Hydrogeology of the Mercosul aquifer system in the Paraná and Chaco-Paraná Basins, South America, and comparison with the Navajo-Nugget aquifer system, USA

L. M. Araújo · A. B. França · P. E. Potter

Abstract The giant Mercosul aquifer system consists of Triassic-Jurassic eolian-fluvio-lacustrine sandstones confined by Cretaceous basalt flows, and it covers about 1,195,500 km^2 (461,583 $miles^2$) in South America. The aquifer system encompasses all of the Paraná Basin and part of the Chaco-Paraná Basin and is one of the world's largest. The eolian Botucatu Sandstone and its equivalents form an important part of this system. Maps of structure, thickness of overlying rocks, and water temperature, and a potentiometric map, all based on 322 wells, define hydrogeologic characteristics and provide the basis for establishing guidelines for the long-term equilibrium use of this important multinational aquifer system. The Mercosul aquifer system is divided into two domains – the larger and better understood Paraná Basin and the smaller and less well understood Chaco-Paraná Basin. Most of the northern part of the Paraná Basin has axially-directed groundwater flow, whereas the southern part of the aquifer discharges mostly to the southwest into the Corrientes Province of Argentina, with negligible discharge into the Atlantic Ocean. The Mercosul aquifer system is conservatively estimated to have been flushed at least 180 times since deposition. Various factors are responsible for this flushing, including appreciable rainfall since the end of the Cretaceous Period, probable uplift of the basins' borders in Late Cretaceous time, simple basin geometry, long-term riverine and groundwater flow to the southwest (ancestral and present Paraná River Systems), and stable cratonic setting.

Key hydraulic properties of the Mercosul aquifer system are compared to those of the eolian Jurassic Navajo-Nugget System of the western United States. The results demonstrate the importance of tectonics and climate on the evolution of sub-continental aquifer systems.

Résumé Le gigantesque système aquifère de Mercosul est constitué de grès du Trias et du Jurassique d'origine éolienne et fluvio-lacustre, recouverts par des coulées basaltiques du Crétacé; il couvre environ 1,195,500 km^2 en Amérique du Sud. Ce système aquifère occupe la totalité du bassin du Parana et une partie de celui du Chaco-Parana ; c'est l'un des plus étendus au monde. Les grès éoliens de Botucatu et leur équivalent forment une grande partie de ce système. Des cartes de la structure et de l'épaisseur de la couverture et de la température de l'eau et une carte piézométrique, basées sur 322 puits, définissent les caractéristiques hydrogéologiques et fournissent les bases nécessaires à l'établissement des recommandations pour une utilisation garantissant un équilibre durable de cet important système aquifère international. Le système aquifère de Mercosul est divisé en deux domaines, celui du bassin du Parana, le plus étendu et le mieux connu, et celui du Chaco-Parana. Presque tout le nord du bassin du Parana est soumis à un écoulement souterrain orienté selon son axe, tandis que la partie sud de cet aquifère s'écoule surtout vers le sud-ouest dans la province de Corrientes en Argentine, avec un écoulement négligeable vers l'Océan Atlantique. On estime que le système aquifère de Mercosul a été vidangé au moins 180 fois depuis son origine. Différents facteurs sont responsables de ces vidanges, dont des précipitations notables depuis la fin du Crétacé, le soulèvement probable des bordures du bassin au Crétacé supérieur, la géométrie simple du bassin, les écoulements à long terme des rivières et des eaux souterraines vers le sud-ouest (les systèmes du fleuve Parana anciens et actuel) et la situation stable du craton.

Les propriétés hydrauliques essentielles du système aquifère de Mercosul sont comparées à celles du système de Navajo-Nugget, établi dans les formations éoliennes jurassiques de l'ouest des États-Unis. Les

Received, September 1997
Revised, December 1998
Accepted, January 1999

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résultats montrent l'importance de la tectonique et du climat sur l'évolution de systèmes aquifères à l'échelle subcontinentale.

Resumen El sistema acuífero Mercosul está formado por areniscas eólico-fluviolacustres del Triásico-Jurásico, confinadas por flujos basálticos del Cretácico. Este gigantesco acuífero sudamericano cubre una extensión de 1,195,500 km^2. El sistema comprende toda la Cuenca del Paraná y parte de la de Chaco-Paraná y es uno de los mayores del mundo. Las areniscas eólicas de Botucatú forman una parte importante del sistema. A partir de información en 322 pozos se han podido trazar mapas de espesor, estructura, potencia de la capa confinante, temperatura del agua, así como una piezometría. Estos mapas proporcionan una base para establecer la gestión sostenible del acuífero. El acuífero Mercosul se divide en dos dominios: la Cuenca del Paraná, la mayor y más conocida, y la Cuenca de Chaco-Paraná, más pequeña y menos estudiada. El flujo en la parte norte de la Cuenca del Paraná es de tipo axial, mientras que en el sur la mayor parte de la descarga es hacia la Provincia de Corrientes, Argentina, con una pequeña descarga hacia el Océano Atlántico. El acuífero ha sido lavado por el agua subterránea un mínimo de 180 veces desde su deposición. Los factores responsables de este lavado incluyen el aumento de la pluviometría a partir de finales del Cretácico, la elevación de la cuenca por procesos tectónicos en el Cretácico Superior, la simplicidad geométrica, la persistencia de los flujos superficial y subterráneo en dirección sudoeste y la presencia de un área cratónica.

Las principales propiedades hidráulicas del acuífero Mercosul se comparan con las del Sistema eólico Navajo-Nugget, en el oeste de los Estados Unidos de América, de edad Jurásica. Los resultados muestran la importancia de la tectónica y el clima en la evolución de los sistemas acuíferos subcontinentales.

Key words South America · Mercosul aquifer system · general hydrogeology · paleohydrology · sedimentary rocks

Introduction

This paper reports on an aquifer of subcontinental scale in South America and compares it with the Navajo-Nugget aquifer system of western United States. Thus it provides two case histories for the study of continental and subcontinental aquifer systems, as reviewed by Garven (1995).

The geohydrologic system (Maxey 1964) of this study is located in the Paraná and Chaco-Paraná Basins of southern South America, in parts of Brazil, Argentina, Paraguay, and Uruguay, and it includes rocks of Cretaceous, Jurassic, and Triassic age. Locations are shown in *Figure 1*, and hydrostratigraphy is summarized in *Table 1*. The Jurassic Botucatu Formation and its equivalents, the Misiones Formation in Argentina and Taquarembó Formation of Paraguay and Uruguay, form its principal aquifer and overlie a less productive Triassic aquifer that includes the Pirambóia and Rosário do Sul Formations of Brazil and their equivalents, the Buena Vista Formation of Argentina and Uruguay. Overlying both aquifers are Cretaceous basalts of the Serrra Geral Formation in Brazil and Argentina and their equivalents, the Alto Paraná Formation of Paraguay and the Arapey Formation of Uruguay, which form an aquitard. Above the basalts in parts of the Paraná Basin are red beds of the Bauru Group (Fernandes and Coimbra 1996). Underlying both aquifers are diverse Permo-Triassic sedimentary rocks, which also form an aquitard. The total area covered by this geohydrologic system is 1,195,500 km^2 (461,583 miles^2), one of the world's largest. This system has an estimated pore volume of 57×10^{12} m^3 (2×10^{15} ft^3).

The name Mercosul aquifer system was given to this system by Araújo et al. (1995), who first systematically mapped its individual geohydrologic units across the Paraná and Chaco-Paraná basins. The term "Mercosul" was chosen because it reflects the new economic trading zone of Brazil, Argentina, Paraguay, and Uruguay, which includes all the area of the Paraná and Chaco-Paraná Basins. Subsequently, the name "Guarani aquifer" was verbally proposed in a congress

Table 1 Stratigraphy and hydrostratigraphy of the Mercosul aquifer system

Hydrostratigraphic unit		Age	Brazil	Argentina	Paraguay	Uruguay
Aquifer		Cretaceous	Bauru Group	Quebrada Monardes Fm.	Acaray Fm.	Ascencio Fm.
Aquitard/aquifer (confining layer)		Cretaceous	Serra Geral Fm.	Serra Geral Fm.	Alto Paraná Fm.	Arapey Fm.
Mercosul aquifer system	Aquifer	Jurassic	Botucatu Fm.	Taquarembó Fm.	Misiones Fm.	Tacuarembó Fm.
	Aquifer	Triassic	Pirambóia/ Rosário do Sul Fms.	Buena Vista Fm.	Misiones Fm.	Buena Vista Fm.
Aquitard/aquifer		Permo – Triassic	Rio do Rasto Fm.	Victorino Rodrigues Fm.	Unnamed	Yaguary Fm.

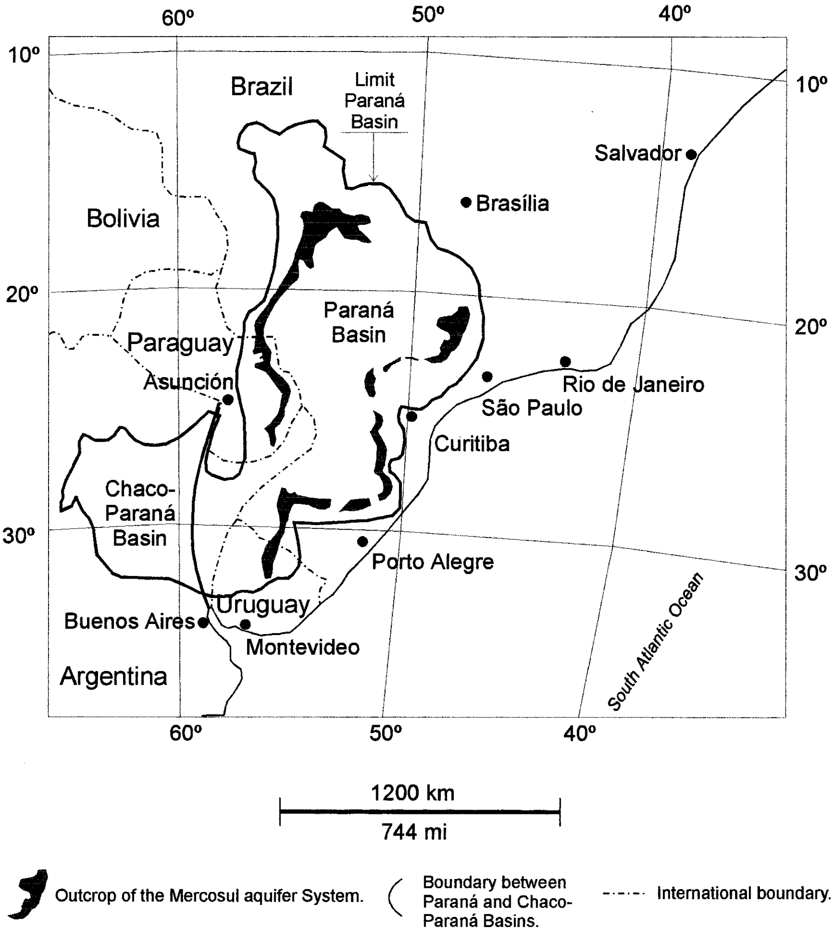


Figure 1 Location of the Mercosul aquifer system in the Paraná and Chaco-Paraná Basins, South America

by Anton (1994; cited in Rocha 1997) and by Rosa et al. (1998), in honor of the Indians who lived in southern South America.

The Mercosul aquifer system underlies an area of about 839,800 km^2 in the Paraná Basin and is present in parts of seven Brasilian states: Mato Grosso do Sul (MS, 213,200 km^2), Rio Grande do Sul (RS, 157,600 km^2), São Paulo (SP, 155,800 km^2), Paraná (PR, 131,300 km^2), Goiás (GO, 55,000 km^2), Minas Gerais (MG, 51,300 km^2), Santa Catarina (SC, 49,200 km^2), and Mato Grosso (MT, 26,400 km^2). The aquifer also covers about 355,700 km^2 in the eastern part of the Chaco-Paraná Basin in Argentina (225,500 km^2), Paraguay (71,700 km^2), and Uruguay (58,500 km^2). The major structures of the Paraná and Chaco-Paraná Basin are several arches and many lineaments and faults; these features are mapped in *Figure 2*.

Jurassic eolianites everywhere form the best reservoir rock of the aquifer, whereas more argillaceous fluvial-lacustrine Triassic sandstones (Pirambóia, Rosário do Sul, and Buena Vista) provide notably inferior sources of groundwater. The higher clay content of the Triassic sandstones, readily apparent in cuttings, is also the principal means of separating the eolianite from underlying units on gamma-ray logs. Evidence supporting a dominantly eolian environment for the Botucatu Sandstone includes large-scale cross-bedding thicker than 10 m, a predominance of subcritical climbing ripples (Hunter 1981; his *Figure 2*), and good sorting. A few wadi deposits are also present. The area of 1,195,500 km^2 of the Jurassic eolianites in South America alone (Botucatu/Misiones/Tacuarembó) is very comparable in size to that of the closed drainage basin of Lake Chad (1,100,000 km^2), the western part of the Sahara desert (1,300,000 km^2) in Africa, and the Rub al Khali (1,200,000 km^2) in Arabia (Burdon 1977).

This study used data from 228 water wells and 94 oil wells to define and regionally characterize this aquifer system and to construct maps of its structure, thickness, overburden, water temperature, and potentiometric surface.[1] Araújo et al. (1995) provide large-scale, full-color maps based on these data. Data distribution is very uneven in the aquifer. The density is highest in São Paulo state, the most populous and most industrial-

[1] All the maps and a diskette with all the information about the data set can be obtained from Universidade Federal do Paraná, Biblioteca de Ciências e Tecnologia, Centro Politécnico – Jardim das Américas. Caixa Postal: 19010. CEP: 81.531.970. Curitiba, PR, Brasil – FAX (041) 366.1205 (attention Sra. Eliane Maria Struparu)

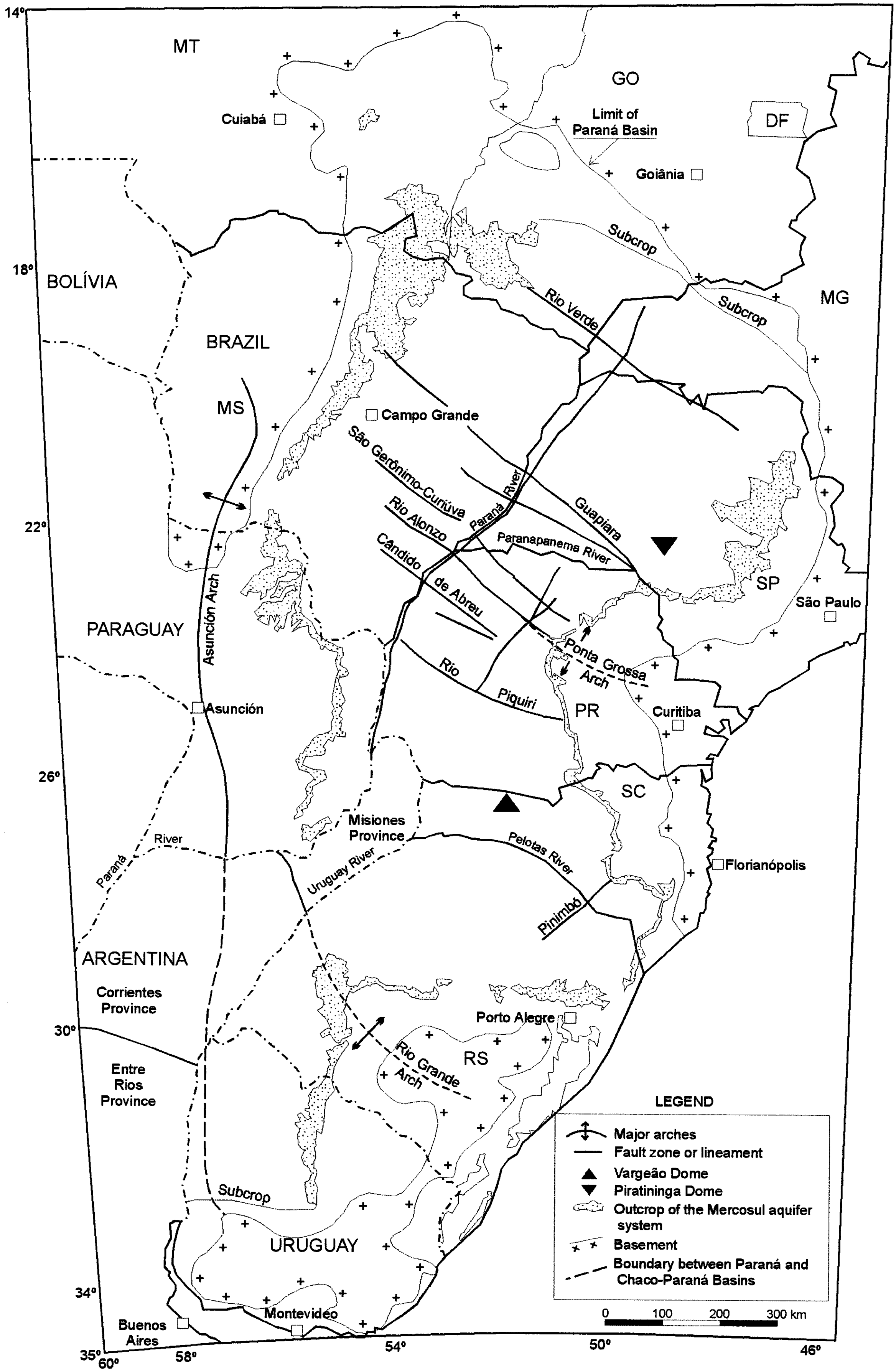


Figure 2 Major structures in the Paraná Basin. The Paraná River broadly follows the structural low at the top of the Botucatu Formation except where it crosses the Rio Grande Arch. *Triangles* are locations of the specific structural uplifts in the Paraná Basin. (After Zanotto and Astolfi 1990; Hachiro et al. 1993, 1994)

ized state of all of Mercosul, but data are very sparse to the west and along the Paraná and Uruguay Rivers (only about 50 wells).

Prior studies of the aquifer system include the pioneering work of Almeida (1953) and Bigarella and Salamuni (1961) on its depositional environment. More recently, Zalán et al. (1990) established the general geologic framework of the Paraná Basin, Milani et al. (1992) provided a recent overview of its origin, Marques et al. (1994) give more details, and França et al. (1995) provided Phanerozoic correlation in southern South America. Broad hydrologic and hydrochemical studies of parts of the aquifer have been made by Leinz and Sallentien (1962), Maack (1970), Gilboa et al. (1976), Rebouças (1976, 1994), Gilboa et al. (1976), Souza Filho and Algarte (1979), Silva (1983), Fraga (1992), and Campos (1994). More specialized studies include those of Sinelli (1979), Gallo and Sinelli (1980), Szikszay et al. (1981), Teissedre and Barner (1981), Lavina et al. (1985), and Kimmelmann et al. (1986, 1989); Hausman (1995) recently published on the aquifer in Rio Grande do Sul, as did Rosa et al. (1998).

Hydrogeologic Framework

The hydrogeologic characteristics of the aquifer system vary significantly across these two large basins and are largely the result of contrasts in depositional environments of their sandstones, the structural evolution of the two basins, and the flow history and residence time of their waters. Hydraulic properties are compared in *Table 2*. The Botucatu and Pirambóia aquifers have comparable average thicknesses, although their ranges differ. The porosity of the Botucatu is greater than that of the Pirambóia, as is its hydraulic conductivity. The lesser clay content of the Botucatu accounts for most of these differences. The outcrop recharge area of the aquifer system forms a very distinctive escarpment around most of the Paraná Basin, as illustrated in *Figure 3*, and part of the Chaco-Paraná Basin. Because of low dips, the outcrop has typical widths of 10–30 km over large areas and locally is wider. Total length of the recharge area is about 3500 km.

Throughout the vast area of this aquifer, most of its water is potable; only a few exceptions are known. The lower contact of the Mercosul aquifer system is generally with the low-permeability Permo-Triassic aquitard, which contains brackish-to-fresh water. In the most confined and deepest parts of the aquifer in the central part of the Paraná Basin and in areas of restricted meteoric inflow, as in parts of Rio Grande do Sul, some cross-stratal flow may occur from the basal aquitard into the Mercosul aquifer system. Although not well studied, some upward leakage probably occurs through fractures of the Serra Geral aquitard. Water from the Mercosul aquifer system is used for industry, agricul-

Table 2 Hydraulic properties of Botucatu and Pirambóia aquifers

Variable	Botucatu aquifer	Pirambóia aquifer
Thickness range	4–484 m (13–1539 ft.)	25–770 m (82–2525 ft)
Average thickness	138 m (453 ft)	139 m (456 ft)
Porosity range from sonic logs	17–30%	14–24%
Average hydraulic conductivity (K)	8.7 m/d (28.5 ft/d)	1.9 m/d (6.2 ft/d)
Transmissivity	2.4–552 m^2/d (25.8–5942 ft^2/d)	No reliable data

Figure 3 Typical expression of the escarpment of Serra Geral lavas overlying the Mercosul aquifer system in the northeastern part of São Paulo state. The height of the escarpment is commonly 100 m or more, and the escarpment can be easily identified along its outcrop of about 3500 km in Brazil, Argentina, Uruguay, and Paraguay. Here, about the uppermost one-third of the escarpement is underlain by lavas of the Serra Geral Formation. Drawn by Karen Kelly from an air photograph by Paul Potter

ture, homes, and tourism (hydrohotels and spas). Water quality is also locally affected by enrichment in fluoride.

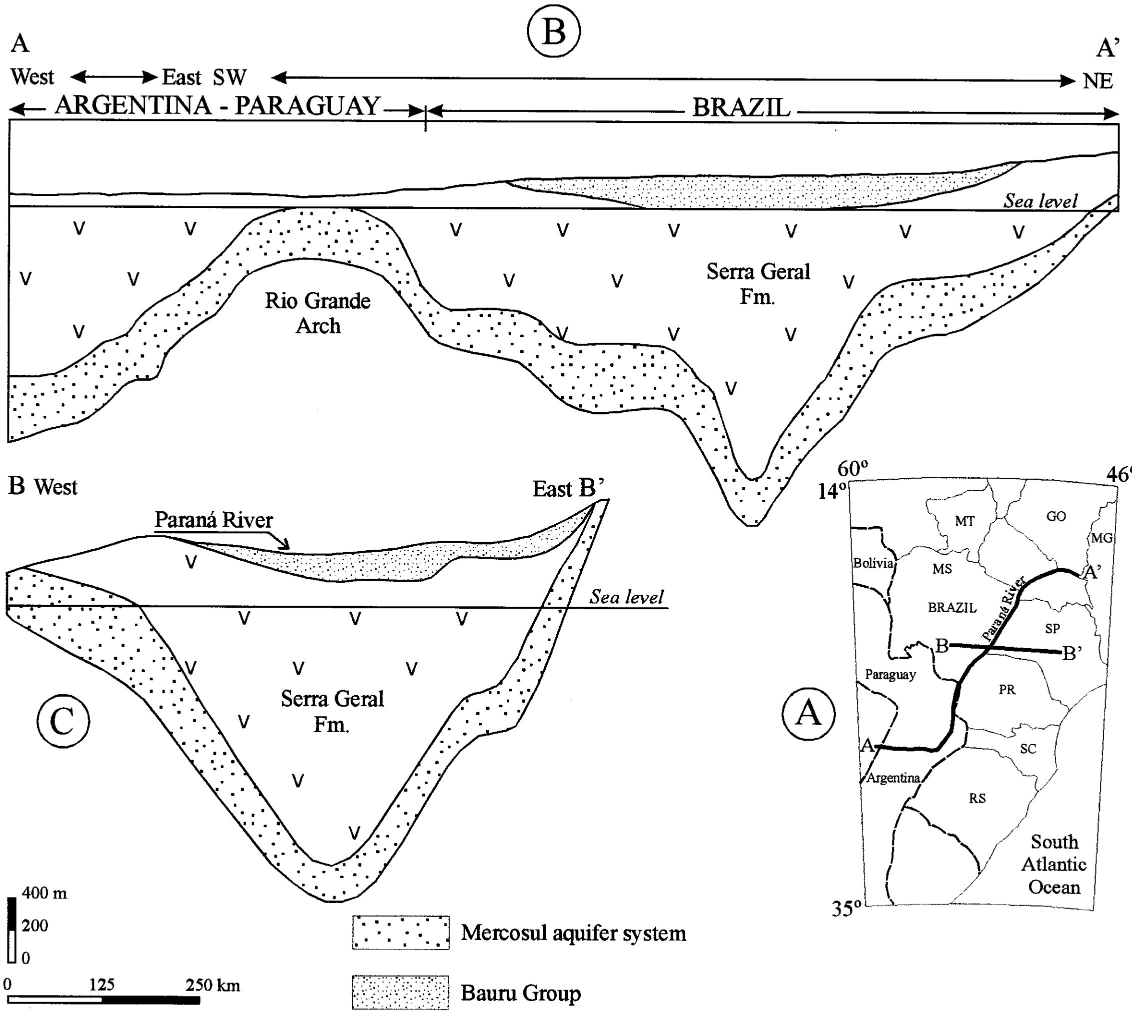
The climate of the region underlain by the Mercosul aquifer system varies from subtropical in its northern part to temperate and almost semi-arid in its far southern part; annual rainfall ranges from about 1 m (southwest) to about 1.5 m at the northern end of the basin (DNM 1992). At the southern end of the basin, in Uruguay, average summer temperature is 24 °C and average winter temperature is 12 °C (Heinzen 1986; Figures 2.3.2 and 2.3.3), whereas at the northern end of the basin, in Goiás, summer temperature averages 29 °C and winter temperature averages 11 °C (DNM 1992). The wide variation of temperature results chiefly from the great length of the aquifer, which extends through 20° of latitude, or about 2200 km.

Structure

The structure of the top of the aquifer evolved from four factors – great depocenters of lavas of the Serra Geral Formation, which depressed the aquifer; regional faulting; activation of arches (Rio Grande and Ponta Grossa); and uplift of the outcrop. The general structural configuration is shown in *Figure 4*.

The structural low defined by the top of the aquifer broadly trends north northeast and coincides with the depositional axis of the basin, which mostly coincides with the present course of the Paraná River. Within this trend are three depositional centers, one in the state of Paraná (PR) and two in the state of São Paulo (SP) – all three are probably the response to the uplift of the Brazilian coast and by reactivation of the regional northwest- and west-trending fault systems within the two basins. Three possible tectonic origins are proposed for these depocenters. The northern structural low, situated in the state of São Paulo (SP), could have been controlled by vertical movements of the northwest-trending Rio Verde lineament and the

Figure 4A–C Longitudinal and transverse sections of the Mercosul aquifer system. **A** Locations of sections; **B** longitudinal section along the Paraná River; **C** transverse section across the Paraná River valley



northwest-trending President Epitácio fault zone. The central structural low, in the state of São Paulo (SP), could have evolved from both the northwest-trending Guapiara fault zone to its north and the northwest-trending São Gerônimo-Curiúva fault to its south. The southern structural low, situated in the State of Paraná, could have been controlled by the northwest-trending Cândido de Abreu fault zone on the north and by the northwest-trending Rio Piquiri fault zone on the south.

The initial uplift of the present borders of the basin occurred during the drift phase of the separation of South America from Africa about 110 Ma ago. There was both a rift shoulder effect on the east side of the basin (Petri and Fulfaro 1983, FigureV-15; Riccomini et al. 1992) and a probable later Andean orogenic effect on its Atlantic, northern, and perhaps even western sides that importantly contributed to its present structure. The principal Andean event was middle Tertiary in age (Jordan and Gardeweg 1989). Although the Rio Grande Arch is much older than the Ponta Grossa Arch, it was probably reactivated at this time.

The Paraná River closely follows the structural axis of the Paraná Basin from northeast to southwest and is the locus of discharge, the "hydraulic backbone," of the basin, providing the regionally lowest elevation from northeast to southwest within the basin. It has been suggested that the ancestral Paraná River has occupied a course closely similar to its present one since the end of the deposition of the Serra Geral Formation (Potter 1997, p. 335). Thus the present flow net of the Paraná and parts of the Chaco-Paraná Basins may have been in existence for as long as 90 Ma. A cross section of the basin (*Figure 4B*) was constructed along the river into Argentina to the western limit of data on the basis of the structure and isopach maps, and another one is approximately perpendicular to the river (*Figure 4C*). *Figure 5* shows the elevation of the top of the Mercosul aquifer system; *Figure 6* shows the distribution of aquifer-system thickness. The longitudinal section shows how the Rio Grande Arch (Zalán et al. 1990) divides the aquifer system into two parts – the larger and more deeply buried part that belongs to the Paraná Basin and the smaller less deeply buried part that belongs to the Chaco-Paraná Basin. In broad terms, the area northeast of the the Rio Grande Arch is the chief recharge area and reservoir of the Mercosul aquifer system, whereas its major discharge area is between the Paraná and Uruguay Rivers west of the Rio Grande Arch. This western area contains hundreds of lakes and many thousand square kilometers of swamps. The transverse section shows how close the present position of the Paraná River is to the present structural axis of the basin.

The Paraná Basin contains two small "pinpoint" uplifts or domes that bring the Botucatu Formation to the surface (Zanotto and Astolfi 1990; Hachiro et al. 1993 and 1994); neither uplift is large enough to influence regional flow within the aquifer system.

Thickness of Aquifer System

The total thickness of the aquifer system ranges from complete absence in the subsurface in the northeastern part in the state of Rio Grande do Sul (RS) to about 800 m in the southern part of the state of Rio Grande do Sul (RS) (*Figure 6*). In broad terms, thicknesses of more than 500 m exist principally along a north northeast-trending axis subparallel to or near the Paraná and Uruguay Rivers. The aquifer system has two major depositional centers – one 600 m thick east of Campo Grande, in Mato Grosso do Sul (MS) in the Paraná Basin, and another 800 m thick west of the Rio Grande Arch, in Argentina and Uruguay. Causes of variation are not fully understood, but include differential subsidence and variation in thickness of both the fluvial/lacustrine and eolian facies, as well as activity of the Ponta Grossa and Rio Grande Arches. Along the outcrop, erosion during Tertiary time is probably the chief control on thickness.

Thickness of Overlying Rocks

The thickness of overburden above the aquifer system is controlled by: (1) variations in lava thickness of the Serra Geral Formation; (2) position of the axis of Cretaceous and Tertiary deposition; (3) the activity of the regional fault system; (4) uplift of the basin's borders; (5) the activity of the Ponta Grossa and Rio Grande Arches; and (6) thickness of the Bauru Group. Overburden thickness is mapped in *Figure 7*. Three areas along the main depositional axis of the Paraná Basin in Brazil all have more than 1000 m of basalt and sandstone above the aquifer: (1) 1200 m north of São Paulo state; (2) more than 2200 m near the boundary among São Paulo (SP), Paraná (PR), and Mato Grosso do Sul (MS) states; and (3) more than 1400 m in the northern part of Paraná state (PR). In Entre Rios Province, Argentina, more than 1400 m of basalt and sandstone overlies the aquifer.

The amount of uplift along the borders of the basin directly determines the thickness of overburden above the aquifer. Around the Ponta Grossa Arch, the aquifer is thin, commonly less than 150 m, because of great uplift and erosion, and thickness of overburden increases rapidly basinward. On the other hand, on the western side of the basin, where the dip is gentle, the thickness of the overburden increases basinward much more gradually. Local abrupt variations of the thickness of overburden may also result from local structural anomalies, of which many, if not most, still remain to be discovered, because of both sparse drilling and few outcrops over wide areas of the two basins.

Potentiometric Surface

The first basin-wide potentiometric map of the Paraná and parts of the Chaco-Paraná Basin was made by

Figure 5 Elevation of the top of the Mercosul aquifer system

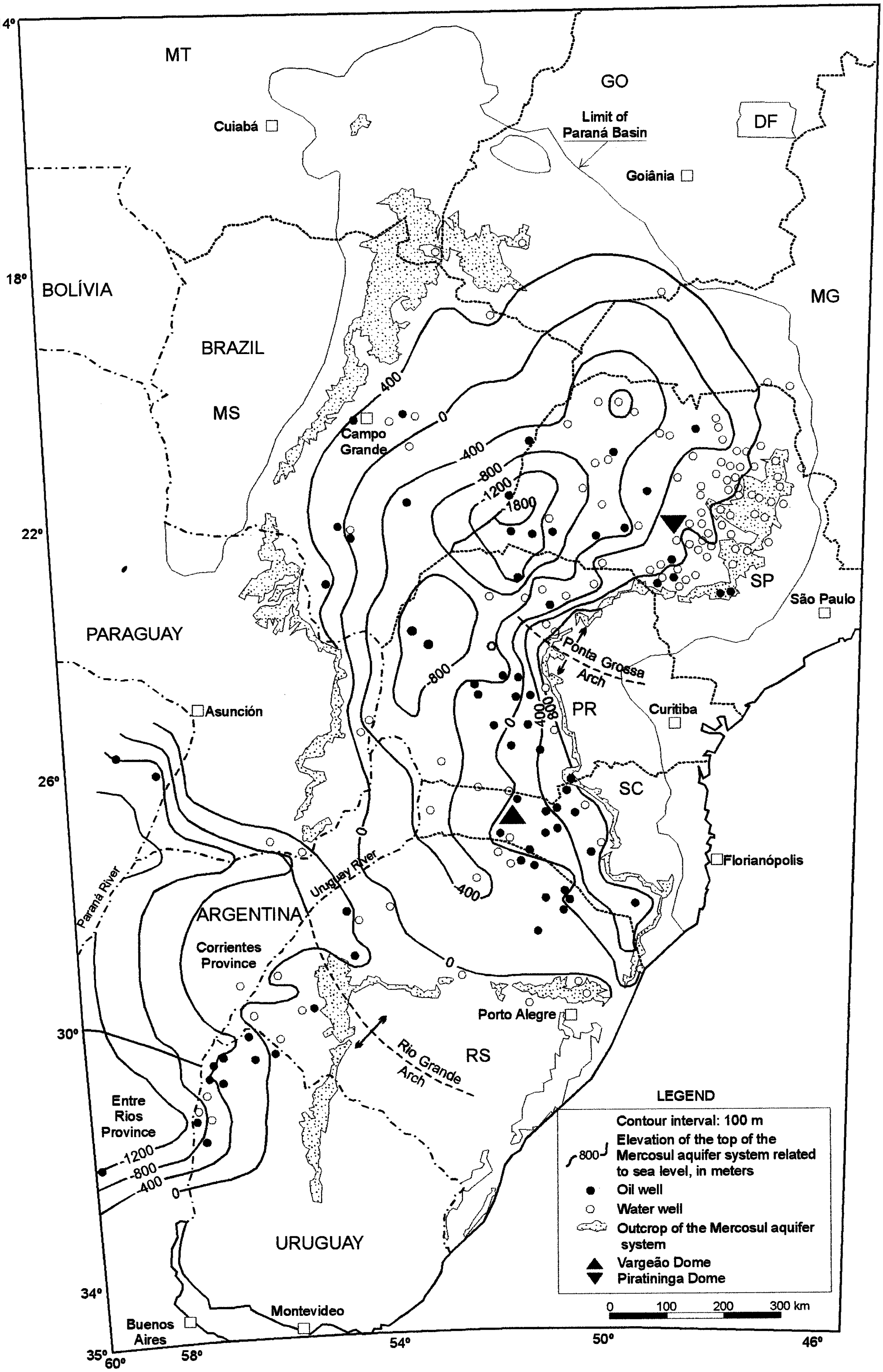
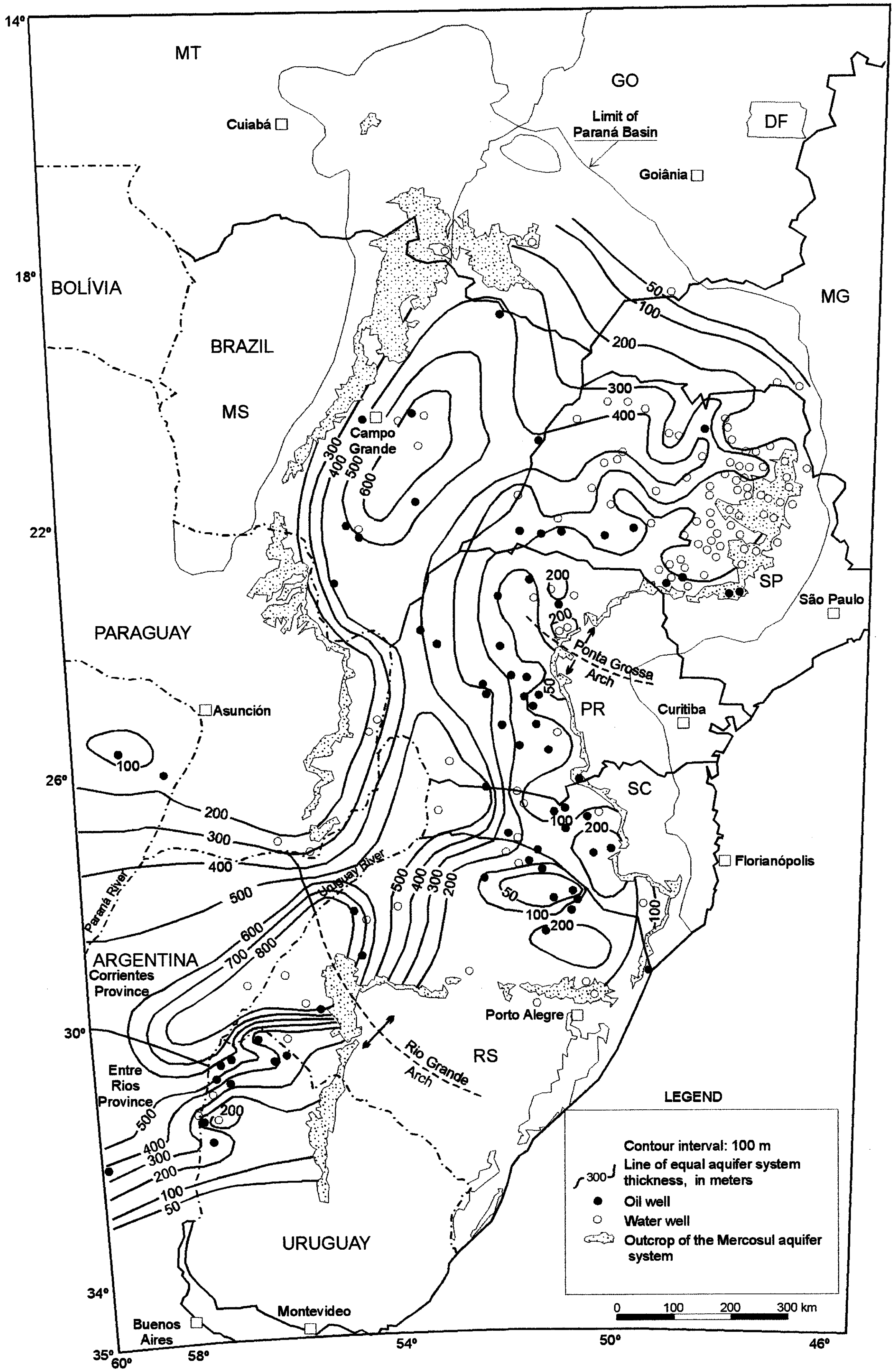


Figure 6 Thickness of the Mercosul aquifer system



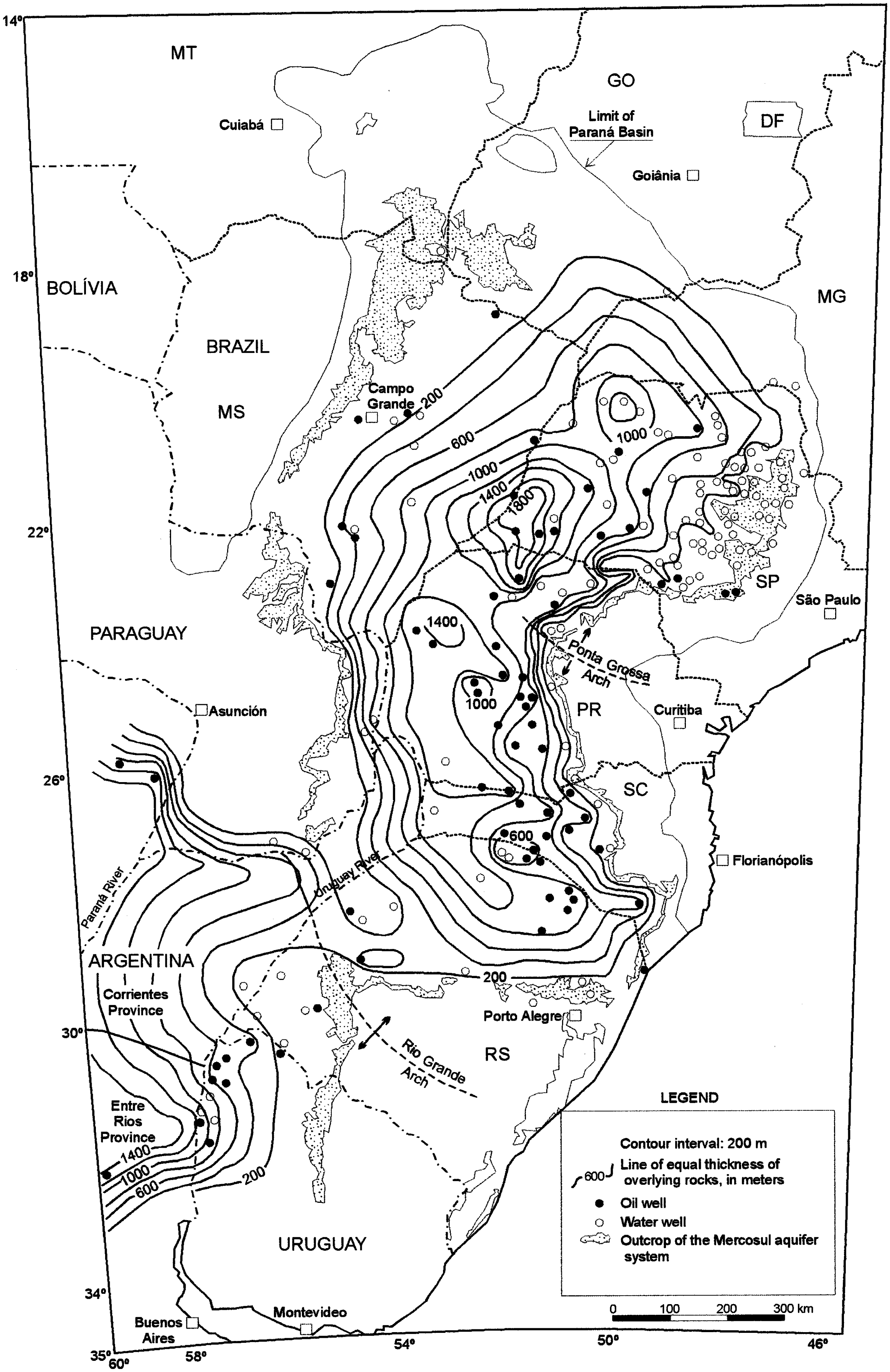


Figure 7 Thickness of sedimentary and volcanic rocks that overlie the Mercosul aquifer system

Gilboa et al. (1976). According to their interpretation, the percolating water moves from the recharge areas surrounding the basin to its central part, and toward its southeastern discharge area in Rio Grande do Sul state. This differs significantly from the one presented herein almost certainly because of the sparse data available for Gilboa and colleagues 20 years ago. The current mapped configuration of the potentiometric surface is shown in *Figure 8*.

The Ponta Grossa Arch, with its great number of diabase dikes, divides the aquifer in the Paraná Basin into two major potentiometric domains (*Figure 8*). North of the arch, the potentiometric surface has a broad centripetal gradient away from recharge areas in the states of Mato Grosso (MT), Mato Grosso do Sul (MS), Goiás (GO), Minas Gerais (MG), and São Paulo (SP). On the northern side of the basin, in Goiás (GO) and northern Mato Grosso do Sul (MS) states, is a second important recharge area. In São Paulo state, an important recharge area, the typical potentiometric surface beneath the outcrop is generally at 600 m, but locally it is 800 m above sea level. Here, the gradient of the potentiometric surface decreases from about 3 m/km near the outcrop to about 0.2 m/km only 50 km downgradient. On the northern side of the basin, in Goiás and northern Mato Grosso do Sul states, is a second important recharge area, where the potentiometric surface is at 600 m above sea level, slopes southwestward, and has a southerly dip toward the center of the basin and toward Paraguay. Here, the gradient decreases from 1.5 m/km near the outcrop to 0.2 m/km downgradient from it.

The second hydrologic domain created by the Ponta Grossa Arch lies to its south, has a larger hydraulic gradient, and has the basin's most significant discharge area, between and along the Uruguay and Paraná Rivers. Here, along the southwestern side of the Ponta Grossa Arch, the potentiometric surface slopes to the southwest from about 1200 m to about 50 m; gradients decrease from 5 m/km to 0.3 m/km along the Uruguay and Paraná Rivers.

The recharge area in the state of Santa Catarina (SC) has two directions of outflow – the principal one is westward across most of the state of Rio Grande do Sul (RS), where the hydraulic gradient is about 3.0 m/km near the outcrop and 0.4 m/km near the Argentina border; a very small one occurs near the northeastern part of Porto Alegre, in Rio Grande do Sul state (RS). Discharge probably also occurs along the Pelotas river, between the states of Rio Grande do Sul (RS) and Santa Catarina (SC), judging by the abrupt decline of the potentiometric surface from 650 m to 350 m in a distance of less than 40 km.

Because of many unrecognized dikes, sills, and faults; local topography; and scant well data, the actual potentiometric surface may locally differ greatly from the surface shown in *Figure 8*, especially near the outcrop.

The vast swamps between and along the Uruguay and Paraná Rivers (Iriondo 1989) represent the principal discharge area of the Mercosul aquifer system, which is brought to the surface by the Rio Grande Arch (Araújo et al. 1995) in Misiones and Corrientes Provinces of Argentina (Herbst and Santa Cruz 1995). The area is shown in *Figure 9*.

Water Temperature

The distribution of groundwater temperature in the aquifer system is shown in *Figure 10*. The map was made from geothermal measurements in water wells and from measurements of maximum bottom temperatures in oil exploration wells. The geothermal gradient calculated from petroleum exploration wells is 29 °C/km. All the calculated temperatures are for the top of the aquifer. Using this gradient and depth to the top of the Botucatu Formation, the temperature was calculated at its top for all the wells that lacked temperature measurements.

The isotherms of the aquifer generally follow the structure of the top of the Botucatu Formation with a few exceptions. Three areas exist in Brazil and one in Entre Rios Province, Argentina, where the temperature is greater than 55 °C. Locally, both positive and negative anomalies occur in the geothermal gradient. Along the river situated on the frontier between Santa Catarina (SC) and Rio Grande do Sul (RS), the geothermal gradient is as low as 20 °C/km. This low anomaly suggests an area of discharge and possibly some mixing with water from the Serra Geral aquitard/aquifer. The second anomalous area is in the state of Minas Gerais (MG), where the aquifer lies directly over basement and is covered by basalt; here the thermal gradient is as high as 55 °C/km. This locally high gradient may be the product of high heat flow from the crystalline basement and from semi-stagnation caused by a tight basaltic seal.

At present, this hot water is used chiefly for "hydrothermal" hotels, plus some applications to space heating for the poultry industry, but this vast reservoir of hot water has a great potential in the 21st century as an energy source (Dorf 1978, p. 289–303; Kraushaar and Ristinen 1984, p. 216–222; Muffler 1993). Freeston (1996, p. 8) reviews the uses of geothermal energy in 1995 in South America, where Argentina has identified the most prospects; for example, Baia Blanca in Argentina has a reservoir with water temperatures of 55–85 °C at depths of 530–1000 m, which is comparable to parts of the Botucatu Formation and its equivalents in the Paraná and Chaco-Paraná Basins.

Water Chemistry

The groundwater chemistry of the aquifer system is best known from São Paulo state (SP), where groundwater use and drilling density are greatest in the two

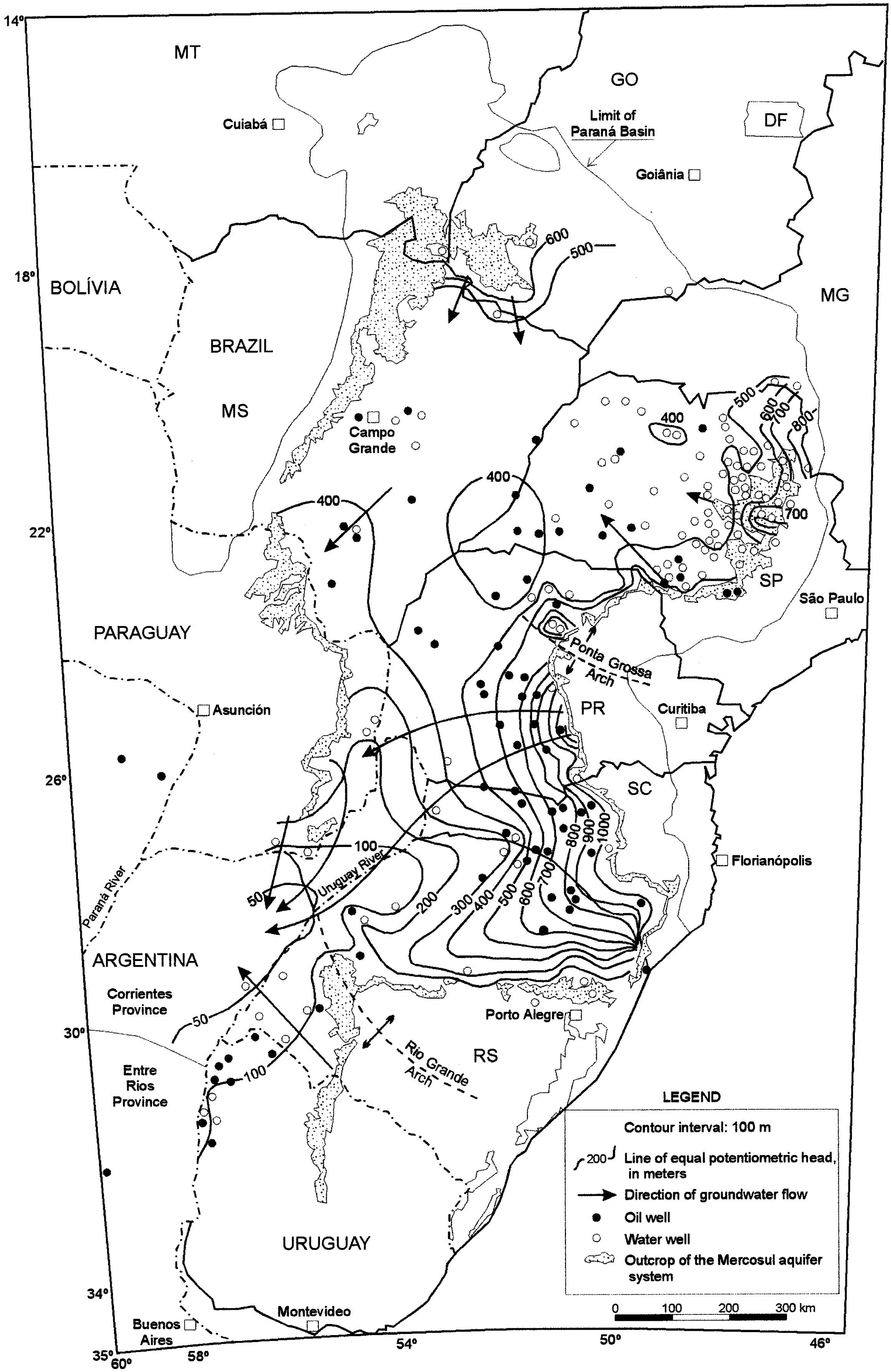


Figure 8 Potentiometric surface of the Mercosul aquifer system. The region between Uruguay and Paraná rivers is the major discharge area of the Mercosul aquifer system

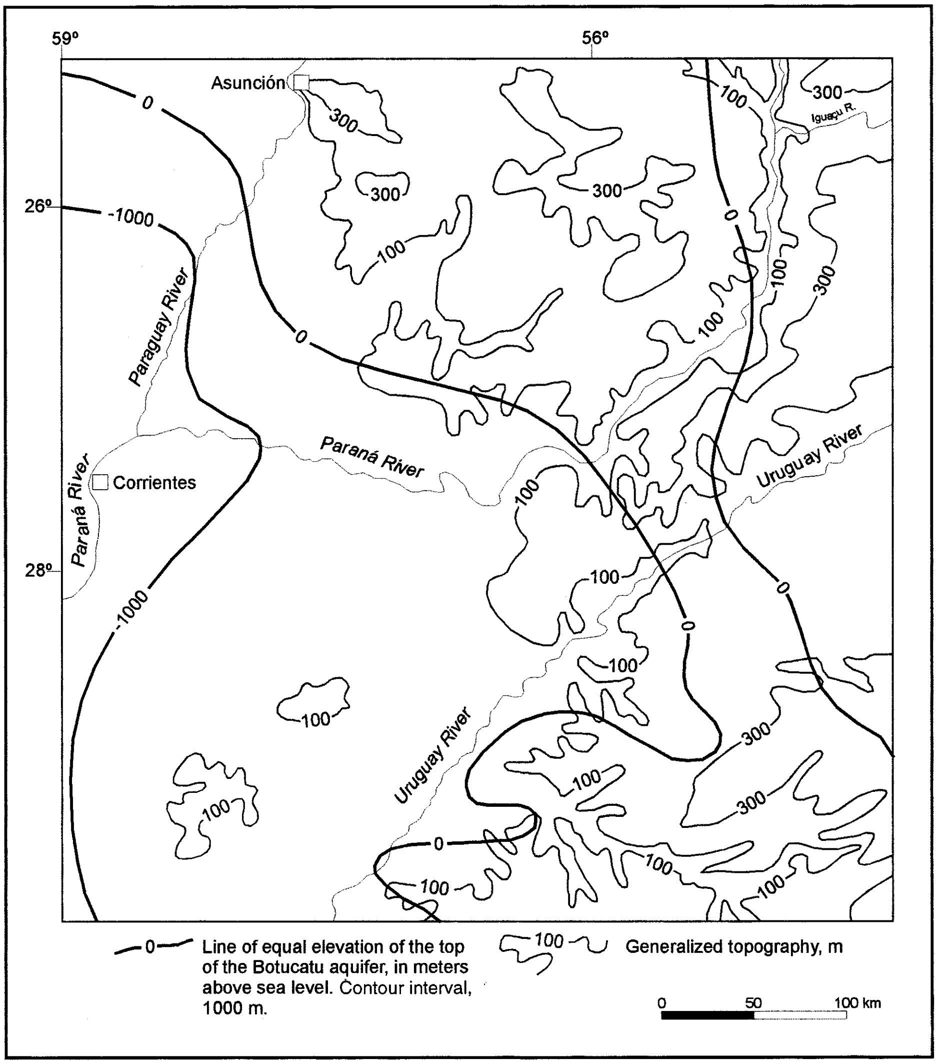


Figure 9 Elevation of the top of Botucatu Formation and generalized topography, Corrientes Province of Argentina and adjacent areas. Area with elevations less than 100 m have many lakes and swamps. We recognize that additional studies of the Mercosul aquifer system will show many more interesting structural features on this region

basins. Silva (1983), using 61 high-quality analyses, concluded that the water of the aquifer system is fresh – about 84% of these analyses had less than 250 mg/L of total dissolved solids, although a sample from one well along the Paraná River had a value of 1216 mg/L. The majority of the waters of the system generally have intermediate hardness, although about 25% are soft and 6% are hard. The value of dissolved silica exceeds 20 mg/L in 52% of the samples; the value of nitrate is more than 1 mg/L in six of the 61 samples, and in two samples the concentration exceeds 10 mg/L (Silva, 1983).

Chemically, these waters predominantly belong to two dominant types – the calcic and calcic-magnesium bicarbonate and sodic bicarbonate families. Some magnesium bicarbonate and chloro-sulfate and sulfate sodic water compositions do occur. The calcic bicarbonate and calcic magnesium compositions generally have total dissolved solids of less than 290 mg/L, pH less than 7.5, calcium 0.04–0.251 meq/L, and magnesium less than 1.13 meq/L. Dominantly bicarbonate waters typically have values of magnesium 0.06–3.16 meq/L, carbonate less than 0.04 meq/L, sulfate less than 0.251 and chloride less than 0.31 meq/L. On the other hand, the sodic bicarbonate waters typically have total dissolved solids of 61–650 mg/L, calcium of 0.02–0.84 meq/L, potassium of 0.01–0.01 meq/L and magnesium less than 0.08 meq/L. Bicarbonate ranges from 0.66–3.4 meq/L, carbonate is commonly less than 2.9 meq/L, sulfate less than 1.92 meq/L, and chloride ranges from 0.01–3.75 meq/L. The magnesium bicarbonate waters are less saline than the calcic bicarbonate waters, whereas the sodic-chloride bicarbonate waters are more saline than the sodic bicarbonate waters.

Fluoride concentrations are locally high. Values that exceed the recommended tolerance limits for fluoride (2 mg/L to a maximum of 4 mg/L; USGPO 1995, Table b), occur in some geographically restricted parts of the aquifer. Fraga (1992) concluded that locally high concentrations of 3.6–12 mg/L are related to areas of stagnant alkaline waters, areas where inflow is greatly restricted and residence time is long in parts of São Paulo (SP) and Paraná (PR) states.

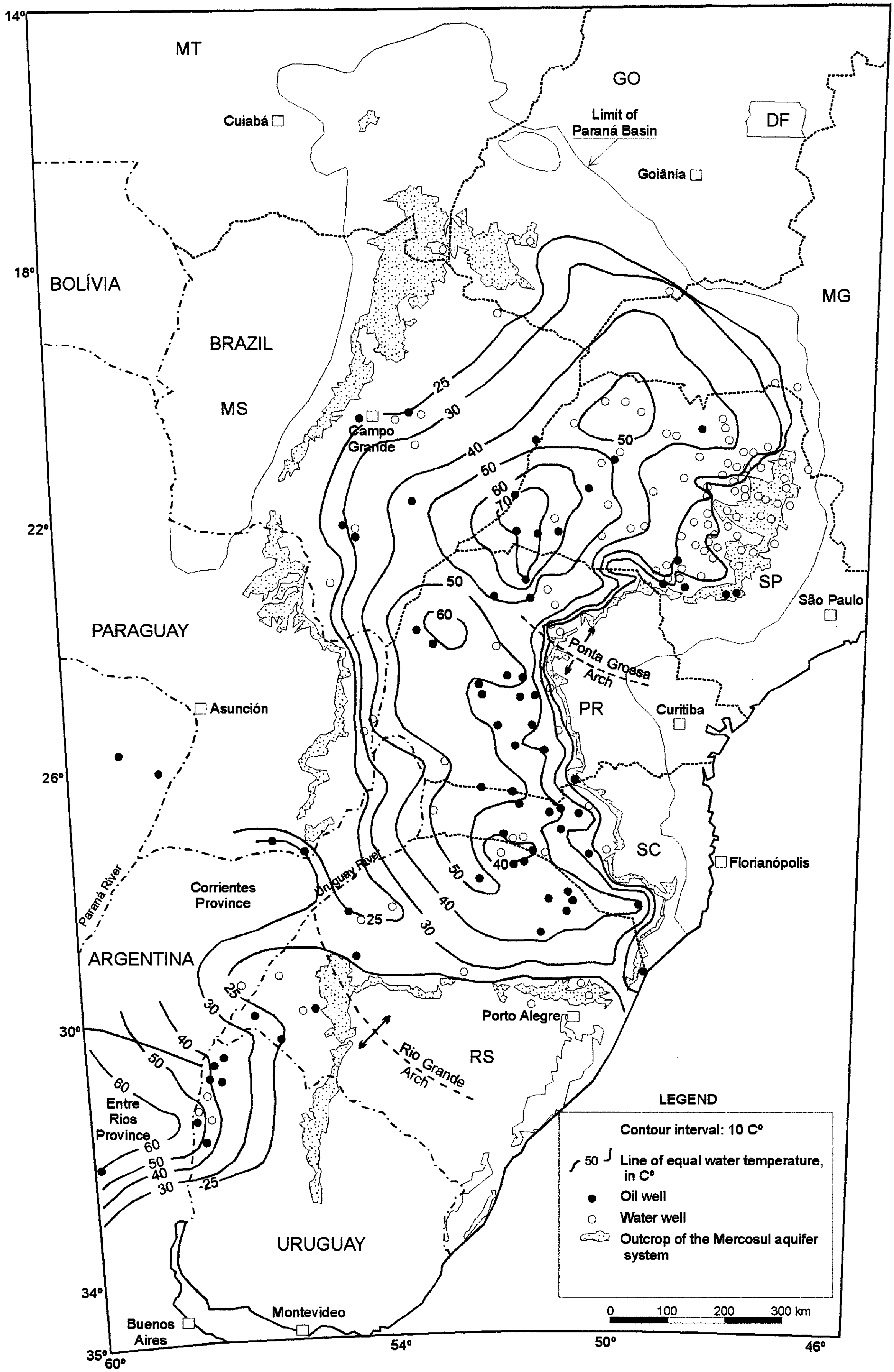


Figure 10 Distribution of groundwater temperatures in the upper part of the Mercosul aquifer system

Geologic History of the Groundwater Flow System

Below, based chiefly on evidence from stratigraphy, regional tectonics, and geomorphic history, a plausible scenario of groundwater evolution of the Mercosul aquifer system has been developed. The proposed history is summarized in *Table 3*.

The geologic evolution of the water in the aquifer system (*Table 3*) started with the burial of the aquifer system units by the lavas of the Serra Geral Formation and its equivalents about 127 or 128 Ma (Turner et al. 1994; Milani 1997, p. 135), followed by deposition of the Bauru Group in the central part of the Paraná Basin, 88–65 Ma (Fernandes and Coimbra 1996, p. 202). Lelarge (1993, p. 181–182), using fission-track dating of apatite, proposes that the first pulses of uplift of the eastern border of the Paraná Basin started at about 110 Ma, with a climax between 100–90 Ma; total erosion is estimated to be 3000 m. Zanotto (1993, p. 58), using the vitranite reflectance method, also estimated about 3000 m of uplift, and thought that most of it was north of the Ponta Grossa Arch. Most of this erosion probably occurred in the Precambrian basement east of the present border of the Paraná Basin. This early uplift provided the initial sustained freshwater recharge to the Mercosul aquifer system. Little probably changed during the deposition of the red beds of the Bauru Group, when climate continued to be arid or semi-arid. Relief in the Paraná Basin was rejuvenated in middle Tertiary time by the uplift of the Andes, at which time most of the geomorphology of much of the Paraná Basin probably became well established.

Thus, the history of groundwater in the Mercosul aquifer system probably had two distinct phases. From initial deposition of the aquifer system to the pronounced uplift of both the Serra do Mar and the basin's northern and eastern margins in late Cretaceous time, 110–90 Ma, the water in the system was probably fresh to slightly alkaline and possibly brackish, as are the waters in many contemporary arid to semi-arid regions today, and groundwater flow was sluggish. But after initial uplift, increased hydraulic gradients resulted in flushing of much of the aquifer, and its water composition became similar to that of today. A transition from arid and semi-arid conditions in the Jurassic and Cretaceous Periods to more humid conditions in the later part of the Tertiary Period and during much of the Pleistocene Epoch (with three dry glacial periods) also probably contributed significantly to changes in both water chemistry and flow rates. According to this scenario, today's water chemistry and flow rates date at least from the middle part of the Tertiary Period and probably even from the Cretaceous uplift 90 Ma ago.

Isotopic data from water in the Mercosul aquifer system in São Paulo state and elsewhere (Silva 1983; Kimmelmann et al. 1986, 1989) permits an estimate of travel times. Based on studies of ^{14}C (Silva 1983; Kimmelmann et al. 1986, 1989), about 15,000 yr are needed for water to travel about 70 km in São Paulo state, a rate of between 4–5 m/yr. If the assumption is made that this rate existed since the beginning of the erosion phase in the basin and initial uplift of its borders about 90 Ma ago, and that the rate applies to

Table 3 Proposed groundwater history of the Mercosul aquifer system

Depositional/Tectonic events	Inferred groundwater response
Eolinites of Botucatu Formation, 188–177 Ma Broad interior, mid-latitude desert, probably with mostly interior drainage; surface elevations of 200–400 m?	Sluggish, slightly mineralized fresh water, possibly 15–20 °C?
Lavas of Serra Geral Formation, 127–138 Ma Initial response to separation of South Africa from Africa causes rapid and deep burial of Botucatu Formation to about 1700 m	Sluggish, somewhat mineralized fresh water warmed to 40°–70 °C by standard geothermal gradient; little effect of lava flows, because they accumulated as distinct flows rather than as a single mass. Paleo Paraná River develops at end of deposition of lava flows?
Serra do Mar uplift, 110–90 Ma Initial uplift of "rift shoulder" (precursor of present Serra do Mar Mountains), when South America first separated from Africa	Initial fresh-water recharge over most of basin from eastern and southeastern margins of basin, plus increased rainfall over all basin. Paleo Paraná River system now probably well established
Bauru Group, 88–65 Ma Thin but widespread redbeds deposited in semi-arid climate form blanket in center of Paraná basin, concurrent with erosion of basin margins	Little change from above, because extra burial is minimal and climate continues semi-arid
Andean Orogeny, 15 Ma Coastal Serra do Mar rejuvenated in mid-Tertiary time elevates eastern and southeastern sides of basin. Uplift probably reactivates Rio Grande and Ponta Grossa Arches	Increased fresh-water flux through aquifer much as today, because of renewed uplift and more rainfall. Pales Paraná River close to present course?
Late Tertiary/Quaternary Continued uplift and erosion with increased rainfall	Today's aquifer with high recharge rates.

most of the basin, then 50,000–62,000 yr are needed for water to travel from the outcrop in São Paulo state to western São Paulo state, near to the junction of the Paraná and Paranapanema Rivers, a distance of about 250 km. Using a rate of 4 m/yr for the 90 Ma since initial uplift, the water of the Mercosul aquifer system would have been exchanged or flushed through it about 1440 times as it flowed 250 km. However, if it flowed directly to Argentina, a distance of about 1000 km, only about 360 cycles would have been made.

If the scenario of *Table 3* is considered, i.e., an initial slow or stagnant flow followed by a later accelerated flow, such as occurs today, these estimates are all too large. Factors that certainly would reduce the above estimates include invasion of salty water into the aquifer from below and leakage through the basalts into tributaries of the Paraná. Hence, perhaps a value equal to one half the value above, or about 180 times (São Paulo to Argentina), is more conservative and realistic. This number of cycles still easily explains today's fresh water throughout the aquifer and implies much leaching of the aquifer and increase in its porosity. It is recognized that in a basin as large as this one, flow rates range greatly from nearly stagnant conditions, such as in much of Mato Grosso state, to relatively high rates, as in much of Paraná and Santa Catarina states.

In both the Chaco-Paraná and Paraná Basins, fresh groundwater has penetrated deeply and extensively into the sedimentary basins. Bloom (1991, p. 117) summarizes the great depths to which fresh water can penetrate along faults and structures – several kilometers or more. What the Chaco-Paraná and Paraná Basins demonstrate is the great lateral extent of deep penetration in a confined aquifer – over thousands of square kilometers. This occurs because the aquifer, instead of pinching out at depth due either to diagenesis or to facies changes, is very homogeneous throughout and is brought to the surface at or near the Rio Grande Arch, a major discharge area (*Figure 9*).

Comparison with the Navajo-Nugget Aquifer System in the Western United States

The most widespread eolianites in the northern hemisphere are the Jurassic Navajo Sandstone and its associated Nugget Sandstone, which form the Navajo-Nugget aquifer system in the western United States. A comparison of these two widely separated aquifer systems is summarized in *Table 4*; although their hydrologies are quite different, they were probably initially quite similar: two widespread cratonic/pericratonic eolianites of similar age. Sources of information

Table 4 Comparison of basinal and hydraulic features of Mercosul and Navajo-Nugget aquifer systems

Characteristic	Mercosul aquifer system	Navajo-Nugget aquifer System
A. Basinal Features		
Area	1,195,500 km^2 (461,583 miles^2)	634,472 km^2 (244,970 miles^2)
Maximum thickness	832 m (2730 ft)	701 m (2300 ft)
Average thickness	400 m (1312 ft)	308 m (1010 ft)
Geological setting	Cratonic/pericratonic basin	Cratonic/pericratonic basin
Deformation	Little; only two regional arches; many diabase dikes and some sills	Laramide Orogeny, multiple deep basins and intervening uplifts
Maximum depth	Greater than 1800 m (5921 ft)	Less than 2134 m (2000 ft) in most areas to greater than 3658 m (12,000 ft) in the Uinta Basin
Sandstone composition	Subarkosic to quartzose	Subarkosic to quartzose
B. Hydraulic Features		
Potentiometric surfaces (datum: sea level)	56–1198 m (184–3930 ft)	Less than 1067 m (3500 ft) to more than 2134 m (7000 ft)
Effective porosity	16% average; 14–30% (about 150 values)	Average, 19%; 2–35% (175 values)
Hydraulic conductivity (K)	1.7–8.5 m/d (5.6–27.9 ft/d)	Less than 3.048×10^{-5} to 1.13 m/d (0.00001 to 3.7 ft/d; average, 6.4×10^{-3} m/d (0.021 ft/d) (620 wells)
Transmissivity (T)	2.4–552 m^2/d (25.8–5942 ft^2/d)	Less than 4.65 to 185.8 m^2/d (50–2000 ft^2/d
Productivity	200 m^3/h average (882 gal/min) with maximum of 700 m^3/h (3088 gal/min) in São Paulo state	Average, 138 m^3/h (600 gal/min). Maximum of 230 m^3/h (1000 gal/min)
Recharge	138×10^9 m^3/yr (1,119,220 acre–feet/year)	Greater than 9.2×10^7 m^3/yr (75,000 acre-feet/yr)
Total dissolved solids	<250 mg/L to 1216 mg/L(84% <250 mg/L)	90 mg/L to greater than 50,000 mg/L

for the Navajo-Nugget aquifer system include Cooley et al. (1969), Hood and Danielson (1979), McKee (1979), Hood (1980), Uygur and Picard (1980), Hood and Danielson (1981), Hood and Patterson (1984), Weigel (1987), Weiss (1987), Peterson (1988), Taylor and Hood (1988), Freethey and Cordy (1991), and Robson and Barta (1995); for the Mercosul system, Rebouças (1976), Silva (1983), Araújo et al. (1995), and Rosa et al. (1998).

Geologically, both aquifer systems developed in shallow basins facing distant Jurassic seaways and geosynclines, both have rather comparable thicknesses, both are typically subarkoses, and both have some of the most spectacular cross bedding on their respective continents. Both also have two large integrated river systems – the Paraná and the Colorado – draining much of the area underlain by the two aquifer systems. But they also differ in significant ways. The Mercosul system underlies an area about 2.5 times larger than the Navajo-Nugget aquifer system, is buried to shallow depths over wide areas, is covered by thick basalts and cut by thousands of diabase dikes, and is little deformed. In contrast, the Navajo-Nugget aquifer system is bounded by mountain ranges on three sides, is deeply buried over wide areas, and is divided into different basins separated by broad swells and arches formed by the Cretaceous-Paleocene Laramide Orogeny. Consequently, parts of the Navajo-Nugget aquifer system are isolated from each other by intervening uplifts. In addition, none of these Navajo-Nugget subsystems discharges near sea level. The landforms of the two regions also differ: the landforms of the region of the Mercosul aquifer include a rugged coastal escarpment, interior plateaus (*planaltos*) up to 1000 m in elevation, and wide, dissected-to-flat lowlands. In contrast, the landforms of the Colorado Plateau and Wyoming Basin underlain by the Navajo-Nugget aquifer system include broad plains, deeply incised canyons, and many scenic erosional features, almost all of which are 1500–2000 m above sea level. Still another contrast between the Mercosul and Navajo-Nugget systems is the climates of the two regions – not only are they quite different today (subtropical verses semi-arid or arid), but they also have been different at least since middle Tertiary time.

Many hydrologic differences follow from these contrasts. The most significant of these is that the water of the Mercosul aquifer system is everywhere fresh because of simple basin geometry with a major discharge area near sea level, plus moderate to heavy rainfall in most of its discharge area; in contrast, much of the water in the Navajo-Nugget aquifer system has either lower quality or is not fresh, and it has smaller flow rates. In addition, recharge rate is much less for the Navajo-Nugget system. Although porosities are broadly comparable in the eolianites of these aquifer systems, hydraulic conductivity, transmissivity, and well yields are larger in the Mercosul than in the Navajo-Nugget system. All these contrasts are probably related to a longer and more complete "flow through" flushing history from peripheral outcrop to well defined discharge area for the Mercosul aquifer system, and to the complex flow systems of the Navajo-Nugget, which occur in various basins and have no single discharge area near sea level. Total dissolved solids have the same explanation – they are low in the Mercosul aquifer system, because of frequent flushing and because no adjacent evaporites exist in its two basins. In contrast, evaporites underlie parts of the Navajo-Nugget system and its equivalents and through-flushing was always much less.

In sum, most of the differences between the Mercosul aquifer system and the Navajo-Nugget system are explainable as the difference between: (1) a single active, long-lived open flow system in two connected basins with simple geometry and one major, well defined discharge area; and (2) the less active, more closed and more inhomogeneous flow systems in geologically separate sub-basins of the Navajo-Nugget system. Contrasting recharge rates due to differences in climate are also important factors. In other words, different subsequent tectonic histories and climates caused two widespread eolianites that initially may well have had broadly similar groundwater hydrologies subsequently to have very different groundwater chemistries and hydrologies.

Conclusions

The giant Mercosul aquifer system of Jurassic and Triassic age is one of the largest in the world and underlies an area of about 1,195,500 km^2 (461,583 miles^2) in the Paraná and Chaco-Paraná Basins, which are separated by the Rio Grande Arch. The basin-wide maps of this study provide, for the first time, a scientific basis for planning for long-term, sustainable development of this important multinational reservoir.

The thickness of the aquifer system ranges from rare local absence in the subsurface to more than 800 m. Two major depositional centers trend approximately north northeast subparallel to the Paraná River. The northern center, in Brazil, has a basin thickness that exceeds 600 m, and the southern one has a basin thickness greater than 800 m, west of the Uruguay River in Argentina. Much of the rest of the aquifer system is less than 200 m thick, especially along the eastern side of the basin. The structural configuration of the aquifer system closely coincides with the depositional and present structural trough of the Paraná Basin, which is approximately followed by the Paraná River.

Reconstruction of basin history indicates that the Mercosul aquifer system has always had predominantly fresh water, but that flow rates and composition have probably varied markedly. Groundwater flow in the aquifer actively started when the coastal Serra do Mar and eastern and northern sides of the basin were uplifted, and flow has continued without interruption to the present. Flow was and is brought to the surface by the barrier of the Rio Grande Arch, and this discharge contributes to the vast swamps in the vicinity the arch. The Ponta Grossa Arch divides the flow in the Paraná Basin into two major domains – a larger domain to the north and a smaller one to the south. The northern domain has a broadly centripetal flow toward the southwest and into the Paraná River, away from bordering recharge areas in the states of São Paulo, Goiás, Mato Grosso, and Mato Grosso do Sul. The southern domain has, on the other hand, greater hydraulic gradients and, because of the Rio Grande Arch, the basin's largest discharge area, which is along and between the Uruguay and Paraná Rivers.

The isotherms of the aquifer generally follow a gradient of 29 °C/km and broadly reflect its structure. Two areas of the basin have temperatures higher than 55 °C – one in the western parts of São Paulo and Paraná states and the other in the province of Entre Rios in Argentina.

Two broad implications follow from this study. First, comparison of the Mercosul with the Navajo-Nugget aquifer system in the USA – the two largest aquifers in the Western Hemisphere that include eolianites – demonstrates the importance of both tectonics and past and present climates on continental-scale aquifer systems. The Mercosul aquifer system is a large "flow-through" system in two, little deformed, large adjacent basins. The Navajo-Nugget aquifer system was separated into different sub-basins by the Laramide Orogeny, and it lacks a single major discharge area near sea level, such as occurs along the Paraná and Uruguay Rivers in Argentina. Secondly, the Mercosul aquifer system illustrates both the great expanse and depth to which fresh water can occur in interior sedimentary basins, and thus it provides a model of the great importance of groundwater flow in sedimentary basins.

The key to managing the Mercosul aquifer system is understanding its principal discharge area, between the Paraná and Uruguay Rivers in Argentina – in front of and over the Rio Grande Arch – which is an outlet for most of the water that enters the aquifer. Without this outlet, both the flow-through and potability of the water in the Mercosul aquifer system would certainly be much less than it is today.

Acknowledgments Many companies and specialists contributed to this study, which was made possible thanks to the sustained and generous support of the Núcleo de Exploração da Bacia do Paraná (NEXPAR) of PETROBRÁS located in Curitiba, PR, and the Department of Sedimentary Geology, UNESP, in Rio Claro, SP, both in Brazil.

Individuals who helped supply widely scattered and hard-to-obtain data include M. Borduque and A. Volpe of CONTEPE and J. L. G. de Mendonça of DAEE, both in Araraguara, SP; F. V. Lopes of Azevedo and Travassos, São Paulo, SP; F. Conte, Jr., of HIDROLOG, Bauru, SP; engineers of SANEPAR, Curitiba, PR; Professor M. L. D. Wrege, UFRGS, Porto Alegre, RS; engineers of CPRM and CORSAM in Porto Alegre; engineers of SANESUL in Campo Grande, MS; Hector de Santa Ana of ANCAP, Montevideo, Uruguay; W. Heinzen of HIDROPLAN, Montevideo, Uruguay; J. N. Santa Cruz and O. Corrall of INCYTH; Dr. G. Chebli of Hunt Oil Argentina and Daniel Lanussol of YPF, both of Buenos Aires, Argentina; and P. M. Gonzales of HIDROGEON Drilling, Ciudad del Este, Paraguay.

Administrative and editorial support was supplied by C. H. Raffaeli, C. A. G. Pereira, C. Reis, G. J. S. Terra, and E. F Oliveira of PETROBRÁS. The authors thank Dr. Aldo Rebouças of São Paulo, SP, for his fine encouragement early in the study. P. E. Potter is most grateful to Geologia Sedimentar/UNESP (SP) and Geociências/UFRGS/Porto Alegre (RS), Brazil, for their support, 1993–1995 and 1996–1998, J. Barry Maynard of the University of Cincinnati and Alfred Clebsch of Denver kindly read early drafts of the manuscript; and Karen Kelly, Cincinnati, made the sketch of the Serra Geral escarpment. Ginny Chasteen, Cincinnati, kindly typed early versions of the manuscript. The authors are also most indebted to the two exceptionally constructive reviews by D. J. Bills, US Geological Survey, Flagstaff, Arizona, and by M. D. Mifflin, Mifflin and Associates, Las Vegas, Nevada.

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