ELSEVIER

Journal of South American Earth Sciences 21 (2006) 267–275

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

Groundwater basin of the Tulum Valley, San Juan, Argentina: A morphohydrogeologic analysis of its central sector

Gustavo Lloret [a,*], Graciela M. Suvires [a,b,*]

[a] *Instituto de Geología, Gabinete de Geología Ambiental, Facultad Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, San Juan, Argentina*

[b] *CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas), Buenos Aires, Argentina*

Received 1 January 2004; accepted 1 November 2005

Abstract

The geometry of a sector in the groundwater basin of the Tulum Valley has been studied to determine the shape, thickness, and vertical and horizontal distribution of the grain size, as well as the depositional environmental conditions of the Quaternary deposits that fill the valley. The geomorphologic features of the area have been investigated on the basis of aerial photographs checked with fieldwork. Three subsurface sections were prepared for a hydrogeological analysis of the area. These cross-sections were prepared by combining information from descriptions of well samples and interpretations of geophysical logs of wells and electric resistivity surveys. Within the studied area, the floor of the groundwater basin is asymmetrically shaped; the Quaternary deposits, which lie on an impervious or poorly pervious electrically conductive hydrogeologic basement of Late Tertiary age, reach a thickness of 670 m in the west and only 215 m in the eastern extreme. The Tulum Valley Basin is divided into two subbasins by a fault system trending NNE–SSW, which plays an important role in the configuration of the basin and the distribution of the Quaternary sediments units, as well as the distribution of aquifers in the subsurface. The western subbasin has a thicker cover and coarser grain sizes than the eastern one, where the sediments have more fine-grained intercalations and hardpans. The latter are probably pedogenic in origin.

Keywords: Groundwater basin; Arid region; Central western Argentina; System fault

Resumen

Se analiza la geomorfología y la hidrogeología de un sector ubicado en la parte central del valle de Tulum, provincia de San Juan, República Argentina, entre los paralelos de 31° 32′ y 31° 40′ de latitud sur y los meridianos de 68°19′ y 68° 27′ de longitud oeste de Greenwich. Las cinco unidades geomorfológicas mapeadas son: el cauce menor del río San Juan, la llanura de inundación, los cauces de los arroyos Agua Negra y Los Tapones, la planicie aluvial antigua y los médanos. Se construyeron tres perfiles hidrogeológicos de los que se desprende que: la forma de la cuenca del Tulum es asimétrica debido a la actividad tectónica ocurrida desde antes del Cuaternario a través del Sistema de fallamiento del Tulum. El relleno cuaternario, de oeste a este, se apoya sobre un basamento impermeable a profundidades que de oeste a este van desde los 670 a los 215 metros. La cuenca se subdivide en dos subcuencas, una al oeste de la falla de Tulum más profunda y otra al este de la falla de menor profundidad. Ambas con características hidrogeológicas diferentes para la prospección del agua subterránea.

1. Introduction

The present article outlines the geomorphological and hydrogeological characteristics of the central area in the Tulum Valley to obtain an interpretation of the evolution of the groundwater basin formed in this valley during Quaternary times. The area is situated approximately 15 km east of the capital of the province of San Juan in central western Argentina. It extends from 31°32′ to 31°40′S latitude and from 68°19′ to 68°27′W longitude (Fig. 1(a)).

Its relief is nearly flat, with altitudes of 600 m in the west and 570 m in the east and a regional slope to the SE. The Tulum Valley is a mountain shade desert created by the upheaval of the Andean Cordillera, which acts as a barrier for the cyclonic circulation from the west. Therefore, the area has a desert climate; its annual average rainfall is less than 100 mm, and its average humidity is approximately 54%. The annual potential

* Corresponding authors. Address: Avenida Ignacio de La Roza y Meglioli, Rivadavia. J 5400 San Juan, Argentina. Fax: +54 264 4265103.
E-mail address: graciela_suvires@yahoo.com.ar (G. Lloret).

0895-9811/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsames.2006.04.002

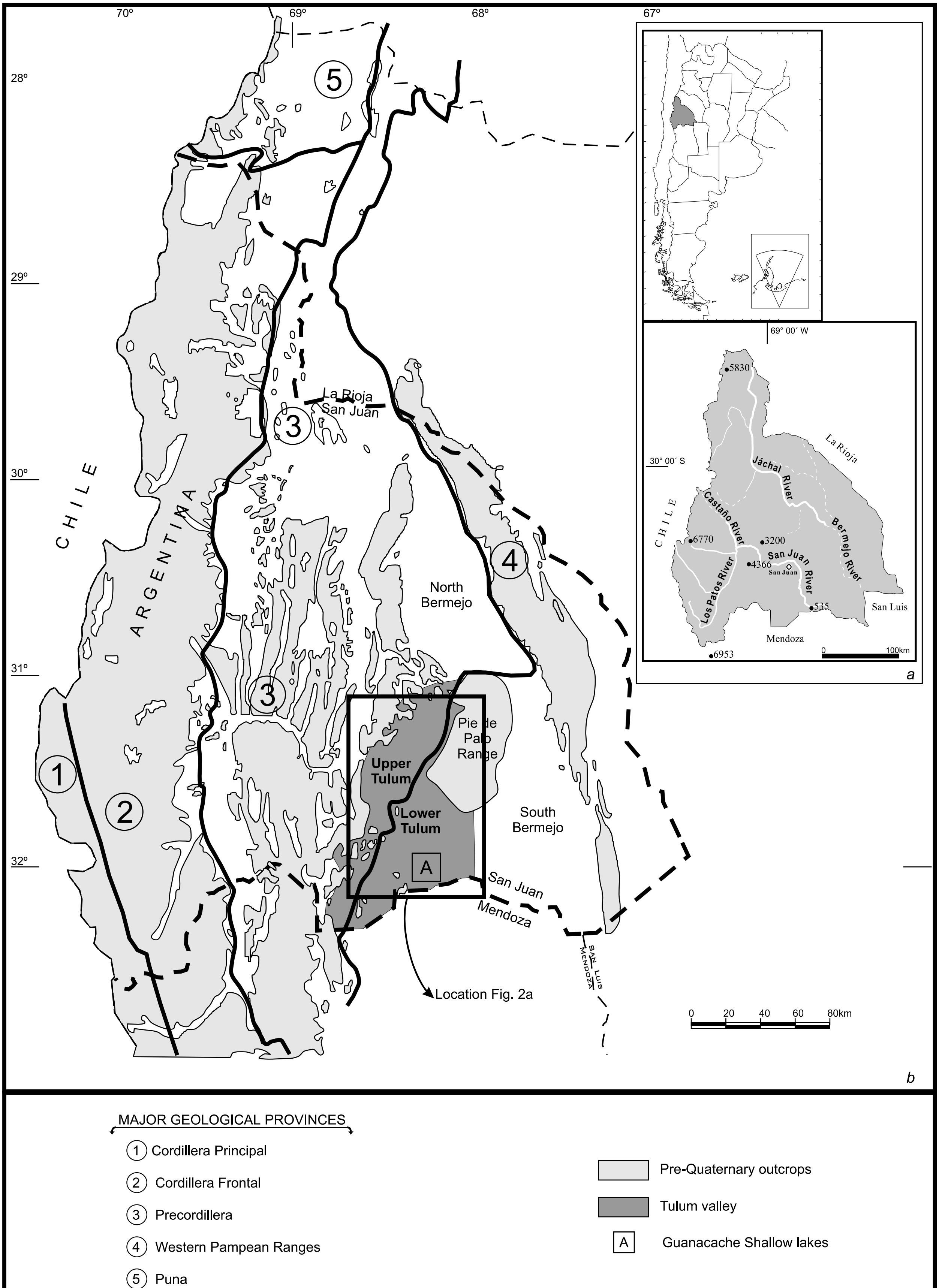


Fig. 1. (a) Location of the study area in the San Juan Province. (b) Outcrop distribution of the Pre-Quaternary units within the Geological Provinces (the heights are given in metres a.s.l.).

evapotranspiration is estimated to be 1500 mm. The maximum and minimum temperatures average 26 and 10 °C, respectively. This high evaporation and low rainfall have given rise to an important hydric deficit.

The Tulum Valley contains the main irrigated oasis in the province of San Juan and therefore is densely populated, with about 450,000 inhabitants. The most important urban center, the capital of the province, is situated here, and approximately 90% of the provincial economic activity is concentrated in this valley.

The regime of the San Juan River is variable during the year and subject to pluriannual cycles of drought and water abundance, according to the variations of the amount of snowfall in the high Andean mountains that feed the river system. The annual modulus for the period 1919–1976 reached 56.41 m^3/s. In December 1919, the absolute maximum reached 669.3 m^3/s, and in December 1968, the absolute minimum was 13.6 m^3/s.

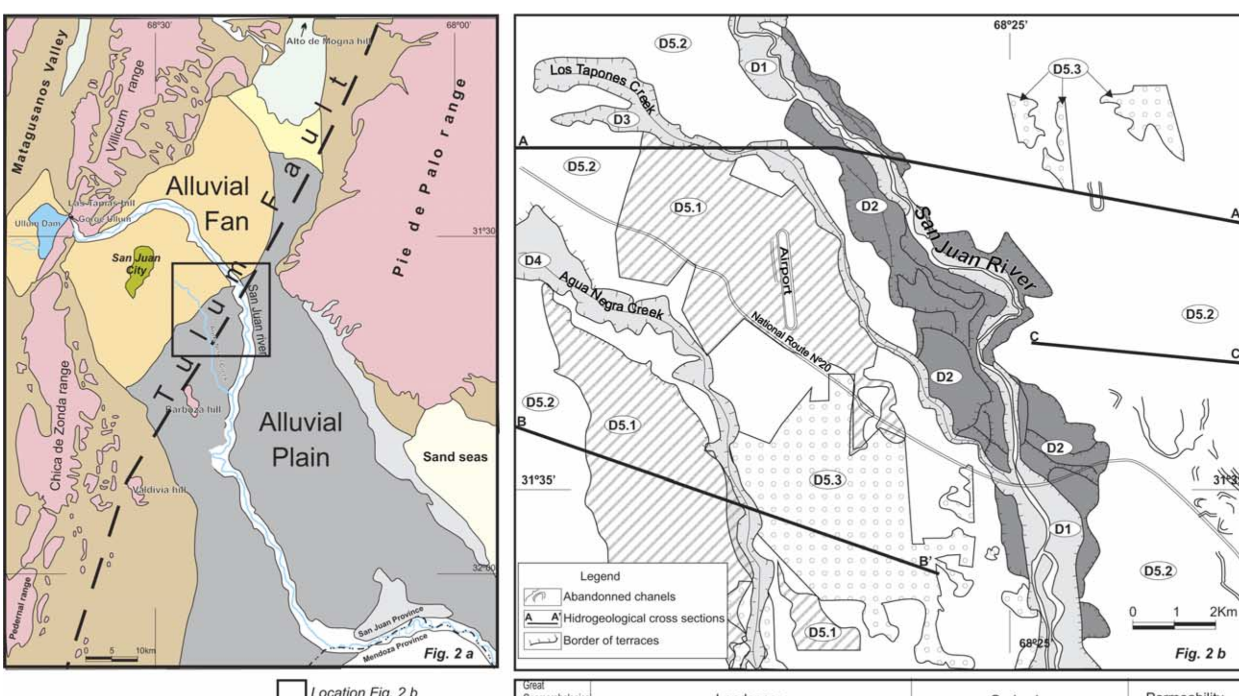
2. Description of the area

The Tulum Valley, whose extension is about 4000 km^2, is a tectonic depression filled with Quaternary alluvial and eolian sediments several hundreds of meters thick. It is bound to the east by the Sierra de Pie de Palo and to north and west by the mountains and hills of the eastern Andean Precordillera. The southern boundary is conventionally placed at the limit with the province of Mendoza, where the San Juan River turns its course to the east and debouches in the Guanacache shallow lakes (Fig. 1(b)).

Fluviatile deposits make up the greater part of the Quaternary sedimentary fill of this tectonic basin and have been transported and laid down by shifting courses of the San Juan River. These sediments have intercalations of windblown sands and loess and contain the developable aquifers in the valley, which have long been investigated in research by the Centro Regional de Agua Subterránea (Regional Center for Ground Water), a national state-owned agency with headquarters in the city of San Juan.

The San Juan River developed an alluvial fan and alluvial plain in the valley during Quaternary times. In the former, where the free aquifer is placed, the sediments are gravels and sands with good permeability, locally with discontinuous intercalations of silts and silty clays (Fig. 2(a)).

In the alluvial plain, the permeable intervals are fine gravels, gravelly sands, and sands that form string-shaped bodies deposited in meandering river channels. These sediments are interbedded with bank deposits made up of fine silty or clayed sands, silts, and clays, which comprise aquicludes or aquifuges because of their poor permeability or imperviousness.



Great Geomorphological Unit	Landscape	Grain size	Permeability
D: Tectonical depression of Tulum valley central sector	D1 Recent valley of San Juan river	———	Permeable
	D2 Flood plain and terraces level of the San Juan river	Gravel,fine gravel, sand, silt and clay	Permeable
	D3 Valley of Los Tapones creek	Sand, silt and clay	Permeable
	D4 Valley of Agua Negra creek	Sand, silt and clay	Permeable
	D5 Alluvial plain of San Juan river D5.1 With saline materials	Silt, clay and salts	Low permeability
	D5.2 With less saline material	Sand, silt and clay	Low permeability to permeable
	D5.3 With aeolian sediments	Sand	Permeable

Fig. 2. (a) Regional geomorphology. (b) Local geomorphology.

Therefore, the vertical and horizontal distribution of aquifers, aquicludes, and aquifuges is very irregular, as demonstrated by the difficult correlation of a given layer in electric logs of nearby wells.

The aquifers in the Tulum Valley are recharged not only directly by the San Juan River but also by water that infiltrates from the irrigation of some 77,000 ha cultivated here. In the alluvial fan, where the San Juan River crosses the free aquifer, several artificial recharge experiments have been carried out, as a result of which it is likely that water infiltrates at the approximate rate of 100 l/seg/ha (360 m^3/h/ha) (Rocca, 1970; Eder et al., 1978; Zambrano, 1986).

The aquifers in the area are exploited for irrigation and human and industrial use. The groundwater is produced from hundreds of state-owned wells grouped in batteries and by approximately 10,000 wells drilled by private companies in farms (Wetten, 1997).

The electric conductivity of the groundwater in the valley varies from 500 μΩ/cm in the proximal part of the alluvial fan to 5000 μΩ/cm in the distal part of alluvial plain (Guimaraes, 1978).

3. Methodology

The local geomorphology was determined with the interpretation of stereo pairs of aerial photographs (scale 1:25,000). The photographs also were used to observe the distribution of permeable intervals in the alluvial fan and plain, in those areas where the distribution of channel and bank deposits has not been obliterated by farming. The subsurface distribution of permeable intervals was studied mainly with electric logs run on many wells in not only the area considered herein but also the greater part of the Tulum Basin. Most of these logs recorded one resistivity and the self-potential curves. Because there is a net resistivity contrast between the channel deposits (permeable) and bank deposits (made up by silts, clays, and very fine silty sands, with low permeability or impermeable), it was possible, in most cases, to determine tops, bases, and thicknesses of the individual aquifers.

The lithologic makeup of the sediments was determined by description of drill cuttings obtained from the wells. However, these samples do not show the tops and bases of each permeable interval drilled.

Few wells were drilled down to the base of the Quaternary sediments. Nevertheless, the thickness of the latter can be determined by resistivity contrasts shown by electric resistivity tests. The Quaternary sediments show moderate to high resistivities, because they contain freshwater in their permeable intervals, whereas the Tertiary basement, which contains salty water, is electrically conductive, with resistivities lower than 10 Ωm in most cases.

4. Regional geomorphology

Rocca (1970) studied the occurrence of exploitable groundwater flow in the Tulum Valley and related it to five geomorphologic units of regional extension, outlined next (Figs. 1(b) and 2(a)).

4.1. Mountain chains

The valley is limited in its eastern and western rims by mountain ranges belonging to two different geological provinces, Western Pampean ranges and Precordillera. The former is represented by the Pie de Palo Range situated east of the basin. The highest summit of this range has an altitude of 3162 m a.s.l.; most outcrops are of Precambrian–Early Paleozoic metamorphic and igneous rocks, with isolated outcrops of Late Tertiary sedimentary rocks at the rims. The Precordillera ranges, namely, Villicum, Chica de Zonda, and Pedernal, make up the western boundary of the Tulum Valley and are 1800–2000 m a.s.l. high. The oldest exposures are of limestones and dolomites laid in a Cambrian–Early Ordovician carbonate platform (Baldis and Chebli, 1969). Other pre-Quaternary units exposed in the nearby Precordillera ranges are Siluro-Devonian marine clastics in small outcrops, Late Paleozoic continental deposits, and Mio-Pliocene synorogenic continental clastics.

4.2. Piedmont hills

This unit comprises (1) the hills of the Alto de Mogna (Mogna High), which make up the northern boundary of the Tulum Valley and separate it from the Bermejo River Valley, and (2) Las Tapias hills, situated to the north of the Ullum gorge, through which the San Juan River enters the Tulum Valley. The altitude of both hill systems is approximately 800 m a.s.l. They are characterized by outcrops of a coarsening-up sequence of Mio-Pliocene sedimentary rocks. The uppermost unit, commonly known as the Mogna Formation, is made up of polygenic conglomerates, predominantly grayish and slightly cemented. These deposits are folded and thrusted, unlike the Quaternary cover, which lies unconformably on them.

4.3. Piedmont alluvial plain

This unit rims the basin along the greater part of its perimeter. It is made up by several piedmont surfaces, gently sloping toward the basin interior. Generally, these piedmont surfaces are grouped in two main units: (1) the older piedmont plains were raised during the Quaternary as a result of several neotectonic phases. Where the erosion has been more intense, at the edges of these piedmont terraces, the Quaternary cover is interrupted by small outcrops of the Tertiary base, as commonly observed in the Precordilleran rim of the Tulum Valley. The Quaternary cover, generally some meters or 10s of meters thick in these piedmont surfaces, consists predominantly of gravels, partly sandy, the clasts of which are coated by a veneer of desert varnish. (2) The younger piedmont plain contains gravels without desert varnish. These deposits are still accumulating, partly in small coalescent alluvial fans that form bahadas. The distal parts intercalate with sediments of the alluvial fan or alluvial plain of the San Juan River.

4.4. Tulum Valley

As noted previously, the Tulum Valley covers an extension of 4000 km^2 and is made up of two main geomorphologic units. First, the alluvial fan of the San Juan River extends over 1000 km^2, and the alluvial plain occupies the remaining 3000 km^2 of the valley. The alluvial fan, at its proximal part, is made up of gravels and coarse sands, with occasional intercalations of silts, partly fine sandy or clayey with little areal extension. Part of the fan surface is covered by windblown loessic material. As expected in alluvial fans, the grain size of the gravels tends to decrease away from the fan apex. In the distal part, the gravels and sands are finer and the interbedded silty layers more frequent. The thickness of the Quaternary deposits, which does not surpass tens of meters near the apical part, increases to about 700 m in some areas in the central and distal parts of the fan. The groundwater stored in its pervious intervals occurs as a free aquifer. Confining or semiconfining conditions are met at the edge of the fan, where it grades laterally into the alluvial plain of the San Juan River.

Second, the alluvial plain, which has a gentle slope to the east and southeast, is made up of channel and bank deposits, as noted previously. In addition, these fluviatile sediments are interbedded with windblown deposits of dune sands and loess. These eolian materials are more frequent in the distal parts of the alluvial plain, commonly present as sheet-shaped bodies. Many dune sands bear water, but, as is the case with the channel deposits, these aquifers are confined or semiconfined.

4.5. Interior mountains

These mountains comprise the Barboza and Valdivia hills, the former 770 m a.s.l. in altitude and the latter 830 m a.s.l. at its summit. These low mountains stand about 200 to nearly 300 m above the surface of the surrounding plains. In both elevations, the Precambrian–Early Paleozoic metamorphic basement crops out, with small exposures of Late Paleozoic and Tertiary sedimentary materials. These isolated mountains thus are part of the Western Pampean ranges and are bound by a NNE–SSW-trending system of faults (Tulum fault system) (Zambrano, 1986).

5. Local geomorphology

By means of an interpretation of aerial photographs checked in the field, five geomorphologic units were identified in the area covered by the present study (Fig. 2(b)). First, the recent valley of the San Juan River (D1) contains the river course and the alluvium deposited in it, which consists of poorly sorted gravel, fine sandy gravel, and coarse to medium sand (Suvires and Zambrano, 2001). The clasts of the gravels derive from sedimentary and igneous rocks coming from the Cordillera and Precordillera. The San Juan River originates in the junction of the Los Patos and Castaño rivers at the western margin of the Precordillera. Both rivers have their catchment basins in the Principal and Frontal Cordilleras, and their headwaters are fed mainly by snow accumulations. The grain size of the gravels in the San Juan River tends to diminish as it crosses the Precordillera ranges, whereas the proportion of sand increases. The river enters the Tulum Valley through the Ullum gorge, in the Las Tapias hills, at 730 m a.s.l. and reaches its base level at the Guanacache shallow lakes at 535 m a.s.l. In addition to gravels and sands, lenticular bodies of fine sediments occur in the area, such as silty fine sands or sandy silts derived from the floodplain or deposited by wind. Nevertheless, the sediments in this unit allow a rapid infiltration of the river waters.

Second, the floodplain and terrace levels of the San Juan River (D2), which form a 1–3 km wide zone parallel to the river valley, trend from NW to SE and, downstream, from N to S in the area. The sediments found here have predominantly fine textures: fine sands and silts upstream and silts and clays downstream. In some tracts of the river, this floodplain and related terraces widen and extend deeply into the alluvial plain. Part of this unit is covered by natural vegetation or vineyards or other cultivated areas.

Third, the present river bed of the Los Tapones Creek (D3) should be considered together with the following unit. Fourth, the present river bed of the Agua Negra Creek (D4), along with D3, has fine-textured sediments: fine sands, silts, clays, and silty clays. Both creeks, which run from NNW to SSE and debouch into the San Juan River, are ephemeral but supplied with water by artificial drainage channels and phreatic discharge. Abundant natural hydrophile vegetation grows along the margins of both courses.

Fifth, the greater part of the area is covered by sediments of the alluvial plain of the San Juan River (D5), here with a meandering course. The deposits are predominantly fine sand—partly with medium and, occasionally, coarse or gravelly sand—deposited in the meandering channels, as well as silts or clays laid in oxbow lakes, levees, or floodplains. Some saline soils have developed due to the concentration of sodium chloride; calcium, magnesium, or potassium sulphates; and sodium carbonate and other salts as a consequence of the capillary rise of salty water, which subsequently evaporates on the surface, giving rise to saline soils and crusts. In this alluvial plain also are found fine, quartzose eolian sands, with subordinate grains of feldspar and lithic material. At the surface, this windblown sand forms discontinuous dune clusters, generally not higher than 3 m.

6. Hydrogeologic cross-sections (Figs. 3 and 4)

Lloret (2000) prepared three cross-sections in the area under consideration. The section A–A′ runs W to E and is 14 km long, whereas B–B′ trends from NW to SE and is 9 km long, and C–C′ has a WNW –ESE direction and a length of 3.4 km. These sections coincide in length and direction with those prepared by the Centro Regional de Agua Subterránea (Regional Center for Ground-Water) in 1978, based on information from lithologic columns of wells and interpretations of

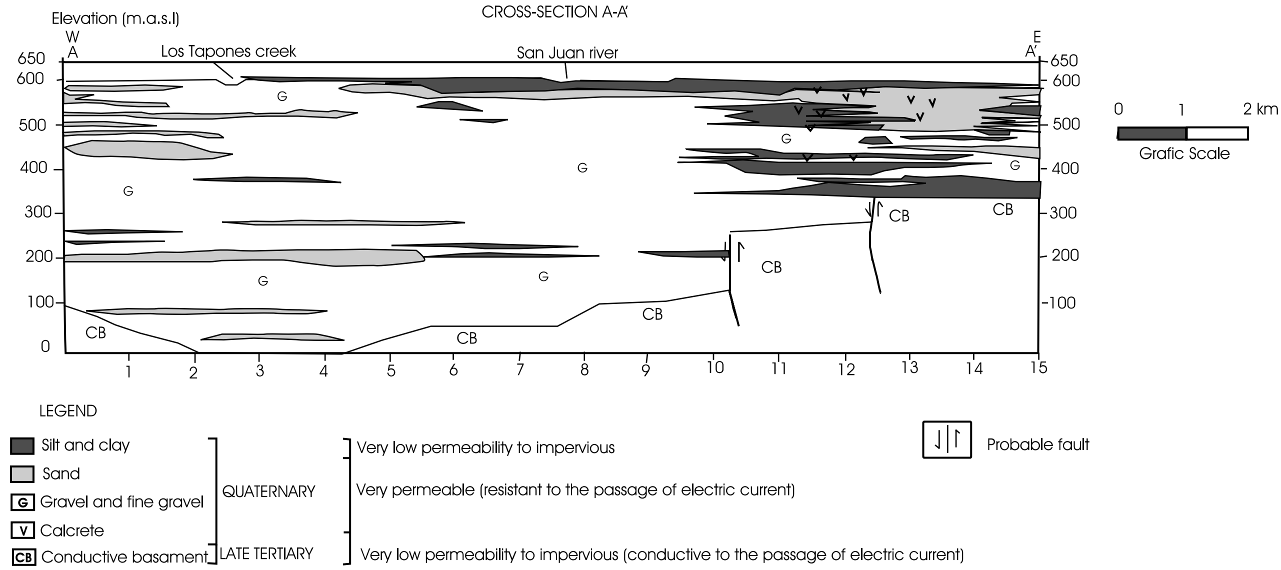


Fig. 3. Hydrogeological section A–A′ (from Lloret, 2000).

electrical resistivity surveys (Eder et al., 1978). The A–A′ section shows that the top of the impervious basement has an irregular configuration, as a result of which the Quaternary basin is asymmetrical in area. This top cannot clearly be identified across the length of the section because it is not well defined in some electrical resistivity tests. But in the western boundary, the basement top has been detected at a depth of 500 m, whereas the maximum depth in this section, 602 m, was found beneath Los Tapones Creek. The basement top rises to the east and was found at 248 m depth at the eastern extreme of the section. Some sharp variations of the depth of the basement top were detected and interpreted as caused by faults, confirmed by wells drilled into this basement. These faults belong to the Tulum fault system (Zambrano, 1986), which gave rise to the basement blocks exposed in the Barboza and Valdivia isolated mountains. These fractures thus have produced changes in the slope of the basement, as well as divided the Tulum Valley Basin into two subbasins, namely, Upper and Lower Tulum.

The Quaternary basin fill consists of alternations of layers of coarse material as gravels and sandy gravels, with beds of fine-grained sediments as silts, fine sands, and clays. This interbedding of pervious and impervious or poorly pervious materials creates semiconfined or confined aquifers. In the eastern part of the section, situated in the San Juan River alluvial plain, are calcretes at different depths. The western part of the A–A′ section is situated in the distal zone of the alluvial fan of the San Juan River. Here, the aquifer is free but grades into the

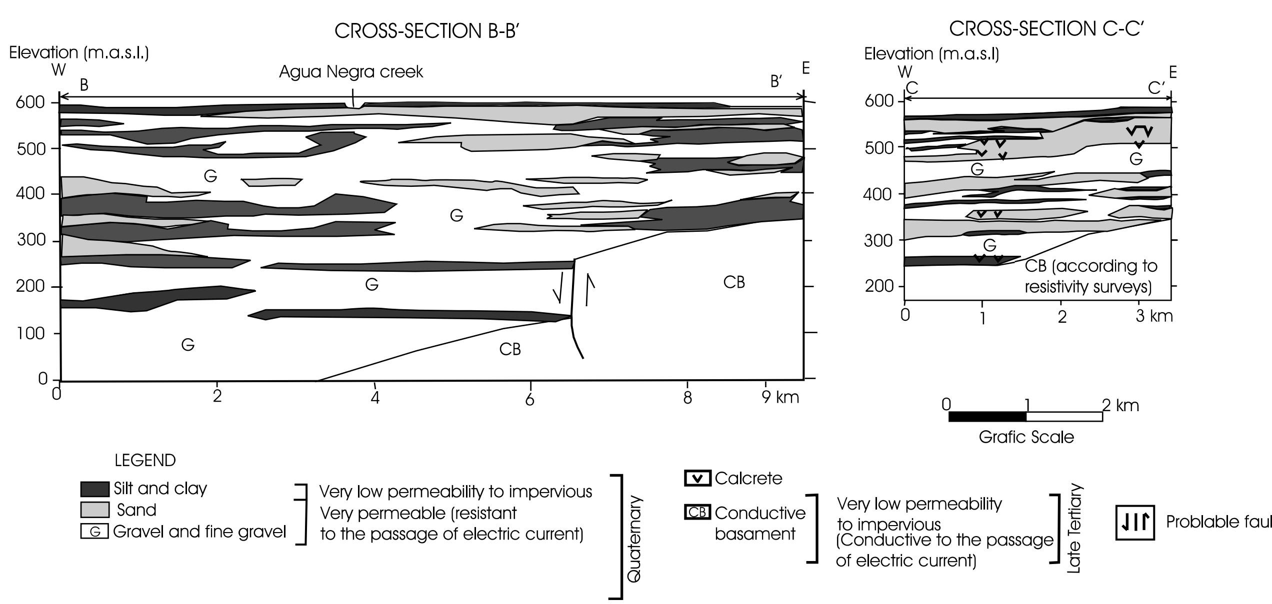


Fig. 4. Hydrogeological cross-sections B–B′ and C–C′ (from Lloret, 2000).

confined aquifers of the alluvial plain as the impervious intercalations become thicker and more continuous to the east.

The irregular horizontal and vertical distribution of sediments observed in this cross-section can be explained by the fluvial environment in which these deposits were laid, that is, by variations in the river discharge and the flow regime—and thus, by the erosion potential and frequent flood periods during the evolution of the basin.

In the three sections, the Quaternary sedimentary bodies show that the permeable intervals have lens-shaped sections;

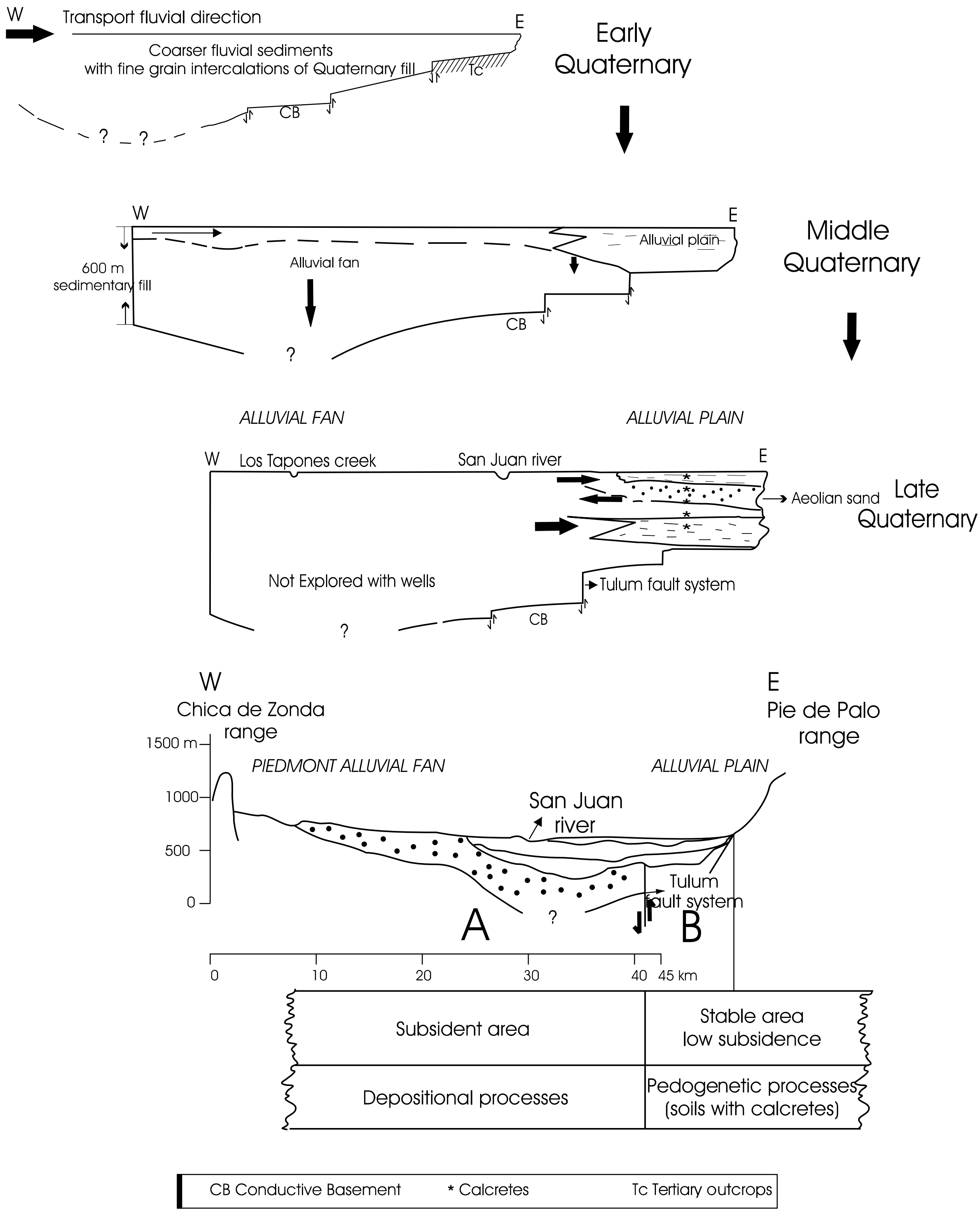


Fig. 5. Evolution during of the Quaternary and Interpretativen cross-sections of a sector inside Tullum Valley.

these sediments were deposited in ancient river channels and therefore are string shaped. The horizontal variations in grain size within each permeable body suggest that the river channels in which such sediments were deposited were meandering, in coincidence with what is observed in the surface.

The impervious or poorly pervious intercalations between the aquifers, which are composed by fine silty sands, silts, and clayed silts, are bank deposits. Their thickness and lateral continuity increase to the east, that is, toward the distal plain.

A similar textural distribution can be observed in sections B–B′ and C–C′ (Fig. 4). In B–B′, the basement top depth takes place at 670 m at its western extreme, whereas to the east, this top is found 255 m beneath the surface. This elevation does not take place gradually but with sharp changes in short distances, which has been interpreted as caused by the presence of a fault of the Tulum system. A similar eastward elevation of the basement is observed in cross-section C–C′.

7. Evolution of the Quaternary basin (Fig. 5)

On the basis of the available subsurface information, the evolution of the Tulum Valley Basin during the Quaternary can be interpreted as the following sections describe.

7.1. Early Quaternary

The Tulum Valley, situated in an area submitted to tectonic compression, was deformed, as a result of which an important subsidence took place. Maximum subsidence occurred in the western part of the basin, and therefore, its base was asymmetrical already during this early stage. The basement upon which the Quaternary sediments began to accumulate consists of two main units, according to electrical resistivities. The upper unit, characterized by its low resistivity (called ‘Conductive Base’ (CB)) is made up of sedimentary rocks of Miocene–Pliocene, and perhaps even Early Pleistocene, age. These rocks are impervious or, where they contain porous intervals, poorly pervious and saturated with saline or brackish water. The lower unit, or resistive base, consists of Precambrian metamorphic rocks or Paleozoic highly indurates sedimentary rocks. These basement rocks are compact and practically impervious, which explains their high resistivity. Both conductive and resistive basements have been tilted and faulted by the Late Tertiary Andean compressive tectonism.

According to subsurface data, the Tulum fault system was active during the Early Quaternary, so it is highly probable that the basin was already divided in two subbasins, namely, Upper Tulum and Lower Tulum. The former received coarse fluvial sediments, especially after the glaciation events in the Andean region, whereas the Lower Tulum subbasin was filled with finer sediments deposited in an alluvial plain. This distribution of facies is very similar to that of the present day.

7.2. Middle Quaternary

The basement continued to subside, and the Tulum fault system remained active, with an increase in the differential displacements of the small basement blocks created by this system of faults. It is estimated that the deeper parts of the basin, situated in its western zone, subsided between 300 and 400 m during the Middle Quaternary, but this hypothesis needs confirmation with further research. The areal distribution of textures—that is, predominantly coarse sediments in the Upper Tulum subbasin and finer materials in the Lower Tulum subbasin—continued during this period.

7.3. Late Quaternary

The subsidence of the basement intensified, and consequently the thickness of the Quaternary fill increased to its present values. In the eastern part, near Pie de Palo Range, the subsidence rate was much lower, probably with periods of relative tectonic stability. This rate allowed the development of pedogenetic processes and the formation of calcrete, which are found at different depths, as shown in cross-sections A–A′ and C–C′ (Figs. 3 and 4). The calcretes thus formed are interpreted as indicative of colder and more humid conditions compared with the present arid and dry conditions in the area.

8. Conclusions

The Tulum fault system gave rise to an asymmetric shape to the basin, which can be divided into a western and eastern sector. This basin geometry is a result of Late Tertiary and Quaternary tectonic episodes. The greatest subsidence during the Quaternary took place in the western part, as indicated by the no less than 670 m thick Quaternary sediments, as well as coarser grain sizes. The Tulum fault system also greatly influenced the present-day shape and pattern of sedimentary textures of the basin and has controlled the distribution of the aquifers in the subsurface.

The petrologic composition of the Quaternary sedimentary fill indicates that the greater part of this material came from the Frontal and Principal Cordilleras. The sediments derived from the Precordillera occur in subordinate proportion.

The greater parts of these Quaternary deposits were laid in the alluvial fan and alluvial plain of the San Juan River. In the former, the sedimentary textures are coarser, as expected, and except for a few clayey or silty intervals, have good permeability, so that the aquifers are generally sheet shaped. These therefore are the areas with free aquifers in the basin.

The permeable layers in the subsurface of the alluvial plain of the San Juan River have lens-shaped sections that, together with grain size variation patterns, indicate they were laid in meandering fluvial channels. The fine-textured intervals are interpreted as bank deposits (levees, floodplains, and oxbow lakes) or laid by the wind (loessic sheets). Unlike in the alluvial fan, most aquifers in the alluvial plain are confined, due to the alternation of permeable and tight layers.

The calcretes and duricrusts, especially in the younger Quaternary layers, have been detected only in the eastern part of the basin, which had low subsidence and where pedogenetic processes probably took place.

Acknowledgements

We thank Drs J. Zambrano and C. Wetten for their invaluable collaboration in the geological discussions and their assistance during the work. This paper is part of the Project PIP 02053-CONICET and P 21E/364, San Juan National University, Argentina, ‘Applied geomorphologic mapping to soils of the Tulum Valley, San Juan province, Argentina’.

References

Baldis, B., Chebli, G., 1969. Estructura profunda del área central de la Precordillera sanjuanina. IV Jornadas Geológicas Argentinas. Actas 1, Buenos Aires, Argentina, pp. 47–66.

Eder, J., Rodriguez, J.C., Coria, A, 1978. Subsurface Geological Study. Tulum valley. Geological cross- sections and possible correlations to Quaternary age Alluvional deposits, from a Lithological–Geophysical data base, T 1, INA - CRAS, San Juan, Argentina, pp. 23–35.

Guimaraes, R., 1978. Estudio de la evolución salina del agua subterránea-valle de Tulum, San Juan. P 173.CRAS. San Juan, Argentina.

Lloret, G., 2000. Hidrogeología del sector central del valle de Tulum. Departamentos de Caucete, 9 de Julio, San Martín y Santa Lucia. Trabajo final de Licenciatura. FCEFN. UNSJ (inédito), San Juan, Argentina.

Rocca, J.A., 1970. Geología de los valles de Tulum y de Ullum-Zonda. Provincia de San Juan. PASNOA, Tomos 1 y 2, CRAS, San Juan, Argentina, pp. 1–210.

Suvires, G.M., Zambrano, J.J., 2001. Unidades geomorfológicas cuaternarias del valle de Tulum, San Juan, Argentina. XI Cong. Uruguayo y III Congreso Geológico Uruguayo. Montevideo. Actas en CD y Abstracts, Uruguay, p. 9.

Wetten, C, 1997. Síntesis del conocimiento hidrogeológico del valle de Tulum. Áreas críticas en Rivadavia, Caucete, San Martín, Sarmiento, Albardón y 25 de Mayo, FCEFN, UNSJ, San Juan, Argentina, vol. 1 y 2, pp. 1–210.

Zambrano, J.J., 1986. Actualización geológica del valle de Tulum en la provincia de San Juan. T 1, Centro Regional de Aguas Subterráneas, San Juan,. Argentina, pp. 1–198.