C18, calibrating with pH buffers (4.0, 7.0 and 9.0), and with a solution of 1000 mg/l of NaCl corresponding to a conductivity value of 1990 μS/cm.

GEOLOGICAL FRAMEWORK

The Valle del Mezquital area is an old lacustrine basin limited by faulted volcanic rock blocks on several flanks. A basin depth of approximately 500 m has been estimated from boreholes. An alluvium unit, formed by the erosion of the volcanic rocks that outcrop around the valley is on the top of the system. A limestone layer possibly from lacustrine origin, and a thick layer of green clay pertaining to the Tarango Formation from the Tertiary, have been reported in deep well boreholes logging. The Tarango Formation (Segerstrom, 1961) in the area is defined as a sequence of:

- Poorly cemented sands and gravels at the surface with a maximum thickness of 5m.
- Poorly cemented sands and clays with an average thickness of 7 m generally wedged with other layers.
- Clastic clay layers with thickness between 10 to 50 m.
- Several fractured and altered basalt layers, wedged or interbedded with debris units to an approximate depth of 150 m.
- Small lens of approximately 1 m of conglomerate or gravel not very compacted.
- Isolated lacustrine porous limestone lens.
- Thin volcanic ash lens, resulting from contemporary volcanic activity, and fine grain tuffs resulting from old tuff erosion.
- Caliche as nodules or as thin layers heterogeneously mixed between surficial layers or in relation with faults or fractures at depth.

Sediments of the Tarango formation were deposited over an erosion surface developed on Cretaceous limestones or

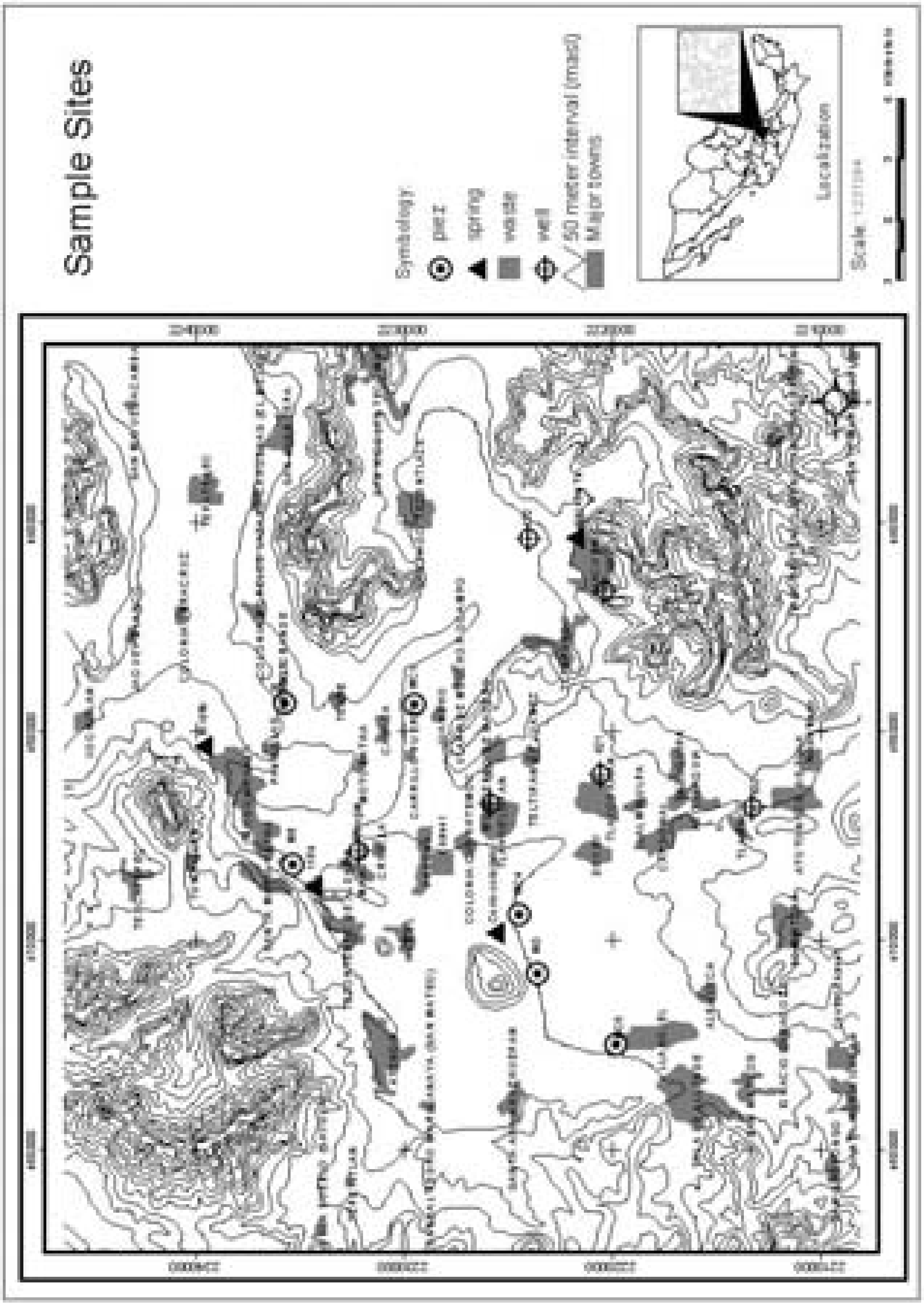

Fig. 2. Sampling sites location.

Tertiary volcanic rocks. Below this detritus, a thick sequence of ignimbrites and tuffs may be found. All the volcanic units forming the lithology of this area are intensely fractured and faulted at the surface; the older ones show an intense erosion degree. The sedimentary units from the Mezcala and Doctor limestone Formations, which lie at the bottom of the sequence, are intensely folded, faulted and fractured at the surface.

STRUCTURAL FEATURES

Fault and fractures orientation field results are shown in Figure 3a. The main trends are NE SW 60-70° and NW-SE 20-30°. Two main fault systems were identified also from the geologic logs in the studied area. Orientation of the fault systems follows those of the Mexican volcanic belt (Figure 3b). The first one has a NW-SE direction and affects the Cretaceous limestones (Ajacuba-Tezontepec). The second system with a SW-NE direction is related to the tensional effects that affected the Tertiary volcanic rocks (San Marcos-Huitel and El Llano-Tepatepec).

The faults and fractures associated to the Tula river, as well as the erosion action of the water, modeled the regional relief and allowed the extension of the drainage system of the watershed.

The geological sections NE-SW and NW-SE (Figure 4) show the relationship between the different fault systems, the Mesozoic rocks and the Tertiary volcanic rocks.

The Cretaceous limestones at the bottom of the stratigraphic sequence, lift in structural blocks limited by faults. The valley is filled by a great thickness of Tertiary volcanic rocks and some thin layers of lacustrine limestone. Some volcanic cones may be observed, as well as contemporary flows related with the faulting zone, that acted as a conduit for these lava flows.

The Xicuco hill is a Tertiary volcanic structure (Tomv) located over a normal fault. This structure is surrounded by tuffs and ignimbrites.

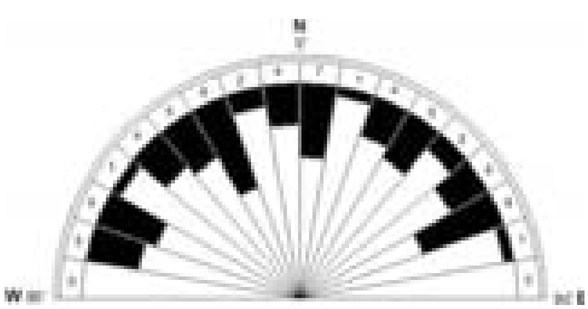

Fig. 3a. Fault and fractures orientation frequency diagram.

HYDROGEOLOGY

The geological framework (Figures 3b and 4) defines a complex heterogeneous aquifer system in which lateral variations occur in hydraulic conductivity. Three aquifers, which appear in different parts of the valley, constitute the aquifer system:

Quaternary material (Qal):

This aquifer is formed by accumulations of alluvial and clastic Quaternary materials. These accumulations are present mainly filling old valleys or as load of the rivers that still drain the area.

Volcanic rocks from the Quaternary and from the Tarango Formation (TsT):

The second aquifer, the most important of the system, is formed by volcanic rocks from the Quaternary and volcanic rocks pertaining to the Tarango Formation.

Several layers of fractured and altered basalt represent the volcanic part of this aquifer (Qb). These layers wedge or interfinger with detritus units to a depth of approximately 150 m. Lava flows are the main hydrological units, with high hydraulic conductivity values (10^{-3} to 10^{-5} m/sec), as shown by the yield of the Thermoelectric Central well system (CFE, 1986). The hydraulic conductivity of this unit is a function of its fracture degree. The lava flows interfinger with thin volcanic ash lenses, produced by contemporary volcanic activity, and with fine grained tuffs produced by the weathering of preexistent low permeability tuffs. One lava flow covers the terraces located on both sides of the Tula river.

Tarango Formation (TsT): Part of the volcanic rocks from the Tarango Formation has a potentially high permeability due to its grain size distribution. Nevertheless, the presence of clay layers decreases the transmissivity .

This aquifer changes from confined to non-confined in different parts of the valley depending on the lythological changes and the thickness of the overlying clay layers that interfinger the volcanic rocks.

Cretaceous limestones (Kmd):

A third aquifer, of great importance due to its storage capacity, is located in the Cretaceous limestones. This aquifer with a thickness of approximately 200 m may supply the volcanic aquifer at depth.

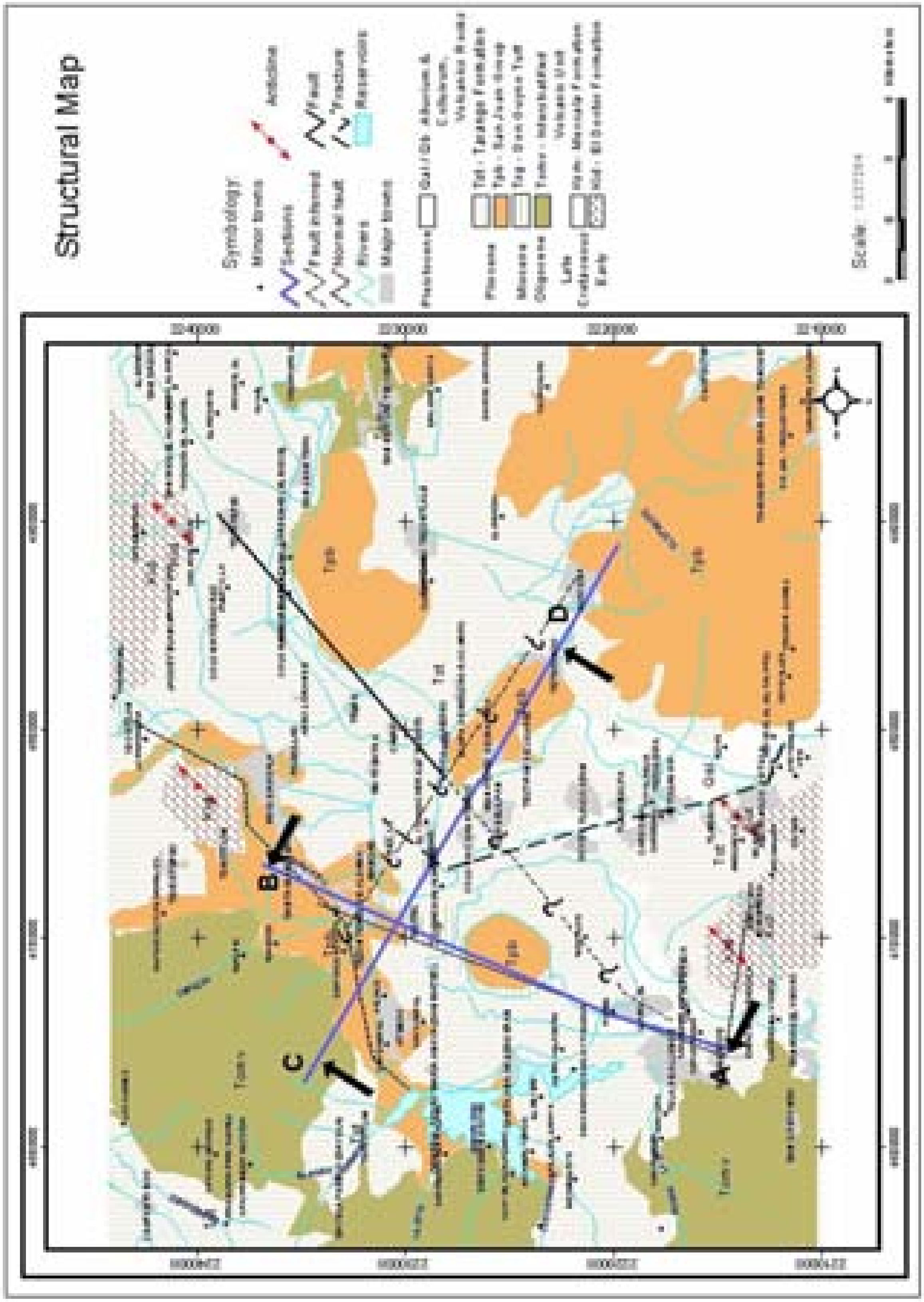

Fig. 3b. Structural map of the studied area.

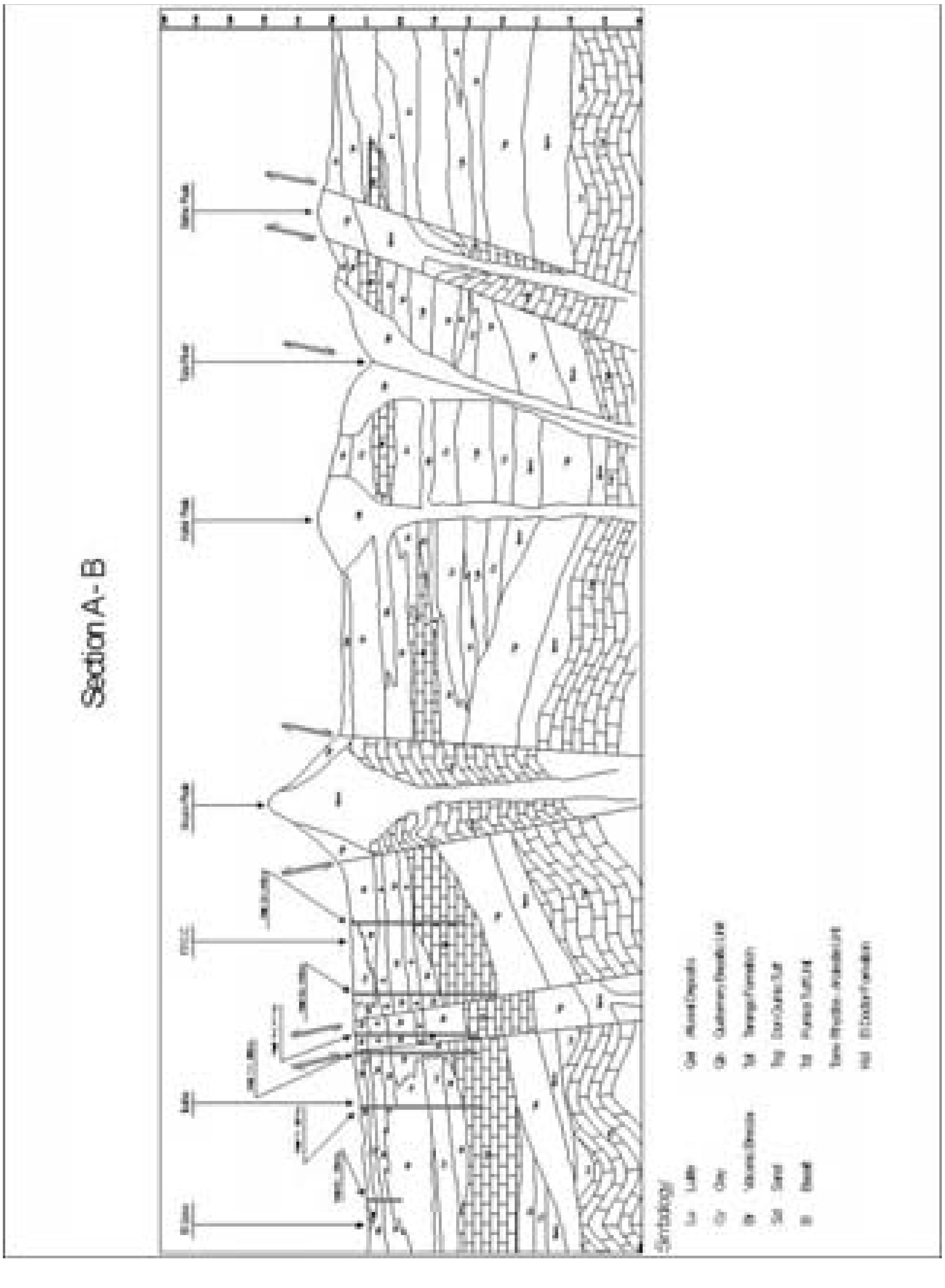

Fig. 4. Geological sections. A-B, Geological section SW-NE. C-D Geological section NW-SE

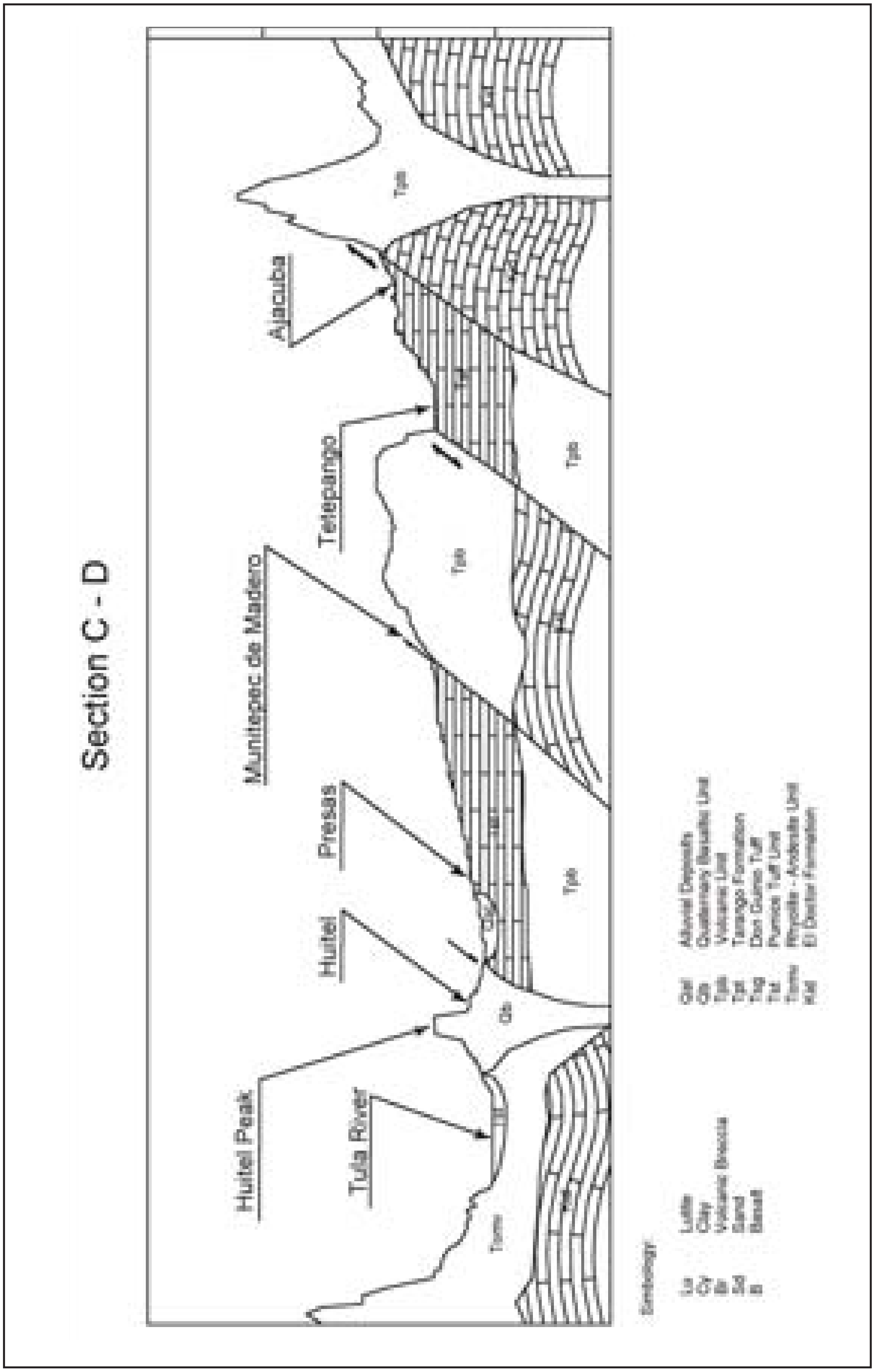

Fig. 4. Continued.

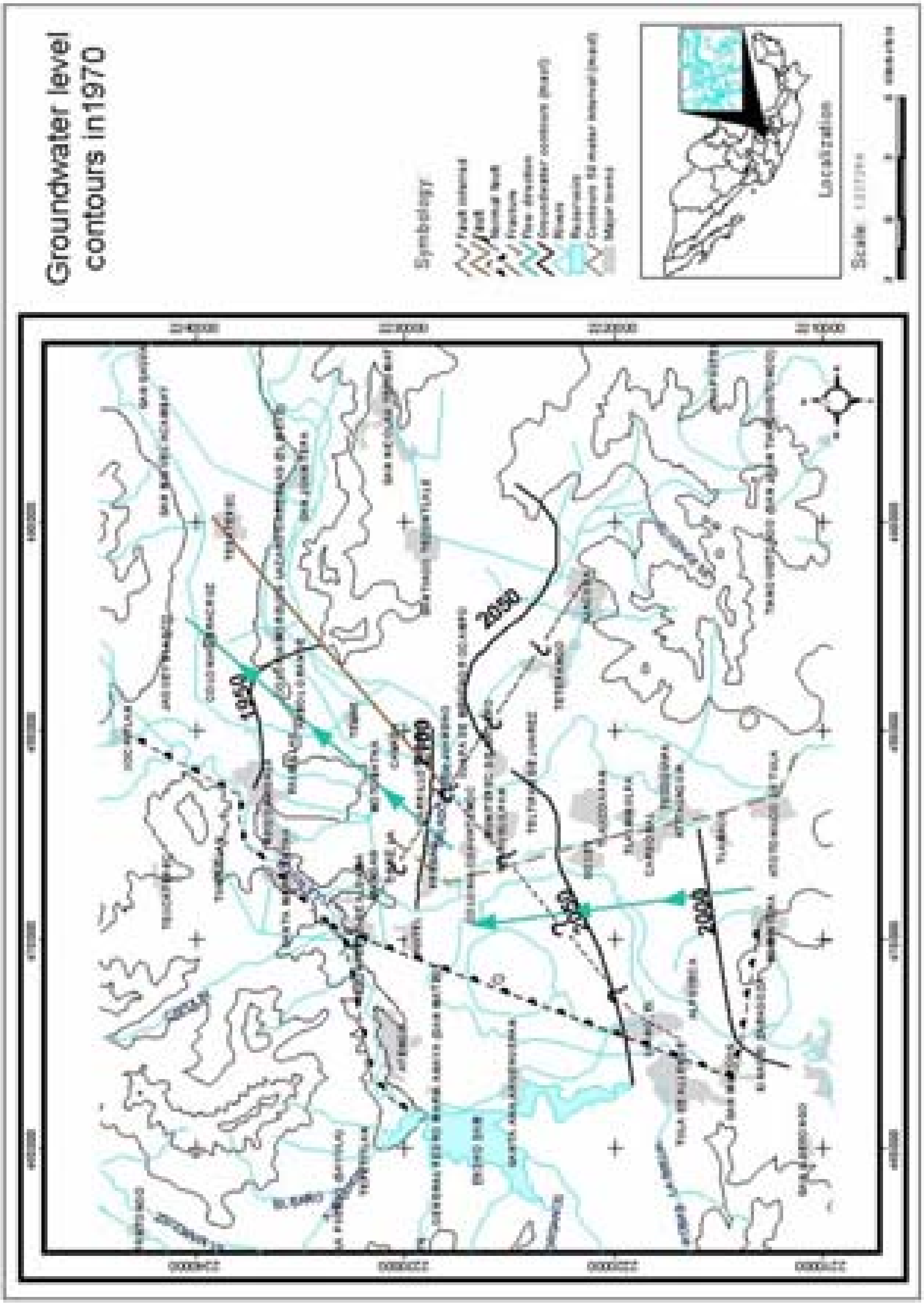

Fig. 5. Groundwater level contours in 1970 (Modified from CNA and BGS, 1995). Groundwater flow direction (blue arrows) shows the influence of faults and fractures.

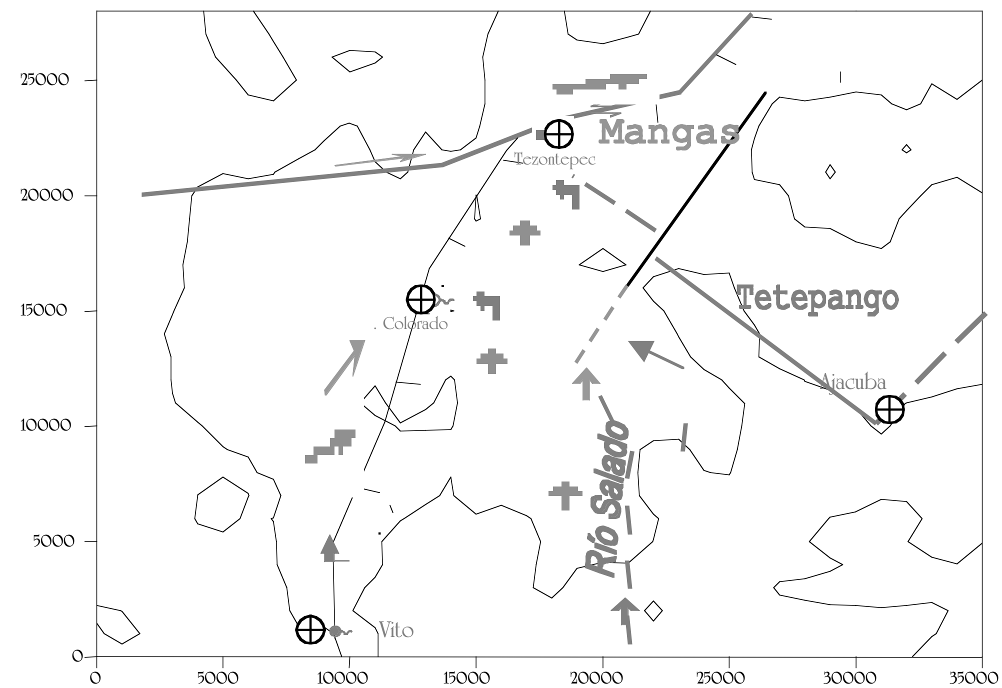

Fig. 6. Relationship of groundwater flow with faults and fractures.

STRUCTURAL CONTROL ON THE HYDROGEOLOGY

Groundwater flow

The complex geology of the area makes it difficult to define the groundwater flow. In general, the main flow patterns shown by the piezometric level contours in 1970 (BGS and CNA, 1995), follow the defined fracture patterns. The direction of flow is SE-NW at the south of the valley, and at the Tula and the Actopan rivers mouths, located NE of the study area (Figure 5). The direction of flow is SW-NE in the center of the basin. A discontinuity in the hydraulic gradient in the Tlahuelilpan area may be caused by a geological structure (possibly a normal fault) (CFE, 1986).

The Tezontepec and Cerro Colorado springs are located over Tertiary volcanic rocks, the first one appears just in the connection of the Tula river fault with the fault trace that goes from Tetepango to Mangas (Figure 6). The Cerro Colorado spring emerges from the volcanic rocks that form the main aquifer (the second one) and is related with the San Marcos-Huitel fault. This spring appeared since the increasing of wastewater use.

In spite of the groundwater pumping rate increase in the recent years, since the built of an oil refinery and an electric power plant around 1970, water discharge from the aquifer is still low (94 Mm^3/y) (CNA and BGS, 1998). The groundwater exploitation regime has led to a main discharge of the aquifer through the Tula river and through several springs, mainly Cerro Colorado and Tezontepec.

Geochemistry and structural control evidences

The travertine reported in some samples obtained at the foot of several mountains next to the Tula river (C. Cruz, Pueblo Nuevo) reveals two important features. The first one is related with the inferred fault creating the Tula river bed, that allows the appearance of groundwater through different locations. The second one is associated with a shallow calcareous environment favoring the precipitation of travertine. Groundwater containing carbonic acid travels through a limestone environment (El Doctor Formation) leaching $CaCO_3$, upon reaching the surface in rivers or springs, carbonic acid is lost, leading to the precipitation of $CaCO_3$, and the travertine formation. The plausibility of this process is supported by the saturation index obtained for calcite and aragonite in Ajacuba, Cerro Colorado and Mangas springs by applying the MINTEQA2 computer code (Allison *et al*., 1991). Values corresponded to oversaturated and near saturated waters. Values of the saturation index varied as follows for Ajacuba, Cerro Colorado, Mangas and Tlahuelilpan springs: log S.I. of calcite from -0.098 at Ajacuba spring to 0.386 at Tlahuelilpan spring; log S.I. of aragonite from 0.237 at Ajacuba spring to 0.247 at Tlahuelilpan spring.

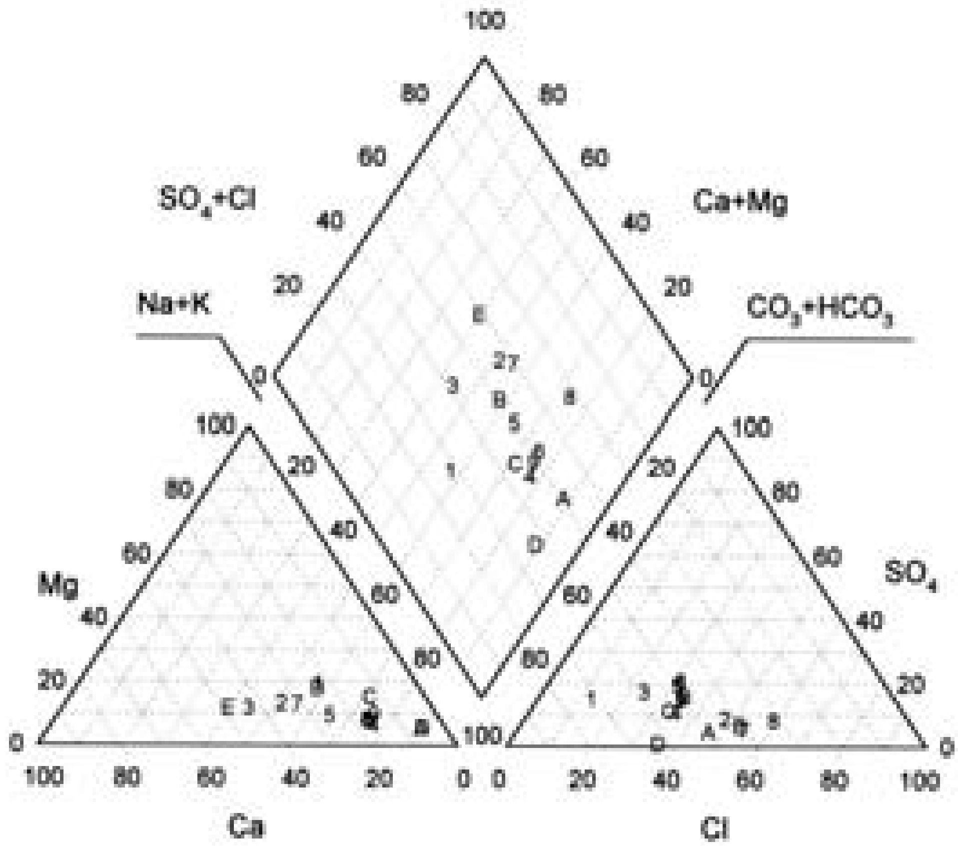

Fig. 7. Piper diagram of sampled springs (B,C,5), piezometers (A,D,E,6,8,9), and wells (1,2,3,4,7).

Local layers of travertine are located at Atitalaquia and El Llano areas. These zones are related to the Atotonilco-Tlahuelilpan fracture, which affects units of the Tarango Formation. The travertine origin is also related with hydrothermal springs, mainly Tezontepec and Vito, since in this type of water the loss of dissolved gases upon cooling and changing to an oxidant environment leads to $CaCO_3$ precipitation and to solid deposits' formation.

Some layers of travertine in the Tarango Formation show pirolusite mineralization that is a typical mineral of a very oxidant lacustrine environment with poor flow. This supports the view of the valley as a basin totally filled by lake water during the Pleistocene, limited by volcanic sequences of different age and composition. Caliche nodules or caliche thin layers, mixed heterogeneously between superficial layers or at depth, are related with faults or fractures, located in the Tarango Formation.

Groundwater chemistry

Groundwater quality in the valley varies with the location. The analyses reported by BGS and CNA (1995 and 1998), and the analyses made for this study in 1998-1999, in fourteen sites at three sampling dates each one, show anion mixed type waters in the center of the valley and bicarbonate type waters to the flanks. Sulfate concentrations vary from 5 to 1360 mg/l, bicarbonates vary from 361 to 781 mg/l with an average value of 500 mg/l. Chlorides (54 to 407 mg/l) have an average value of 170 mg/l. Sodium is the main cation in the waters (125 to 367 mg/l) with an average concentration of 192 mg/l.

Groundwater in the study area is classified mainly as bicarbonate sodium and mixed sodium type (Figure 7). Irrigation wastewater contains sodium as the main cation and bicarbonate and chloride as the main anions (Siebe and Cifuentes, 1995). Chemical differences were observed among different groundwater sources (shallow piezometers next to channels, springs and wells) as shown in Schoeller diagrams (Figure 8). A similar chemical pattern was observed among spring waters linked with the main structures (Figure 8b). These springs also had higher sulfate concentrations than deep wells (M1 and M11, Figure 8a) and most of the piezometers (Figure 8c). Sulfate content may result from the interaction with the volcanic rocks in the area, implying a deeper source,

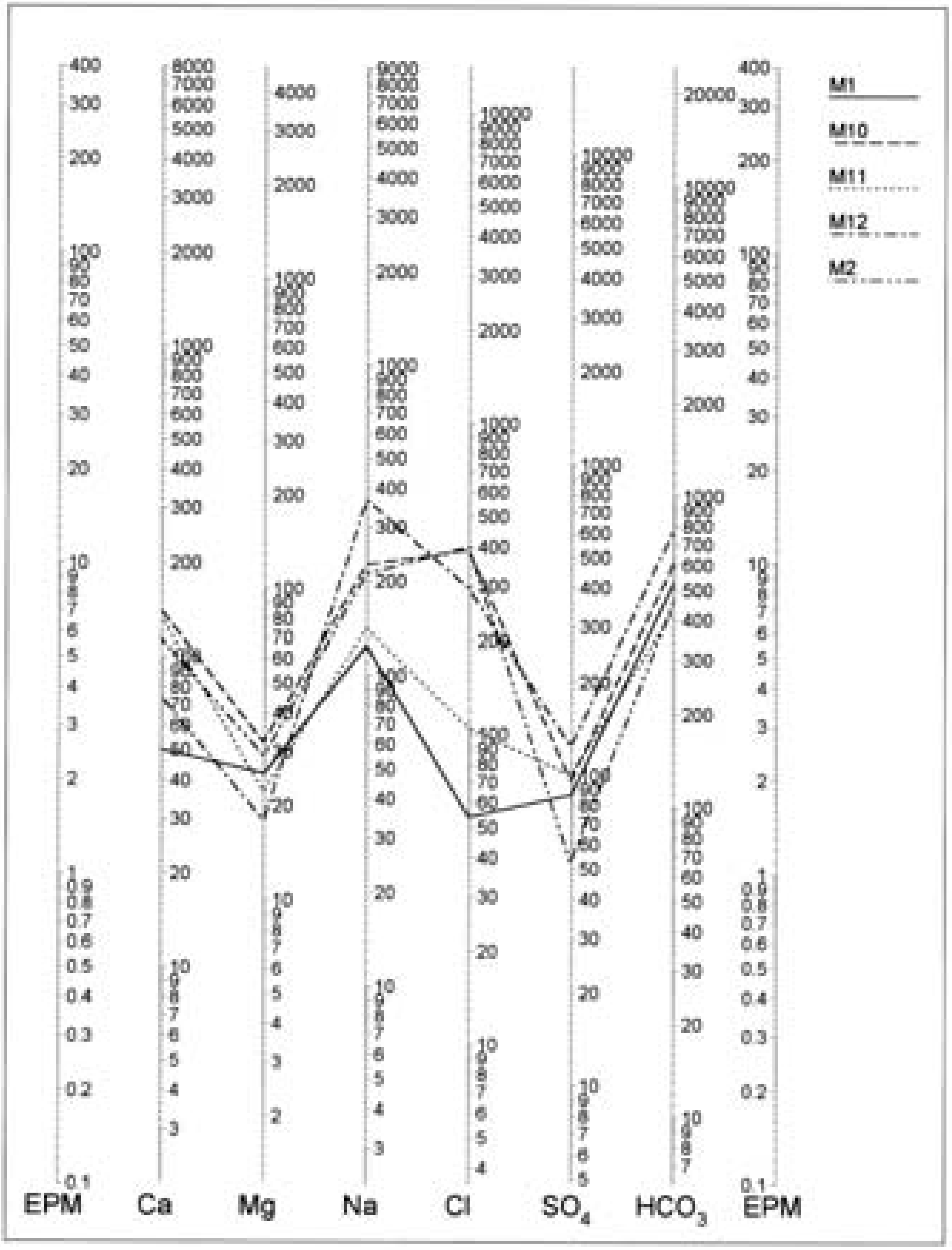

Fig. 8 a. Schoeller diagram. Samples from wells.

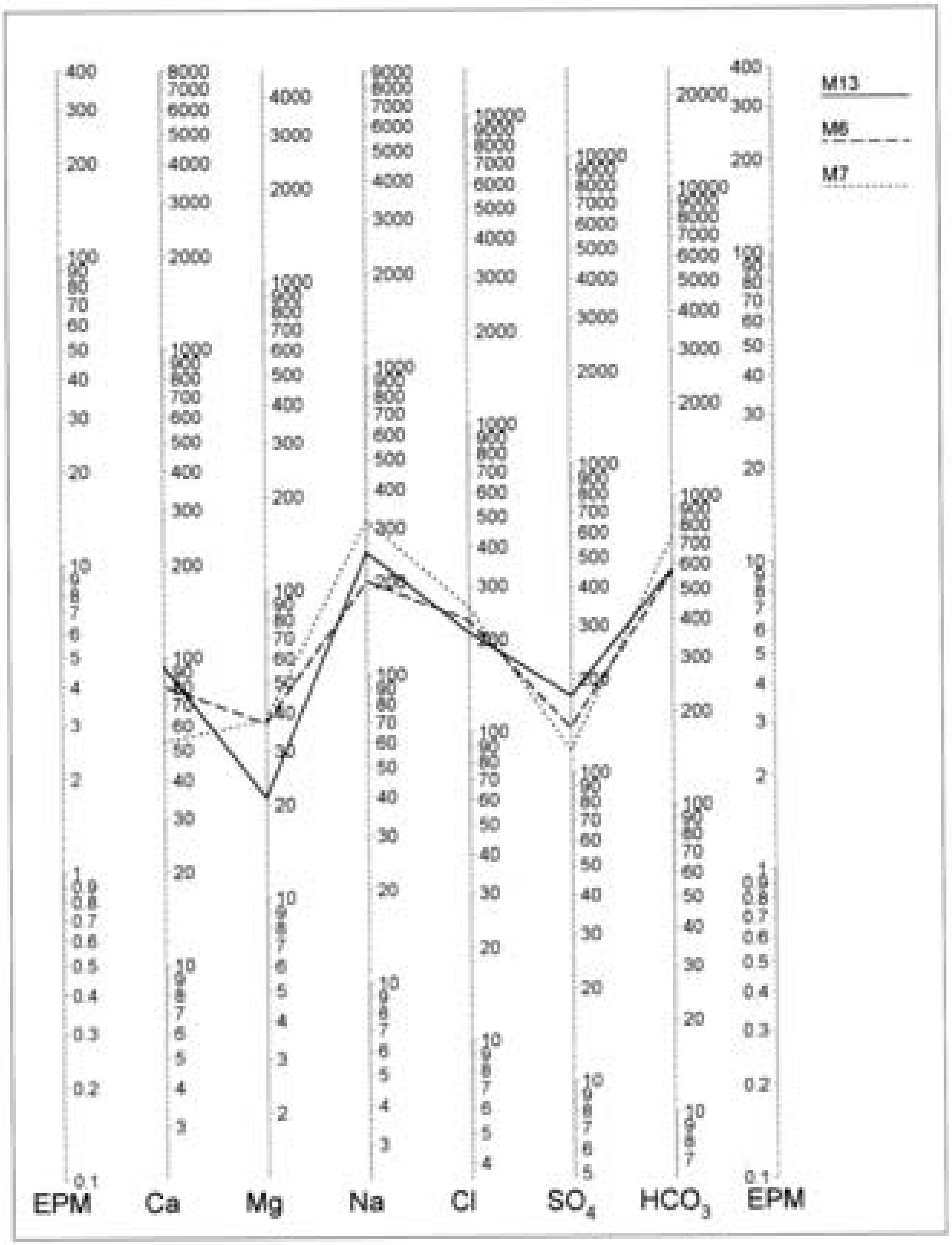

Fig. 8b. Schoeller diagram. Samples from springs.

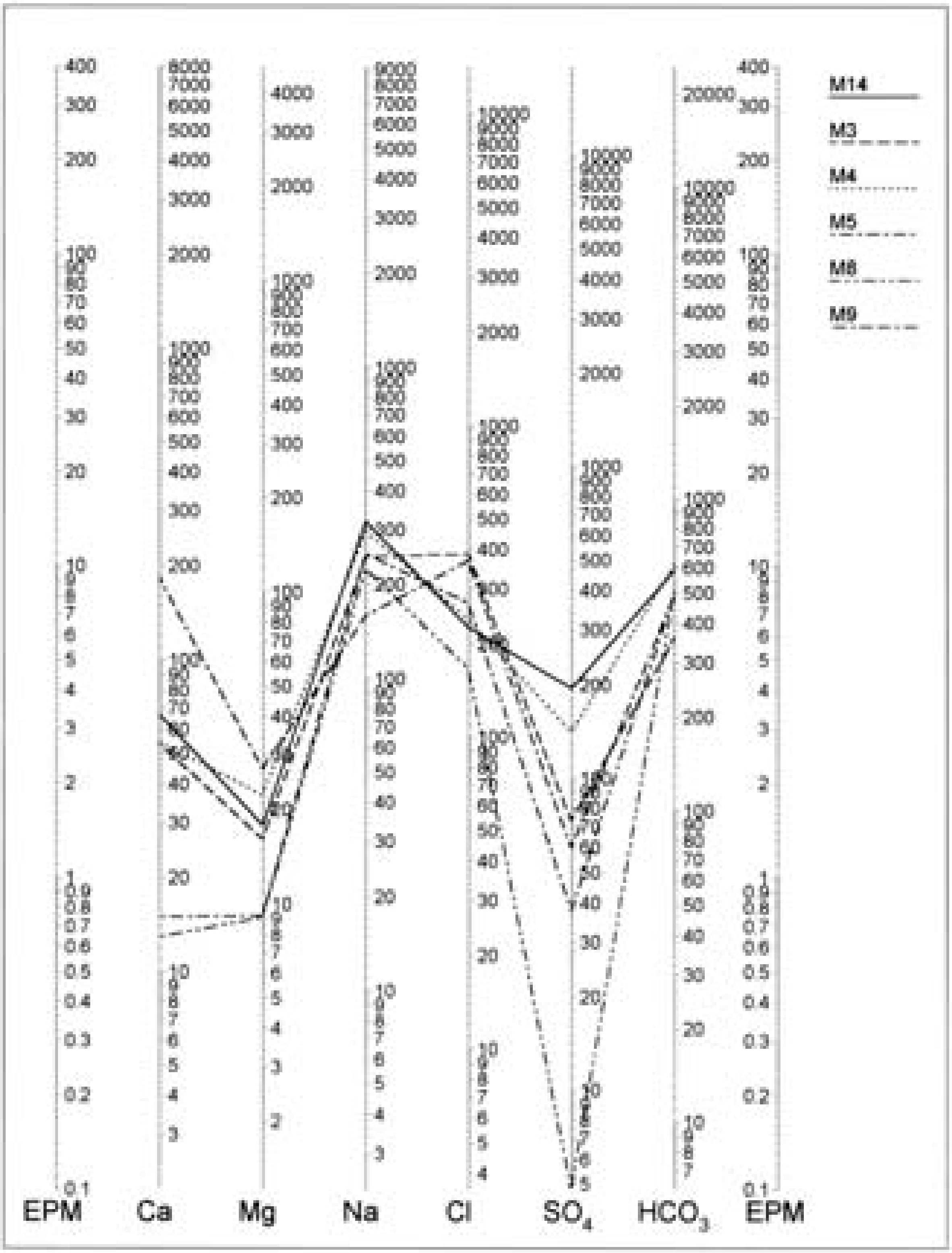

Fig. 8c. Schoeller diagram. Samples from piezometers.

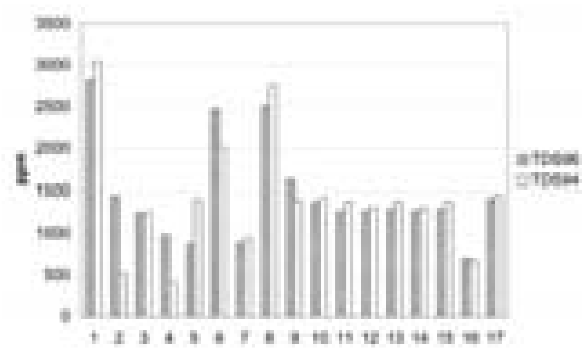

Fig. 9. Comparison of TDS concentrations in 1996 and 1994 in the same well or spring (Data from CNA and BGS, 1995, and CNA *et al*., 1998). Column pairs correspond to ■ TDS 1996 □ TDS 94 for the same sampling point.

since the volcanic aquifer underlies the Quaternary alluvial aquifer. Besides, water from deep wells exploiting the limestone aquifer presented lower Na and Cl contents than the other sampled waters, reflecting a lack of influence of the Na-Cl type irrigation wastewater. All samples presented a high salinity hazard but only samples M5, M8 corresponding to piezometers next to waste channels, and one well exploiting the volcanic aquifer (M12), had also a high sodium hazard.

The Valle del Mezquital wastewater has an average concentration of 25 mg/l of NH_4-N, 35.5 mg/l of total nitrogen and low concentrations of heavy metals (<1 mg/l). Microbiological parameters are above the allowed values for irrigation waters (Jiménez and Homero, 1998).

After about 100 years of irrigation with wastewater with a high total dissolved solids content (more than 1000 mg/l) (Gallegos *et al*., 1999), above a shallow aquifer, an increase of TDS in groundwater would be expected. Nevertheless, an improvement on the groundwater quality of more than 1000 wells, based on nitrate and sulfate concentrations was observed between 1985 and 1986 (CFE, 1986) in the Valle del Mezquital area. Total dissolved solids concentrations in 1996 were generally lower than those reported in 1994 (Figure 9). Although there is a lack of information regarding other chemical parameters over time, the reported concentration trends indicate that the overall groundwater quality is not getting worse in the recent years.

Nitrate concentrations in the groundwater measured in 1998 and 1999 are shown in Figure 10. Lower nitrate contents (average of 4.3 mg/l) were measured in samples out of the fault zone regarding those close to the faults (average of 12.5 mg/l). Nitrates were not detected in the piezometers lo-

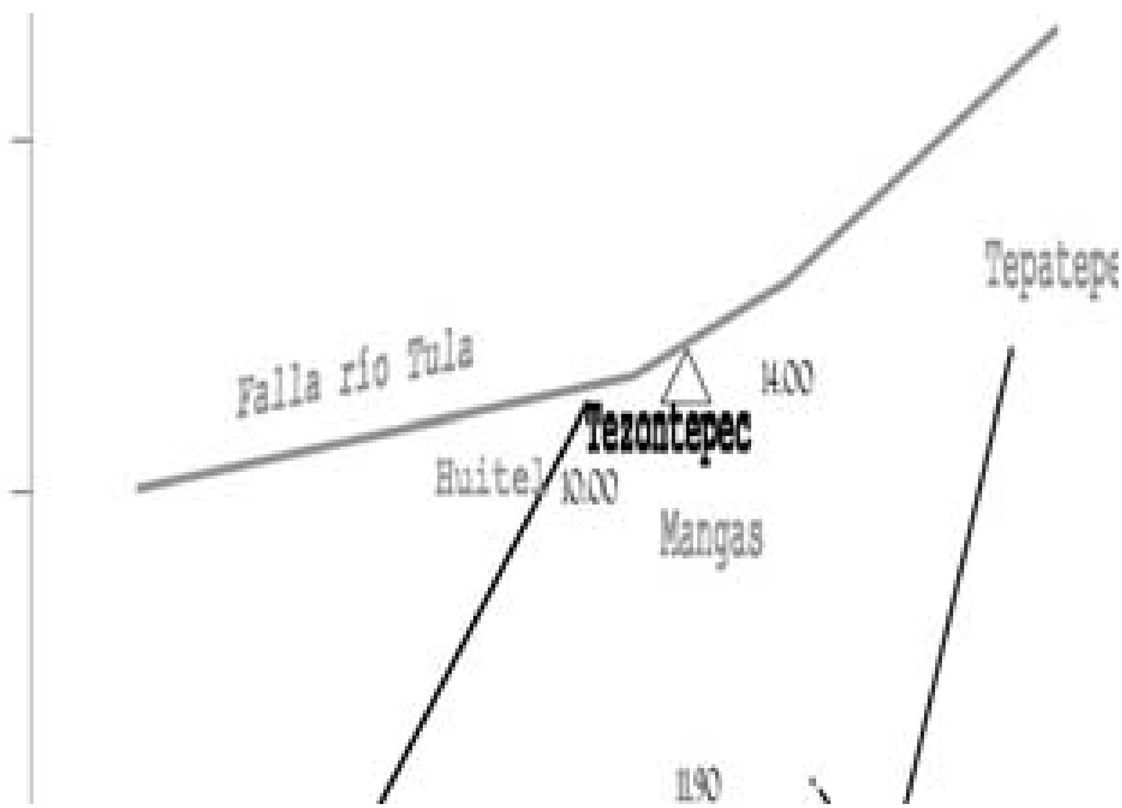

Fig. 10. Relation between nitrate concentrations (mg/L) and faults.

Table 1

Wastewater used for irrigation and groundwater discharge in the Valle del Mezquital from 1960 to 1995 (INEGI, 1992; BGS and CNA 1995)

Year	Irrigation wastewater (Mm^3)	Groundwater discharge (Mm^3)
1960	700	15
1965	500	20
1970	975	24
1975	925	60
1980	1225	72
1985	1125	84
1990	1150	120
1995	1160	123

cated next to two of the main wastewater channels. Wastewater contaminated with NH_4-N (18.2 to 29.43 mg/l) and total N (31.13 to 39.6 mg/l) (Jiménez and Homero, 1998), is irrigated over the land acting as a non-pollution source. As a result of this practice, nitrate contents in the groundwater of the study area would be expected from wastewater infiltration through the soil. Nevertheless, the concentration trends of nitrates show differences among sampling points near and far from the faults.

The concentration distribution of nitrates indicates that wastewater is infiltrating through the faults reaching the upper alluvial aquifer. Lower nitrate contents far from the faults may also result from biotic and abiotic nitrogen transformations occurring within the unsaturated and saturated zones in this area (Canter, 1997).

Recharge zones and wastewater

Rainwater (which infiltrates in the valley soils and its margins), subsurface stormflow and groundwater flow from the hills, infiltration of wastewater from the channel distribution system, and infiltration of wastewater excess used for irrigation (resulting from the practice of soil flooding with a 30 cm wastewater layer), have been identified as the main recharge sources in the Valle del Mezquital (BGS and CNA, 1995). Flow through faults, namely: Tula river fault, San Marcos Huitel fault, Tetepango-Tezontepec fault, and Tula and Salado rivers, may be also an important recharge source in the Valle del Mezquital.

The increase of wastewater use and groundwater pumping rate since 1960 in the Valle del Mezquital is shown in Table 1. In 1995 groundwater extraction was 123 Mm^3 and wastewater volume was 1160 Mm^3. An increase of 460 Mm^3 of irrigation wastewater was observed in 35 years.

If 750 mm/y of rain in the ravines with an infiltration coefficient of 0.15 (based on the type of aquifer material) is considered, a recharge of 280 Mm^3/y would be produced by rainwater. The recharge from precipitation within the valley would result in 600 Mm^3/y with an infiltration coefficient of 0.12 (considering the presence of clay lenses). Nevertheless, according to the study done by BGS and CNA (1995), the induced recharge from the irrigation flooding, besides infiltration from channels would result in 1539 mm/y in the studied area. These results indicate a greater recharge coming from wastewater infiltration regarding the other good quality sources. The recharge ratios would have produced worsening on the groundwater quality. Nevertheless, this worsening has not been observed from the groundwater analyses made in different years. Various explanations have been given to this fact (Jiménez *et al.*, 2000). Flow through faults may also play an important role on the groundwater recharge, explaining the observed results on the groundwater quality. Faults may allow the infiltration of wastewater polluting the shallow aquifer in its surroundings as observed in the nitrate concentrations distribution. At the same time, good quality groundwater from the limestone aquifer may recharge the main volcanic aquifer through the faults.

CONCLUSIONS

A strong relation was observed between the hydrogeological behavior of the Mezquital valley and its structural framework. The various faults and fractures act as deep and shallow recharge sites in the Valley. The deep recharge coming from the limestones may be one cause of the lack of worsening on the groundwater quality in spite of the increased wastewater irrigation use. The distribution of nitrates in groundwater may be explained by a shallow recharge from the wastewater through faults. The underlying limestones from the Doctor Formation constitute a deep aquifer that supplies the overlying aquifer. The springs act as discharge sites of deep groundwater.

The hydraulic head from the south of the Valley produced from the recharge in the ravines and from wastewater channels infiltration, is an important water supply to the aquifer. The presence of the C. Cuauhtémoc-Tepatepec fault directs the flow towards its own trend. A direct hydraulic communication between the bottom of the Endho dam and the aquifer was not observed. The structural features of the valley play a role on the spatial and temporal behavior of the groundwater pollution.

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BIBLIOGRAPHY

ALLISON, J. D., D. S. BROWN and K. J. NOVOGRADAC, 1991. MINTEQA2/PRODEFA2, a geochemical assesment model for enviromental systems: version 3.0. User's Manual. EPA/600/3-91/021, Washington, DC. USA.

APHA, AWWA, WEF, 1995. Standard Methods for the Examination of Water and Wastewater. Washington, D.C.

BAHRI, A., 1999. Agricultural reuse of wastewater and global water management. *Wat. Sci. Tech. 40,* 339-346.

BGS, CNA, 1995. Impact of wastewater reuse on groundwater in the Mezquital Valley, Hidalgo State, Mexico. Phase 1 Report, February 1995. BGS Technical report WD/95/24

CANTER, L. W., 1997. Nitrates in groundwater. Lewis Publishers, N.Y.

CFE, 1986. Resumen Geohidrológico C. T. Tula. Internal Report.

CNA and BGS, 1998. London School of Hygiene and Tropical Medicine, University of Birmingham, Impact of wastewater reuse on groundwater in the Mezquital Valley, Hidalgo State, Mexico. Final Report-November 1998. BGS Technical report WC/98/42

DOWNS, T. J., E. CIFUENTES, E. RUTH and I. M. SUFFET, 2000. Effectiveness of a natural treatment in a wastewater irrigation district of the Mexico City region: a synoptic field survey. *Water Environ. Res., 72,* 4-21.

GALLEGOS, E., A. WARREN, E. ROBLES, E. CAMPOS, A. CALDERÓN, M. G. SAINZ, P. BONILLA and O. ESCOLERO, 1999. The effects of wastewater irrigation on groundwater quality in Mexico. *Wat. Sci. Tech. 40,* 45-52

INEGI, 1992. Síntesis Geográfica del Estado de Hidalgo. Instituto Nacional de Geografía y Estadística, México D.F.

JIMÉNEZ, B. C. and L. HOMERO, 1998. Physico-chemical and bacteriological characterization of wastewater from Mexico City. *Wat. Sci. Tech. 37,* 1-8

JIMÉNEZ, B. C., A. CHÁVEZ, J. E. BARRIOS and R. PÉREZ, 2000. Impact and potential of reused water in the Mezquital Valley. Water 21, June 2000, 34-36.

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.

SIEBE, C. and E. CIFUENTES, 1995. Environmental impact of wastewater irrigation in Central Mexico: An overview. *Int J. Environ. Health Res. 5,* 161-173.

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