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Journal of South American Earth Sciences 14 (2001) 641–650

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

Hydrogeological study of the Burruyacu basin, Tucumán province, Argentina

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Accepted 1 May 2001

Abstract

A geoelectrical survey (VES) was performed in the Burruyacu hydrogeological basin in the northeastern sector of Tucumán Province, Argentina. The area under study is bounded on the west by the Sierras de La Ramada and El Cajón, and on the east by Santiago del Estero Province (SEP). The Tajamar River is the only surface runway in the area; its source is west of the study area on the eastern slope of the mountains. The geoelectrical models, together with data from existing wells, made it possible to identify the permeable zones. Two aquifer systems have been distinguished. An upper unconfined aquifer system has sediments with larger grain size in the piedmont zone and the alluvial fan of Tajamar River, with aquifer levels at depths from 30 to 180 m and waters suitable for irrigation.

A lower confined aquifer system with artesian water is composed of mostly clay layers intercalated with sharp quartzy sands of medium to thick grain size. The sands are well developed throughout the depressed plain and beyond the boundary with SEP. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Vertical electrical soundings; Aquifer systems; Hydrogeological

1. Introduction

Hydrogeological and geophysical investigations were carried out in the sedimentary basin located close to 26°30′S, in the Department of Burruyacu, in the northeastern sector of Tucumán Province (Fig. 1). The study area is bounded by the Sierras de La Ramada and El Cajón on the west and by Santiago del Estero Province (SEP) on the east (Fig. 2). Good roads provide access, and livestock and agricultural activities make this area one of the most important economic regions in the province. Sugar cane, citrus fruits, grains, and extensive livestock production require intensive use of groundwater resources. The most important river is the Tajamar, with headwaters west of the study area and a location on the eastern slope of the mountains. Its hydrographic network is formed by mostly temporary rivers and streams that infiltrate upon reaching the piedmont, with an annual runoff of 22.3 hm^3 and a catchment area of 250 km^2.

Several papers have been published about this zone and were used as background for this research. Stappenbeck (1921) delineated the artesian natural area and Mon et al. (1971) described the structure, geomorphology, and stratigraphy of the Sierras del Campo and La Ramada. The hydrochemical and hydrogeological features and hydrogeological environments of the basin have been described by Tineo et al. (1991, 1992, 1994, 1997).

The purpose of this study is to define the geometry of the hydrogeological basin, determining the depths, dimensions, and structures of the aquifer zones and the physical characteristics of the substratum. On the basis of previous geomorphological, geological, hydrochemical, and climate studies, and with the addition of the hydrogeological and geophysical results of this investigation, the morphology and the degree of confinement of the aquifer systems have been determined, establishing recharge and discharge zones. Additionally, water quality has been assessed in an effort to establish the suitability of the basin's groundwater for human consumption as well as for agriculture and livestock.

1.1. Climate

The Department of Burrucayú is located in a continental subtropical region with high summer and low winter

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PII: S0895-9811(01)00056-6

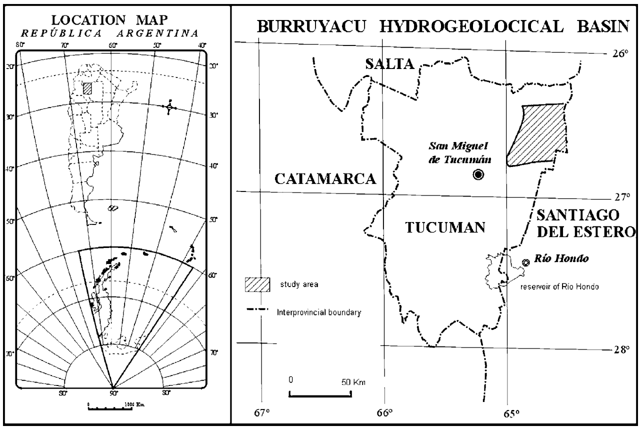

Fig. 1. Location of the study area: Burruyacu Department, Tucumán Province, Argentina.

temperatures, i.e. with a wide thermal range. The climate is quasi-monsoonal with a maximum of 85% of annual precipitation in the summer, and the remaining in the winter. Rainfall concentrates on the eastern mountain slopes, averaging 900 mm yearly and decreasing eastward to 600 mm on the boundary with SEP. The highest precipitation levels thus occur in the piedmont zone, where Quaternary deposits of high porosity and permeability exist, ensuring recharge of the aquifers in this sector.

According to Torres Bruchman (1978), three different climate types are found in this zone: (1) Cwak, typical of the mountain zone, moderate temperate humid climate with non-severe dry winters; (2) Cwah, mesothermal climate with dry winter in the piedmont area; and (3) Bshwa, dry

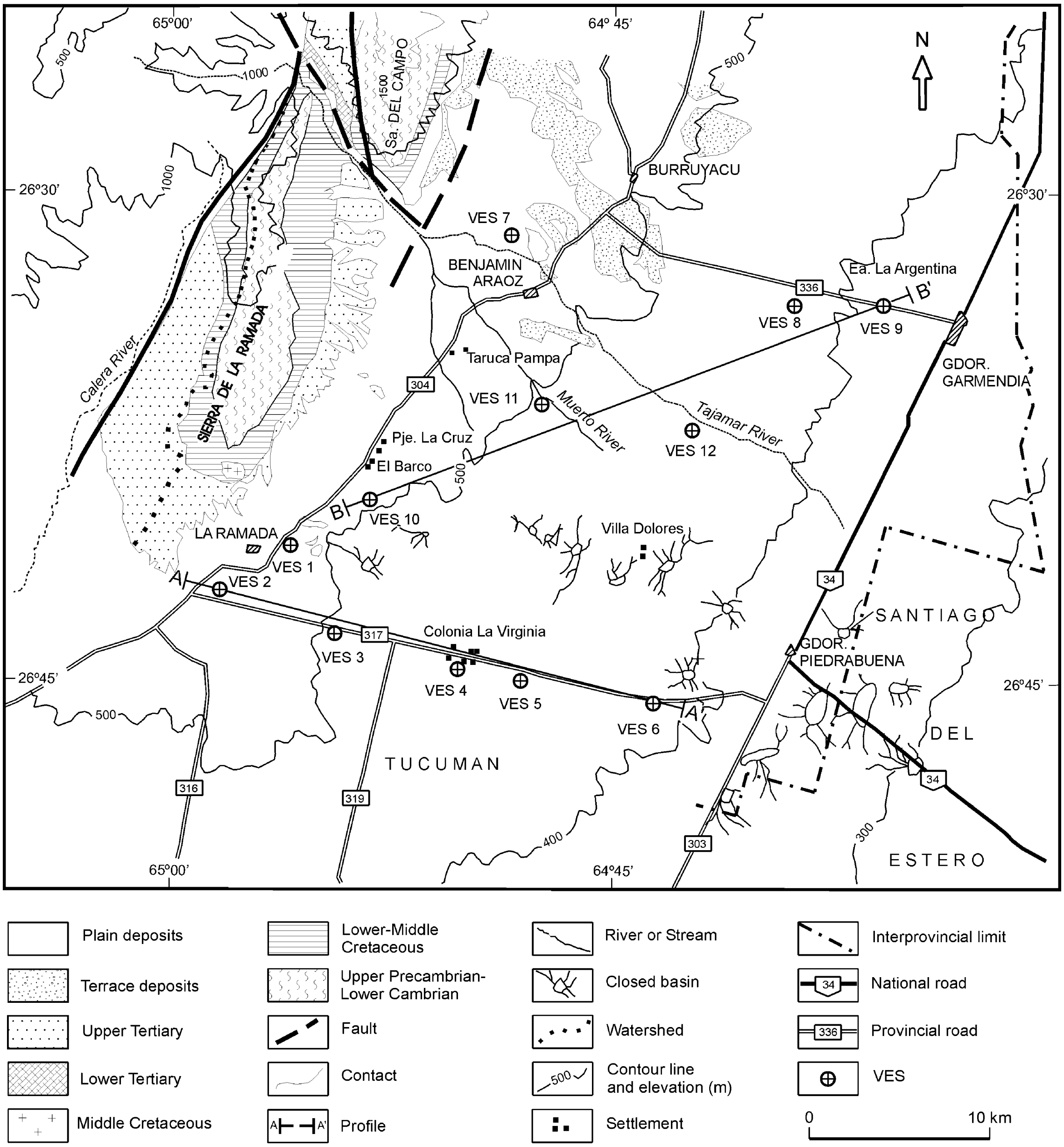

Fig. 2. Geological map of Burruyacu zone, Tucumán Province, Argentina.

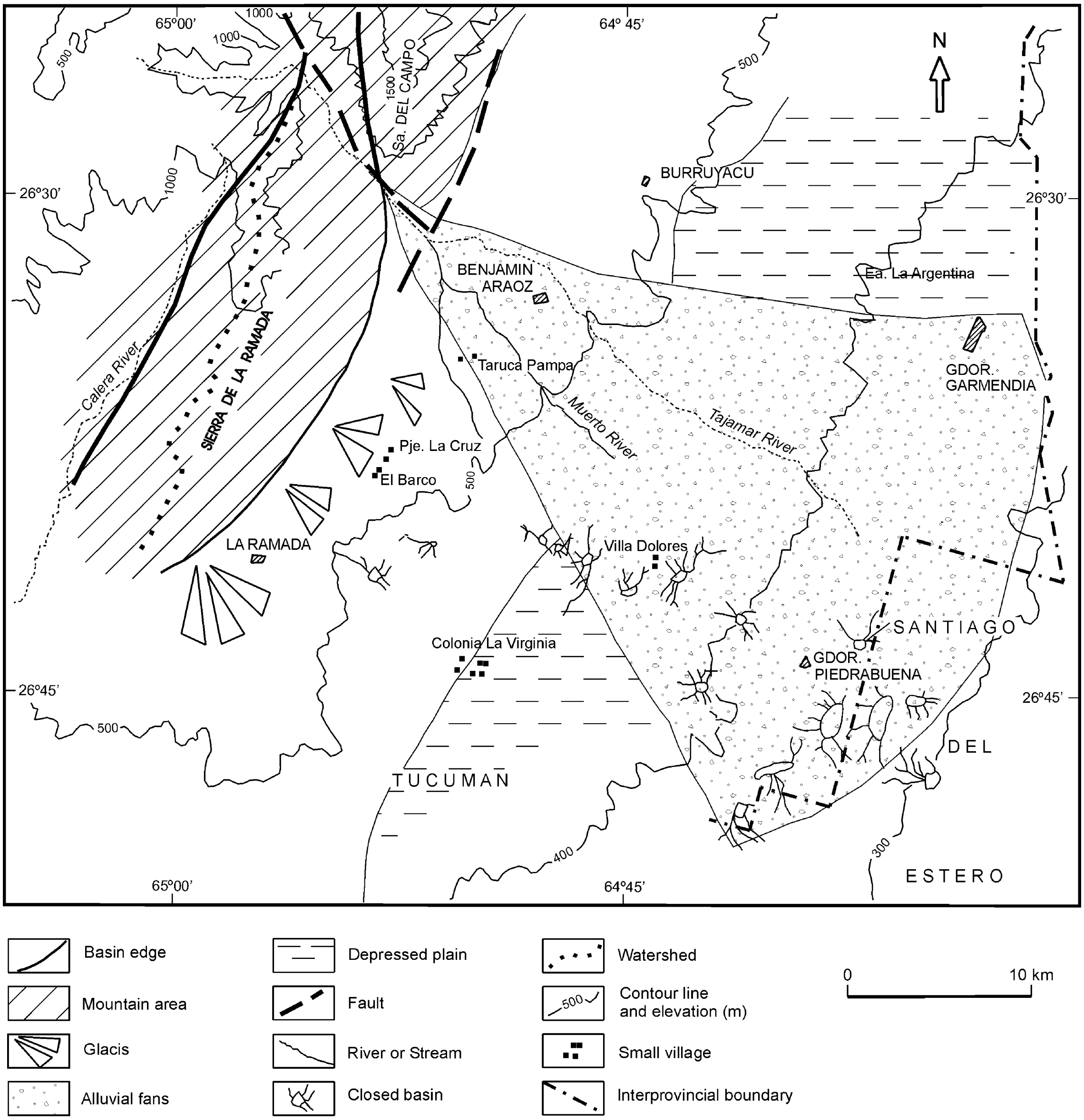

Fig. 3. Hydrogeological environments showing the boundary of the Burruyacu Basin, alluvial fan of Tajamar River, mainly alluvial fans of loess reworked by wind and hydric erosion called glacis, and depressed plain.

steppe climate with xerophilous vegetation, typical of the plains area.

1.2. Geomorphology

The dominant orographic units are the Sierras del Campo (maximum altitude of 2000 m a.s.l.) and the Sierras de La Ramada (maximum altitude of 1160 m a.s.l.), which are located west of the study area (Fig. 2) and extend NNE–SSW for approximately 30 km. The two ranges are divided from each other by a diagonal fault striking NNW–SSE where the Tajamar River flows. The western slopes of both ranges are steep and narrow and limited by a southern fault; the eastern slopes are softer and extend toward the Burruyacu plain.

At the piedmont of both ranges, there is a series of low hills and topographic lows, made up of Tertiary deposits covered by Quaternary sediments, mainly alluvial fans of loess reworked by wind and hydric erosion, which is called 'glacis' (Fig. 3). The Burruyacu plain is formed by Quaternary silty-loessic and sandy sediments, with good soil development.

Upon reaching the piedmont, the Tajamar River (Tineo et al., 1992) forms an alluvial fan approximately 470 km^2 in area, between 600 and 350 m a.s.l., on the SEP boundary. Several paleochannels have been found on the fan surface; they show recent north-to-south meandering of the river.

During part of the year, the Tajamar River is lost on the plain due to the high permeability of the sediments and intensive irrigation.

1.3. Stratigraphy

Knowledge of the stratigraphy of the sedimentary basin is limited to the outcropping units and shallow wells that penetrate the Quaternary sequences. The oldest units are slates and gray phyllites of low metamorphic degree (late Precambrian to early Cambrian in age) that make up the nucleus of the Sierras del Campo and La Ramada (Mon et al., 1971). These units exhibit a high surface runoff and low-to-medium secondary permeability due to jointing and faulting. Compact red conglomerates and sandstones of early to mid-Cretaceous age are found in unconformity; they crop out along the Sierras del Campo and La Ramada. At some locations, basalt bodies intrude the units in the form of dikes and sheets attributed to the mid-Cretaceous (Pirgüa Group).

Tertiary deposits lie in unconformity and consist of sandstones, conglomerates, red Paleocene–Eocene claystones (Santa Bárbara Group), white sandstones, green marls, gypsum beds, and Miocene–Pliocene tuffaceous deposits that crop out on the mountain flanks (Río Salí Formation; Ruiz Huidobro, 1975). These sediments have low permeability, although some sand layers behave like aquifers and contain mostly average to poor quality water, mainly due to chemical contamination from sulfates and carbonates.

The most productive and highest quality aquifers are found in the Quaternary sediments.

These deposits resulted from the transport of gravel, sands, and pelites by rivers that flow down from the mountains. The coarser materials might have been formed by the destruction of basement rocks and Cretaceous rocks, while the pelitic materials originated in erosion of the Tertiary deposits.

East of the mountains, the percentage of coarse material decreases and silty level intercalations appear on the plains; they are somehow clayey, with sands and fine gravel embedded in them. The thickness and prevalence of fine levels increase toward the SEP boundary, where there is a dominance of silty-clayey levels and loess of eolian origin.

1.4. Structure

The present structure of this region is related to the Andean Orogeny (Late Tertiary–Early Quaternary) that influenced the basement and the sedimentary cover (Mon et al., 1971).

Positive expressions such as the Sierras del Campo and La Ramada belong to the system called the Sierras Subandinas, where the dominant structures are N–S faults bordering the mountains.

A southern fault borders the western skirts of the ranges. Gravimetric studies performed in this area (Galindo et al., 1997) made it possible to define both the marked structural feature represented by the fault where the Tajamar River flows and the symmetry of the alluvial fan that developed.

A structural high in the subsurface, the Espolón de Tacanas, has been identified southeast of the region of study. From analysis of the BA, it exhibits a coincidence with the contour lines, and shapes the drainage divide of both hydrogeological basins of the Eastern Tucumán Plain: the Salí River and the Burruyacu Basin (Tineo et al., 1994).

2. Hydrogeology

The Burruyacu hydrogeological basin is developed in the northeastern sector of Tucumán Province; its western border is located in the piedmont sector of the mountains (Fig. 3), and its southern boundary is the Espolón de Tacanas. Hydrogeological environments of the basin have been differentiated by Tineo et al. (1994), based on differing Quaternary conditions and structural settings. These environments include: basin boundary, alluvial fan, glacis, and depressed plain (Fig. 3).

The Tajamar River, with a modern fill over Tertiary structures, flows over the piedmont zone. From there on, the Tajamar River developed an important alluvial fan (Tineo et al., 1991) that controls the distribution and behavior of the aquifers, with artesian conditions and excellent discharges and quality of water in its distal part. This fan extends beyond the boundary with SEP.

The piedmont sector of the Sierra de La Ramada toward the depressed plain on the east is represented by glacis and a series of low hills and topographic lows exhibiting great subsurface heterogeneity; the water reservoirs have little discharge and an increased salt content.

Finally, there is a area that covers the depressed plain limited by the periphery of the artesian wells area toward the west. Multiple confined aquifers located below the 100–200 m depth are found there.

At the discharge zone, southeast of the study area, the best natural artesian well outputs have been obtained; in some cases, pressures cannot be controlled if small drilling equipment is used.

2.1. Hydrochemistry

Hydrochemical studies were performed on the basis of 28 wells sunk in 1992 or before (Tineo et al., 1992). In general, the studies show the well water to be potable, with total dissolved solid concentrations under 1000 mg/l, temperatures from 17 to 45°C (at ground level), and pH from 7.1 to 8.5. Sediment grain size becomes finer and salinity increases with groundwater flow NW–SE toward the border of SEP. There is a remarkable decrease in the Mg/Ca ratio as water runs off in the direction of the subsurface flow. This trend could be attributed to an increase in Ca and SO_4 ion concentration due to the presence of Tertiary sediment-containing gypsum beds. This conclusion coincides with the increase in sulfate ion concentration. The groundwater of the Tajamar River alluvial fan is appropriate for human consumption, good-to-average for irrigation, and suitable for cattle.

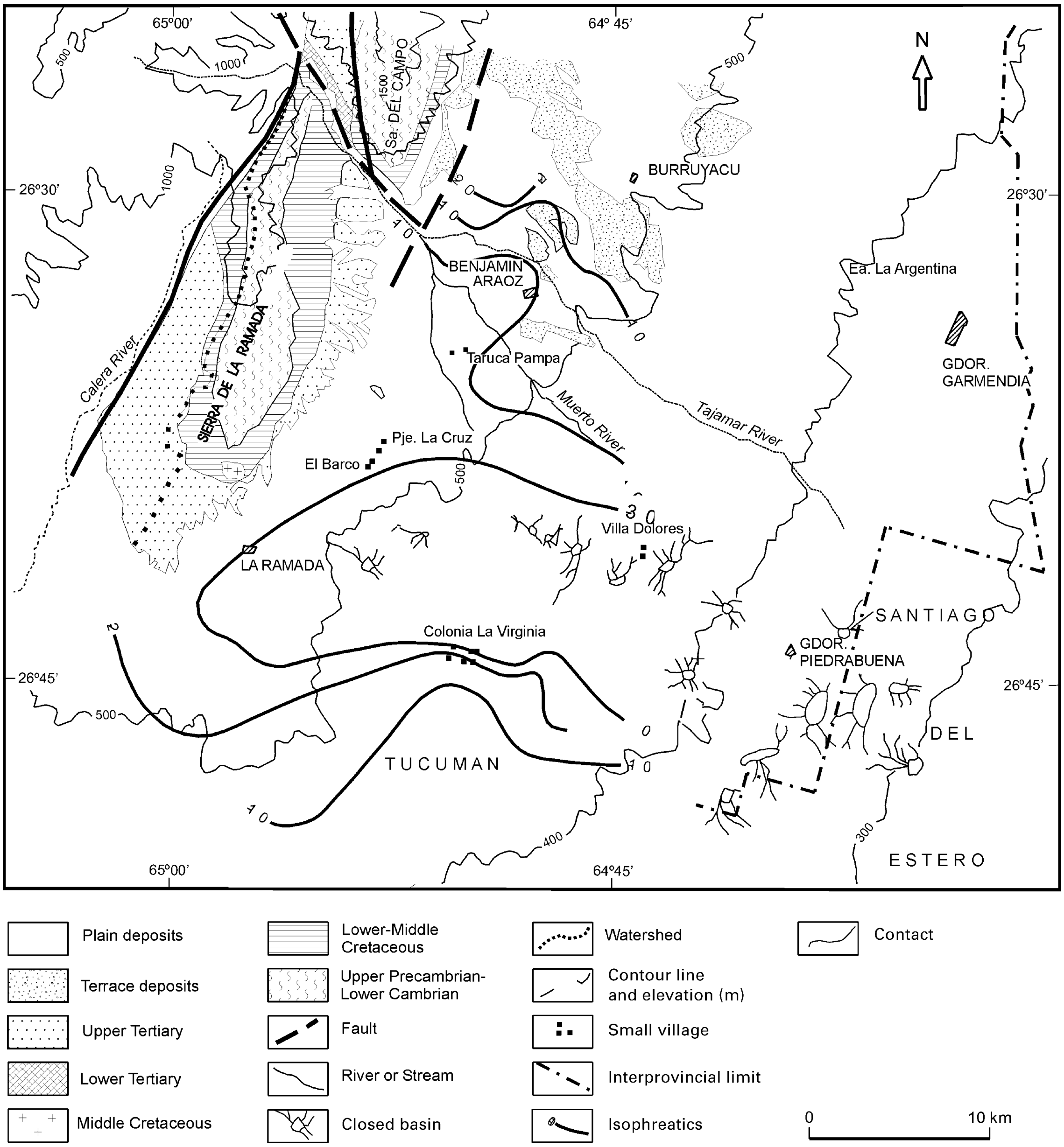

Fig. 4. Potentiometric contours map showing the direction of the free groundwater flow toward a zone of centripetal drainage network.

2.2. Methodology

In the hydrogeological study of the zone, the topographic map and past geological information was used to interpret the vertical soundings in the area. A well census was performed, and the lithology, levels, discharge, depth, and geological background as well as meteorological data were analyzed. The isolines of free groundwater level and the confined potentiometric contours were constructed from well data.

Ten vertical electrical soundings (VES) were performed in the study area, and data from two soundings (VES 11 and 12) from Ponti (personal communication, 1997) (Fig. 2) were integrated. By this method, an electrical current is injected into the earth by means of a power generator, with a maximum of 1.5 kW, through a pair of electrodes, usually called the current ones (AB). This circuit is completed with a milliamperimeter, which measures the current value. Through another pair of electrodes (MN) colineal with AB, the potential electrical difference between them is measured with a millivoltimeter. The distance between MN electrodes is small compared to AB distance (Schlumberger configuration). The half distance between current electrodes (AB/2) was varied up to 1000 m; as the separation between current electrodes is increased, information about greater depths is attained. It was then possible to obtain depth information, which in some cases reached down to 250 m. The value of apparent

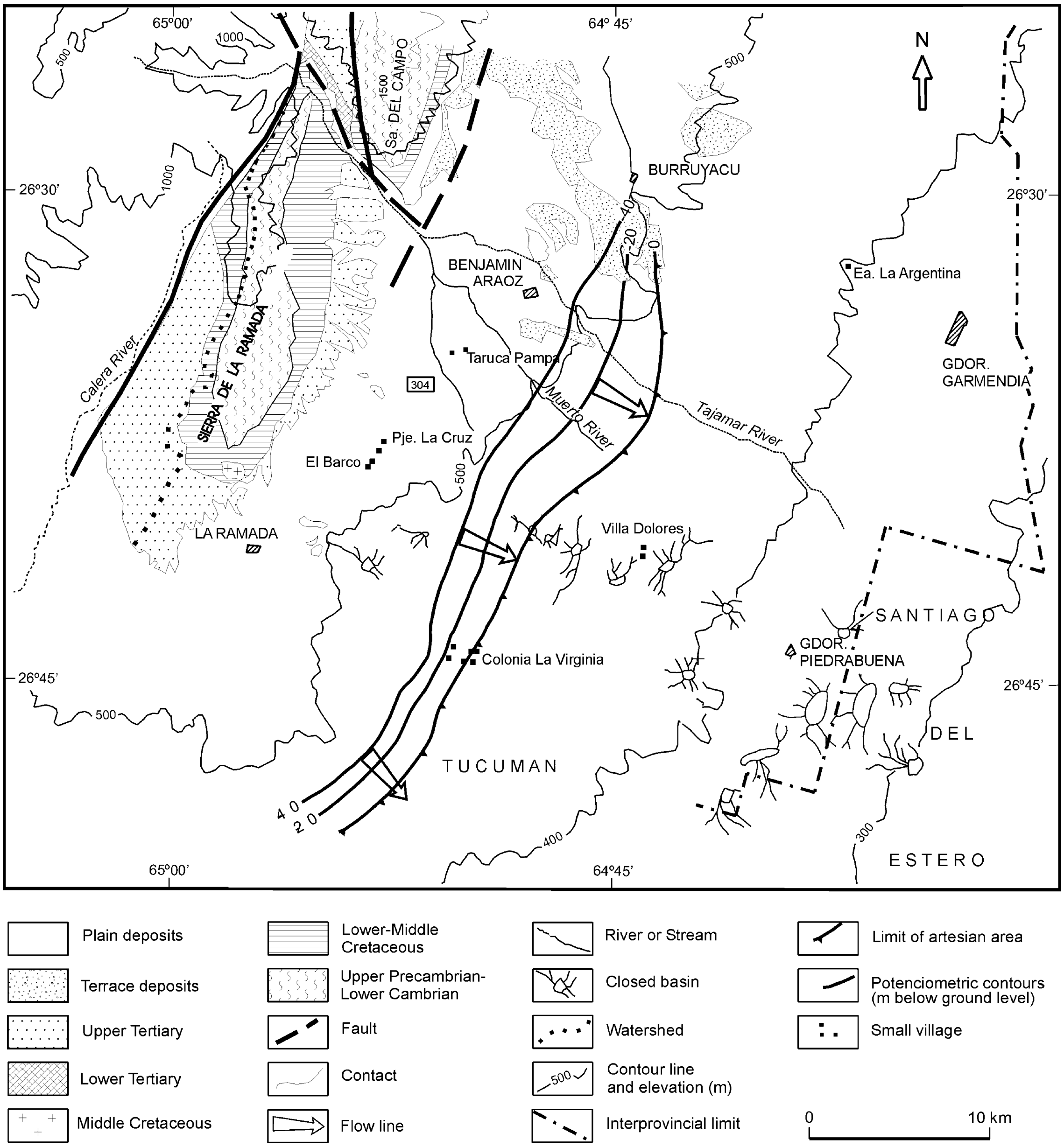

Fig. 5. Piezometric map that indicates a NW–SE confined groundwater flow coinciding with the slope of the terrain.

resistivity is calculated with the current *i*, the potential difference ΔV, and a geometrical factor *K*, which depends on the electrode configuration.

The apparent resistivity curves were fitted initially to theoretical models of horizontal electrical resistivity layers using Vozoff and Jupp's (1975) fitting method of least squares. A revision of the inversion was carried on with Cooper's (1992) program, allowing a more detailed fitting.

Finally, permeable strata were identified from the lithological interpretation obtained through the well census and the geoelectrical results. Low resistivities are identified with clayey sediments while higher resistivities are related to sands if freshwater fills the pores. Obviously, these values change regarding water resistivity, and salty water may significantly lower the whole layer's resistivity.

3. Results from the hydrogeological prospecting

On the basis of the hydrogeological background analyzed, two types of aquifers have been identified: free groundwater and confined groundwater.

3.1. Free groundwater

From the map of the potentiometric surface shown in Fig. 4, it can be inferred that in general, free horizon depths are within 40 m of surface. In the study area, the depth to free groundwater ranges from −1.5 to −40 m, depending on topography and recharge. East of the mountains, the undulating plain develops with important variations in free groundwater levels. Close to the boundary with SEP, there

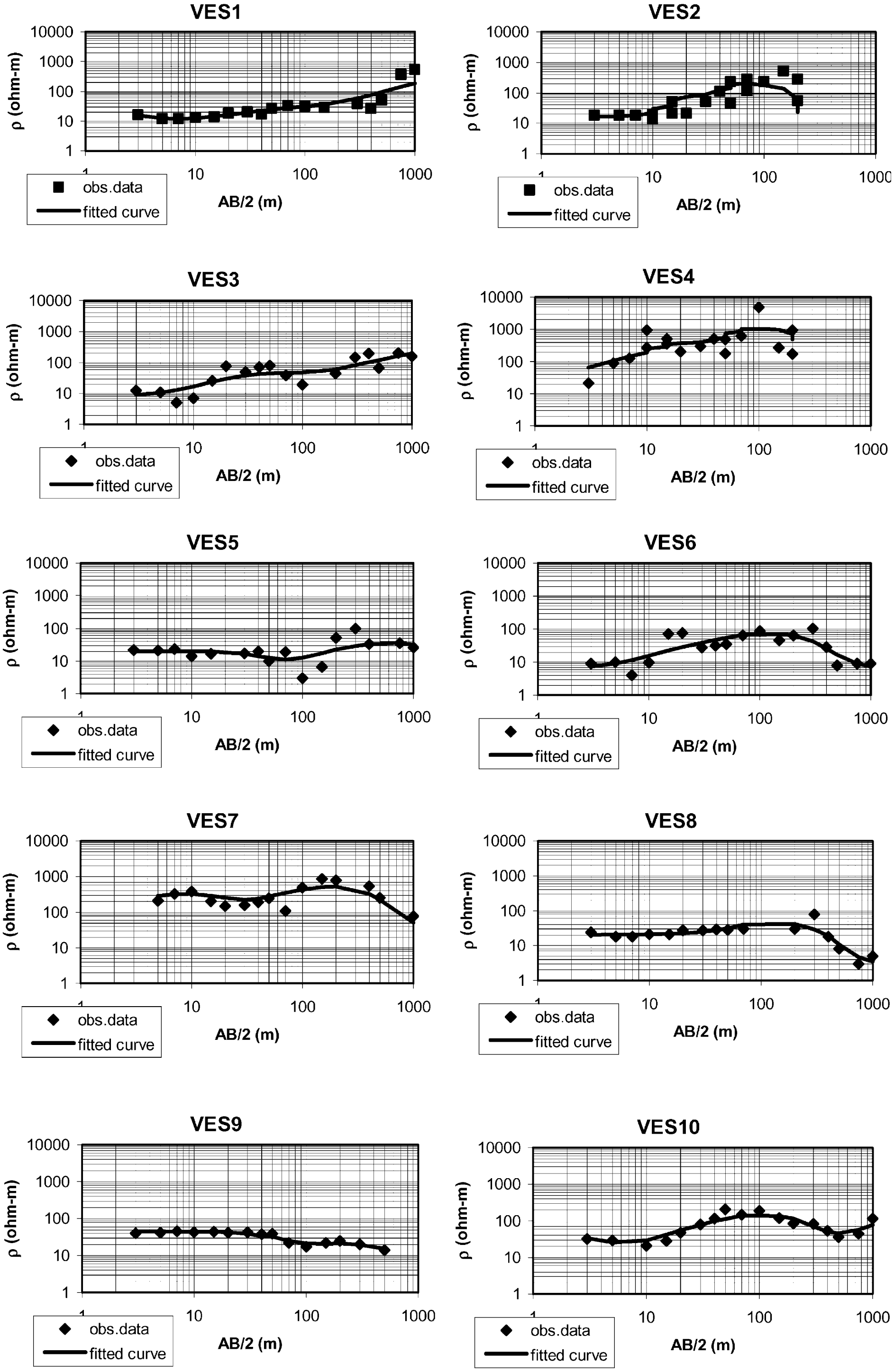

Fig. 6. Apparent resistivity curves as a function of half distance between current electrodes (AB/2) for each sounding. Solid line shows the curve calculated from the interpreted models in Table 1.

are circular-to-semicircular depressions due to the development of a centripetal drainage network. These depressions serve as intake basins favoring infiltration and thus increasing the free groundwater levels at these points. The direction of the groundwater is S–E, but the flow discharges during the rainy season in the zone of the centripetal basin. This great level variation could be the result of structural control existing in the development of the sedimentary sequence of the plain.

3.2. Confined groundwater

The map of the potentiometric surface of the confined aquifer is shown in Fig. 5. It may be concluded that the

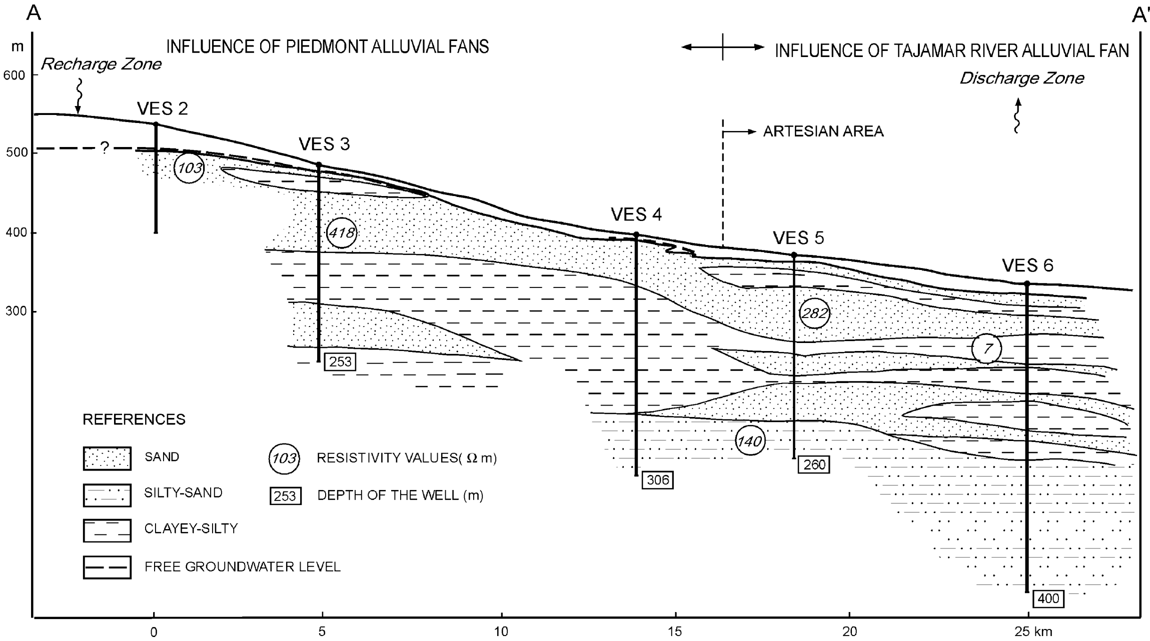

Fig. 7. Hydrogeological profile AA′, based on VES results and well log data, showing the depth of the free and confined aquifers.

groundwater flow generally coincides with the regional NW–SE slope of the terrain. Piezometric levels are deep in the piedmont zone with levels around −20 m b.g.l. and positive in the eastern plain. On the basis of information supplied by the logs from regularly distributed and conveniently selected wells, an outline has been proposed for the facies changes in the subsurface materials as a result of the meanderings of the surface riverbeds on the plain area. The potentiometric contour lines mark the fans at the piedmont and the largest alluvial fan formed by the Tajamar River. The recharge is located at the eastern skirt of the Sierras del Campo and La Ramada, where the greatest rainfalls occur and where, in addition, the most permeable sediments are developed. The artesian zone is located east of the zero-meter-potential contour in the central and eastern sectors of the study area, where the deepest and most productive wells are located. A flow with a vertical downward component is established. The recharge and discharge zones are connected by an area extending from the piedmont to the boundary with SEP. The depth of water-well development ranges from 100 m b.g.l. in the piedmont area to 500 m b.g.l. in the eastern plain. In general, they are deep wells (more

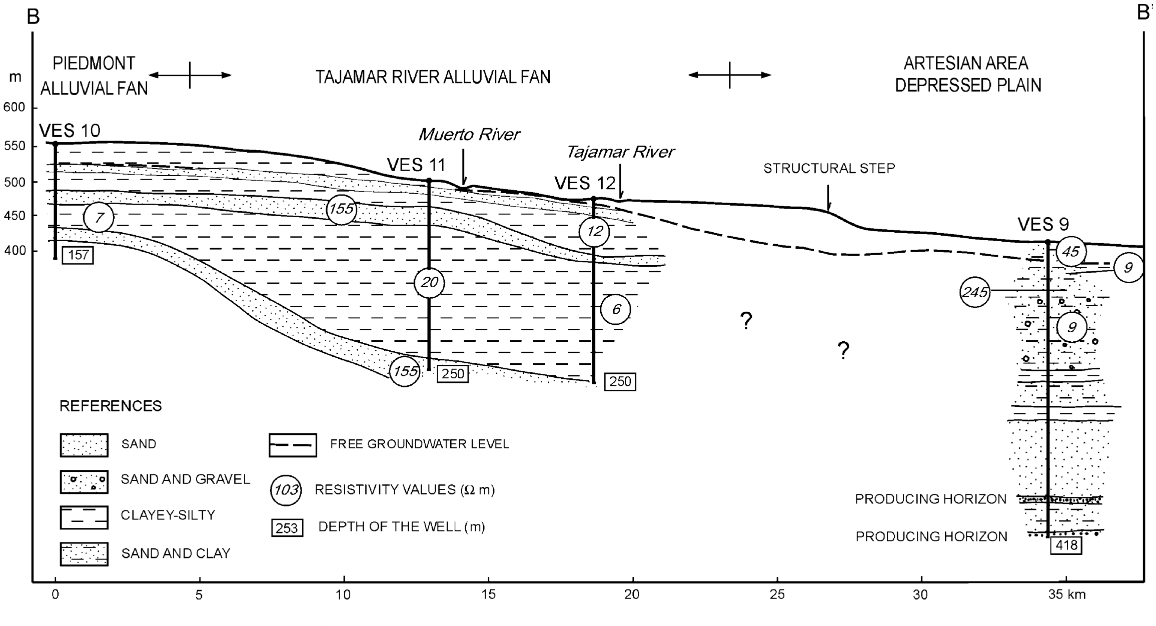

Fig. 8. Hydrogeological profile BB′, based on VES results and well log data, showing the depth of the free and confined aquifers.

Table 1
Interpreted resistivities and depths in the Burruyacu zone, Tucumán Province, Argentina

VES[a]	Resistivity (Ωm)	Depth (m)	VES	Resistivity (Ωm)	Depth (m)
1	36	0.8	2	16	7.4
	11	10		34	9
	36	70		1000	35
	7	83		103	46
	57	100		0.6	
	21	109			
	Resistive				
3	8.5	4.5	4	13	0.7
	245	12.5		1005	11
	12	42.5		66	22
	418			1314	90
				96	
5	20	13	6	7	3
	39	4		10	4.5
	11	5		254	12.5
	0.95	6		61	20
	282	93		212	33
	2.5			100	
				7	
7	149	1.5	8	25	1.7
	583	6.1		21	29
	87	18		232	55
	1727	80		25	70
	29			10	90
				3	
9	45	27	10	45	2
	9	60		7	4
	245	72		1448	16
	9			7	100
				Resistive	

[a] Vertical electrical soundings (see Fig. 2 for locations).

than 100 m deep) that catch from 2 to 10 layers. The specific flows are variable and range from 1 to 5.6 m^3/h/m, and the artesian flows range from 2 to 130 m^3/h.

4. Geoelectrical results

The apparent resistivity curves as a function of the half distance between the current electrodes (AB/2) are shown in Fig. 6. In addition, a theoretical sounding curve calculated from the interpreted model is plotted. Table 1 shows the resistivity and depth to the base of the different layers of the interpreted models for each sounding. The layer model for each site was used to make two representative profiles (Fig. 2, AA′ and BB′). Information from nearby wells was also used.

4.1. Interpretation of hydrogeological and geoelectrical results

Fig. 7 presents profile AA′, which extends from the piedmont of the Sierra de La Ramada (VES 2) eastward on the plain as far as La Tuna (VES 6). Free groundwater levels from 35 to 40 m have been defined at the piedmont, from 11 to 13 m near VES 4 and 5, and down to 33 m at the eastern end.

The recharge area is the piedmont zone where coalescent fans begin to develop. There is evidence of an eastward increase in the thickness of the finer material as shown by lithological logs and VES results. The discharge zone is located SE of the artesian area.

The artesian boundary (Fig. 5), which coincides with the union of piedmont small alluvial fans and the Tajamar River fan, is located at Colonia La Virginia, based on existing wells. The artesian boundary, as it may be observed in Fig. 7, is placed between VES 4 and 5, where the lithological pattern changes abruptly. On the basis of stratigraphy, it was possible to establish that in the profile's eastern zone, the cone cross-section has a minimum depth of 400 m.

Fig. 8 presents profile BB′, which is located between the Sierra de La Ramada piedmont at La Cruz (VES 10) and extends northeastward as far as El Triunfo (VES 9).

In this profile, there are three sectors corresponding to the existing fans. At VES 10, thick permeable layers prevail that might correspond to minor cones of the Sierra de La Ramada. Between VES 10 and 11, the Tajamar River cone begins to show up as far as the artesian boundary.

The depressed plain extends eastward with an important structural step.

The free groundwater level is located about 30 m deep in the piedmont, 5 m close to the Muerto River bed, 11 m near the Tajamar River bed, and it is deeper than 27 m toward the NE.

From the piedmont and under the phreatic level, there is finer material in a layer of increasing thickness as far as the artesian boundary. This layer includes sandy material with water at 63 m in the piedmont, 40 m in VES 11, and 80 m in VES 12. The structural control in the deposition of coarse material in the depressed plain should be emphasized.

The resistivity values obtained for the two aquifer systems confirm good water quality.

5. Conclusions

Past hydrogeological information about the Burruyacu Basin includes local, partial, and scattered data. In this work, a detailed study of the zone's hydrogeology was performed using VES soundings that allowed the establishment of the free groundwater levels and the correlation of the confined aquifers, as well as the aid of well data, which allowed a more regional description of the basin. The depth of investigation that may be achieved from VES results are limited by the noise of data resulting from the complexity of lithology.

With the support of existing wells and the VES results of the subsurface layers, it was possible to extrapolate the correlation of permeable zones in the low plain and to identify the different environments that make up the Burruyacu hydrogeological basin.

In addition, two differentiated aquifer systems were identified. The first is an upper unconfined aquifer system hosted in sediments of coarser grain size in the piedmont zone and the alluvial fan of the Tajamar River, with aquifer levels of 30–180 m deep. This system contains good water quality with yields apt for irrigation. Its surface and subsurface development slightly exceeds the border of the depressed plain.

Below, a lower confined aquifer system is formed by clayey levels intercalated with quartzy medium-to-coarse sands, with strong artesian pressure. These aquifer horizons are well developed throughout the depressed plain until they exceed the interprovincial boundary with Santiago del Estero. Water salinity increases remarkably eastward, and the exploitation flow volumes are lower because the sandy horizons are less permeable.

The geoelectrical prospection method, with a higher number of VESs and the support of subsurface geological information, can be used for programming the future development of the hydrogeological Burruyacu Basin.

Acknowledgements

This research was supported by Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, Argentina). The authors thank the research group of Hydrogeology of the Tucuman University (Argentina) for their assistance in the field, and thanks to Amalia Gonzalez and Gabriel Giordanengo for help with the drawings. The review comments of Dr Oscar Ruiz Huidobro are gratefully acknowledged.

References

Cooper, G.R.J., 1992. Forward modelling and inversion for Schlumberger resistivity soundings. http://www.wits.ac.za/science/geophysics/gc.htm.

Galindo, G., Pomposiello, M.C., Sainato, C.M., 1997. Análisis de perfiles gravimétricos en la cuenca hidrogeológica del noreste de Tucumán. I Cong. Nac. de Hidrogeología. Bahía Blanca, Bs.As. pp. 53–62.

Mon, R., Urdaneta, A., Suayter, L., 1971. Estudio geológico de la sierra del Campo y La Ramada, Prov. de Tucumán. Acta Geol. Lilloana XI-15.UNT.

Ruiz Huidobro, O., 1975. El paleozoico inferior del centro y sur de Salta y su correlación con el Grupo Mesón. Actas del I Cong. Arg. de Paleo. y Bioestr. S.M. de Tucumán 1, 91–107.

Stappenbeck, R., 1921. Reseña hidrogeológica del noreste de la Prov. de Tucumán y partes adyacentes. Direc. Nac. de Min. Geol. e Hidro. Buenos Aires, Argentina.

Tineo, A., García, J.W., Falcón, C.M., 1991. El cono aluvial del río El Cajón, Prov. de Tucumán, Rep.Arg. VI Congreso Geológico Chileno. Viña del Mar. Chile. ACTAS 1, 373–422.

Tineo, A., D'Urso, C., Falcón, C., García, J., 1992. Hidrogeología del sector oriental de la sierra de La Ramada, Provincia de Tucumán, Rep. Arg. I Congreso Hidrogeológico Latinoamericano. Merida, Venezuela.

Tineo, A., Falcón, C.M., García, J.W., Galindo, G., Rodriguez, G., Urso, C., 1994. Ambientes hidrogeológicos y los riesgos de contaminación en la prov. de Tucumán. Temas actuales de la hidrología subterránea. Univ. Nac. de Mar del Plata y CFI pp. 331–348.

Tineo, A., García, J.W., Falcón, C., Apella, C., Hidalgo, M., Rodriguez, G., D'Urso, C., 1997. Características hidroquímicas del borde oriental de la sierra Del Campo provincia de Tucumán, República Argentina. VIII Congreso Geológico Chileno. ACTAS 1, 810–814.

Torres Bruchman, E.T., 1978. Las clasificaciones climáticas de Köppen y Thornthwaite. Ediciones Sección Publicaciones de la Fac. de Agronomía y Zootecnia, Universidad Nacional de Tucumán. Serie Didáctica No. 48. S.M. de Tucumán, 27 pp.

Vozoff, K., Jupp, D.L.B., 1975. Joint inversion of geophysical data. Geophys. J. R. Astr. Soc. 42, 977–991.