Anais da Academia Brasileira de Ciências (2007) 79(2): 307-320
(Annals of the Brazilian Academy of Sciences)
ISSN 0001-3765
www.scielo.br/aabc

Structural control over well productivity in the Jundiaí River Catchment, Southeastern Brazil

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Manuscript received on February 2, 2006; accepted for publication on August 23, 2006;
presented by Yociteru Hasui

ABSTRACT

The well productivity in crystalline terrains is extremely changeable and depends on external factors, in addition to the intrinsic properties of rocks. In the Jundiaí River Catchment, Southeastern Brazil, the main factor that influences well productivity is the existence of open discontinuities permeability in geologic environments that favor groundwater recharge. In that area, Pre-Cambrian shear and fault zones were reactivated throughout geologic time, controlling the morphostructural compartments and the Cenozoic sedimentary deposition. Superposition of productivity data and structural maps showed that more productive wells are concentrated mainly along the regional geologic structures. The structural control over well productivity is also noticeable in detailed scale. Using fine scale maps we show that the most productive wells are located in areas where brittle structures with NW–SE and E–W directions denote the action of neotectonic transtensional stress. The comprehension of evolutionary geologic history allied to fracturing analysis proved to be an efficient and a low cost technique, which is adequate for selecting areas for further developments using more expensive methods.

Key words: groundwater, crystalline rocks, tectonics, Jundiaí, Southeastern Brazil.

INTRODUCTION

The industrialization in Southeastern Brazil, allied to a lack of investments in water resources management, brought the unbalance between water supply and water demand, particularly in the neighborhood of São Paulo Metropolitan Area, as the one studied in this report. This situation led to an increasing quest for groundwater, despite the unfavorable conditions of the geologic substratum. Most of the area is located in the crystalline basement, where groundwater behavior is complex and still is not very well understood.

The hydraulic behavior of the aquifers that occur in crystalline terrains is extremely variable and depends on the presence of rock discontinuities, among other factors. Many approaches have been developed to understand the variations of well productivity in crystalline terrains by defining a factor or a group of factors that influences groundwater flow (e.g. Le Grand 1954, Siddiqui and Parizek 1971, Yin and Brook 1992, Briz-Kishore 1993, Henriksen 1995, Mabee et al. 1994, Knopman and Hollyday 1996). The lithotype, the presence of sedimentary cover and/or weathering layer, the geologic structures, the tectonics and *in situ* tension are between the most studied factors.

In the Jundiaí River Catchment, the structural control on well productivity is pronounced, although influences of other factors may also exist (Neves 2005). In the present study we investigate the structural control

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through the analysis of well productivity variation according to the position of geologic structures, in regional and local scales. The Jundiaí River Catchment offers excellent opportunities for these studies due to the presence of geologic structures reactivated by tectonic events that control the landforms and the formation of sedimentary deposits. Furthermore, the occurrence of sedimentary coverings in the crystalline basement allows for the definition of geologic evolution and permits the identification of neotectonic activity.

MATERIALS AND METHODS

Well data compiled by Neves (2005) were obtained from the governmental agency responsible for water management in São Paulo State, the DAEE – *Departamento de Águas e Energia Elétrica* (Water and Electric Energy Department), from the CPRM – *Serviço Geológico Nacional* (National Geologic Survey) and from a well-drilling company. Only the wells that have measures of static level, dynamic level and pumping rate, besides co-ordinates for their location, were considered. The study relies on data from 590 wells that exploit the Crystalline Aquifer System, 33 wells that exploit the Tubarão Aquifer System and 25 that exploit both.

The specific capacity (m^3/h/m) was used in this work as the measure of well productivity. It is determined from a test that involves pumping a well at a constant rate and measuring the resulting drawdown in water level (Mace 1997). Such measure has been adopted as a representative parameter of well productivity (Bertachini 1988, Chilton and Foster 1995) and is also known as "Q/s".

The study was conducted in two ways: in regional scale, involving all the Jundiaí River Catchment and neighborhood, and in local scale, through the investigation of cases in several selected areas.

For the regional scale analysis (1:250,000), the simple planar surface was used to calculate the residuals map of specific capacity. The simple planar surface is defined as the surface that best fix to a group of mapped data and the residuals constitute local variations that deviate from the regional tendency toward negative or positive values, which are used for anomalies detection (Agterberg 1974, Davis 1986, Landim 2003). Thereby, the most productive wells appear in the residuals map as elevated positive residuals. These maps were superposed to the lineaments and regional structures maps in order to detect possible correlations by visual inspection.

The methodologies proposed by Liu (1987) and Wise (1982) were pursued for tracing lineaments, making use of radar imagery and aerial photographs. The term "lineament" was adopted according to O'Leary et al. (1976), who consider a lineament as a simple or composed linear feature whose parts are aligned in a rectilinear or curvilinear way, which differ from the adjacent feature patterns presumably as a reflex of a sub-superficial phenomenon.

In the local scale study (1:50,000), some areas were selected according to the availability of well and structural data collected in survey works or extracted from thematic maps. The explanations to the "productivity anomalies", i.e., to the situations where highly productive wells are close to lowly productive or unproductive wells, were investigated by constructing geologic-structural sections. Wells considered as "lowly productive" have specific capacity smaller than 0.05 m^3/h/m and the "highly productive" ones have specific capacity greater than or equal to 0.5 m^3/h/m.

CHARACTERIZATION OF THE STUDY AREA

The study area constitutes a rectangular polygon that involves all the Jundiaí River Catchment, between 46°30′ and 47°20′ W Gr. and 23°00′ and 23°20′ S (Figure 1). This basin is located less than 100 km from the Atlantic coast, but the mountains of the Atlantic Plateau direct the drainage towards inland. The Jundiaí River begins in the *Serra da Mantiqueira* (Mantiqueira Mountain Range), where the altitudes vary from 1,000 to 1,200 meters above sea level, and ends up in the Tietê River, in altitudes of approximately 550 meters (São Paulo 2000). The area of the basin is about 1,114 km^2 and its main tributaries are the Jundiaí-Mirim River and the Piraí Stream.

GEOLOGIC AND HYDROGEOLOGIC SETTING

Most of the catchment is located on the crystalline or Pre-Cambrian basement area (Figure 2a). Rocks of the Amparo Complex predominate, composed mainly of gneiss with intercalations of quartzites, schists and amphibolites (Hasui et al. 1981). In the southern part of the area, rocks of the São Roque Domain occur, which

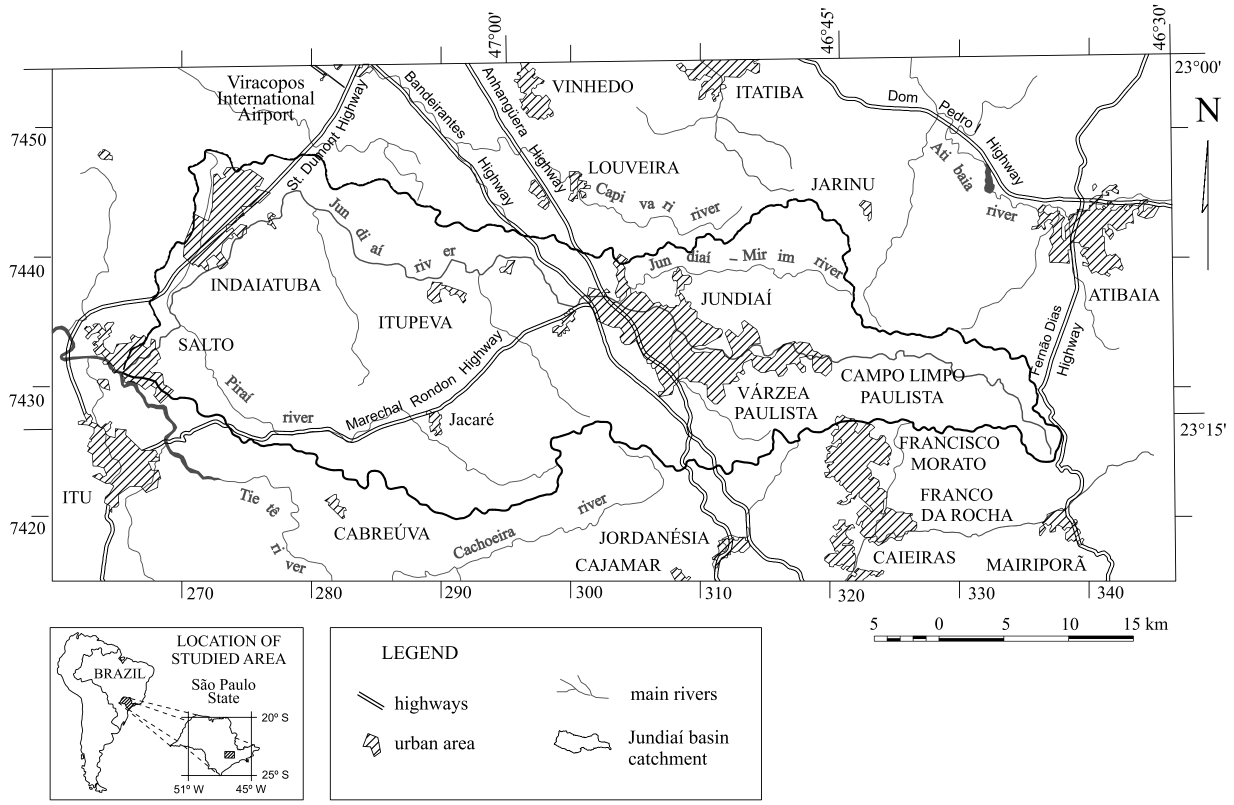

Fig. 1 – Location of the Jundiaí River Catchment, the main highways and urban areas.

is constituted mainly by phyllites with intercalations of quartzites and calc-silicate rocks, beyond schists, metacherts and marbles (Juliani and Beljavskis 1995). Granitic intrusions are very common for both units.

The Crystalline Aquifer System is composed of Pre-Cambrian basement units (Figure 2b) and, therefore, its permeability depends on the occurrence of discontinuities such as faults and joints and, sometimes, lithologic contacts (Neves 2005). Over the fractured rock, the weathering layer can form an aquifer of granular porosity, responsible by the most part of the catchment base flow (M.F.C. Lopes, unpublished data).

Sedimentary rocks of Paleozoic age belonging to Itararé Group occupy the west side of the area, in the Paraná Sedimentary Basin (Figure 2a), where compose the Tubarão Aquifer System (Figure 2b). The influence of glacial climate in the genesis of these rocks gives heterogeneous characteristics to them, as the vertical and horizontal compositional variability, which induces low permeability and limited potentiality to the aquifer (Stevaux et al. 1987, Diogo et al. 1984). Even where sandstone layers are considerably thick, there is a great variability of specific capacity of wells due to the layers discontinuity (A.C. Vidal, unpublished data).

Alluvial Quaternary deposits, that occupy the alluvial plain along the main rivers (Neves et al. 2005a), compose the Cenozoic Aquifer System (Figure 2b). Other sedimentary Cenozoic deposits are also present but do not form aquifers due to their restrict occurrence, just covering tops and hill slopes. These are the Tertiary deposits – that registry an ancient alluvial fan system originated from Japi Mountain Range – and the colluvial-elluvial deposits – spread along the hills (Neves et al. 2005b) (Figure 2a).

STRUCTURAL AND TECTONIC SETTING

Ductile shear zones and faults with regional extension (Figure 2a) compartment the area in tectonic blocks, control the relief, the deposition of sediments and the configuration of the Jundiaí River Catchment (Neves et

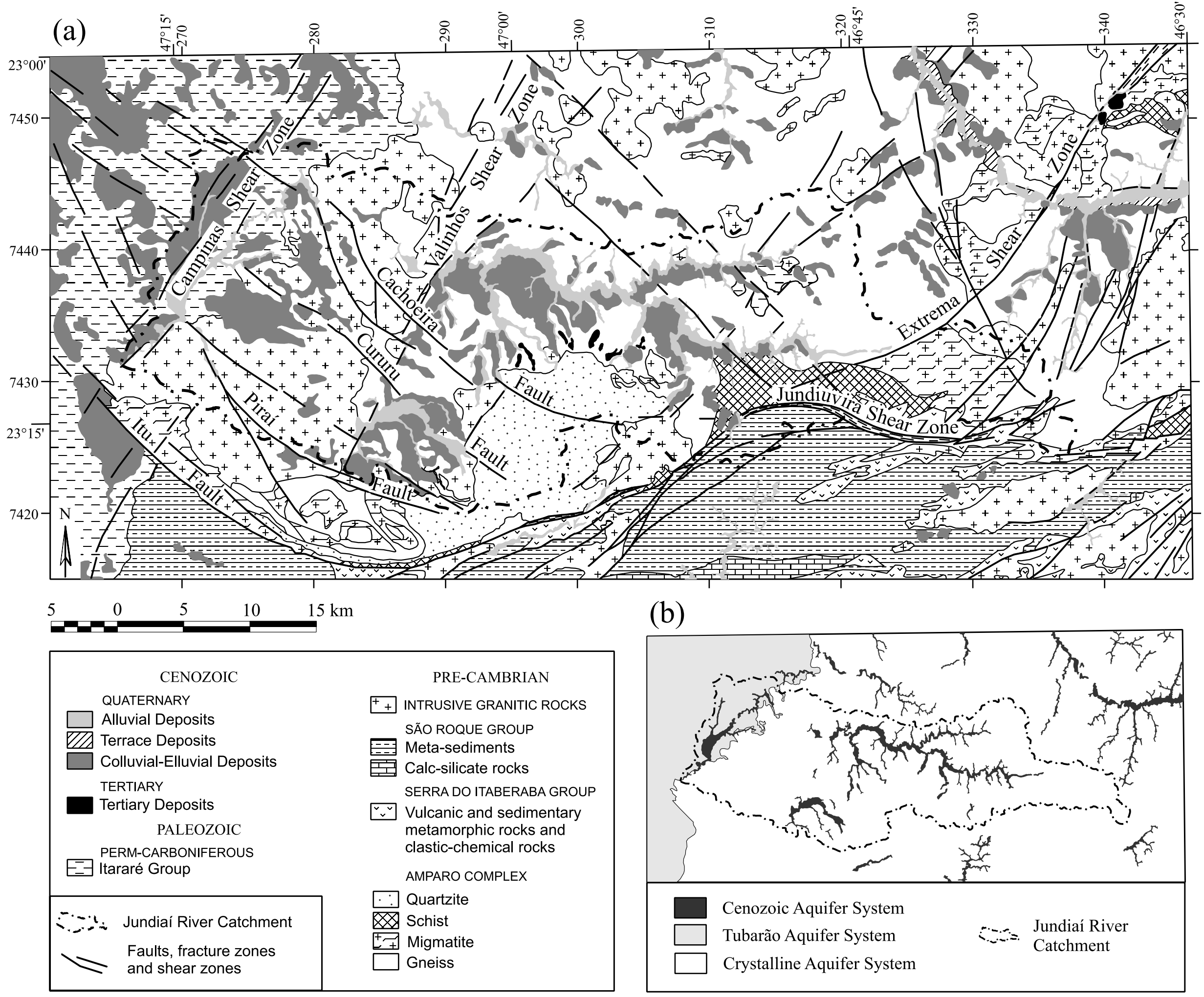

Fig. 2 – (a) Geologic map and (b) hydrogeologic map of the Jundiaí River Catchment.

al. 2003). The Jundiuvira Shear Zone (Figure 2a) has NE–SW direction that inflects to E–W, and the Itu, Piraí, Cururu and Cachoeira faults have NW–SE direction that also inflects to E–W (Hasui et al. 1978). The Valinhos and Campinas shear zones (Brasil 1979, S.R.F. Vlach 1985, unpublished data) are also important in this area and cross by the Jundiaí River Catchment following NNE–SSW to NE–SW directions (Neves 2005). The Extrema Shear Zone, with the same direction, cut the east side of the area, in the Atibaia region.

Such structures, inherited from the Pre-Cambrian, arose under ductile conditions and developed outstanding mylonitic foliation and mineral remobilization. Throughout geologic time, the conditions became more and more brittle, but the tectonic tensions continued being alleviated along those regional geologic structures. In other words, the Pre-Cambrian structures acted as crustal weakness zones during all the geologic evolution of the area.

From this evolutionary history it is important to define two main tectonic phases, which understanding is fundamental to this work: the extensional regime that acted in the Gondwana break-up and the transcurrent neotectonic regime that came later.

The extensional regime, that culminated with the continental separation, had a regional tensor with σ_1 vertical, σ_2 NE–SW horizontal and σ_3 NW–SE horizontal (Figure 3a). Under this arrangement, normal faults and open joints arise predominantly in NE–SW direction and there is tendency of opening in discontinuities with NE–SW direction inherited from the Pre-Cambrian.

This extensional regime progressively was substituted by a transcurrent regime linked to the rotation of the South-American Plate to the West, process that has been defined as a neotectonic event (e.g. Hasui 1990, Saadi 1993, Riccomini and Assumpção 1999). Some divergences exist in the literature about the neotectonic deformational events, but there is an agreement with respect to the existence of a transcurrent dextral phase, that would be unique or, at least, very important. Under this regime, a conjugated pair of tensions acts along the E–W direction (Figure 3b) and tends to form open discontinuities in NW–SE direction and transcurrent dextral faults in E–W direction, between other structures.

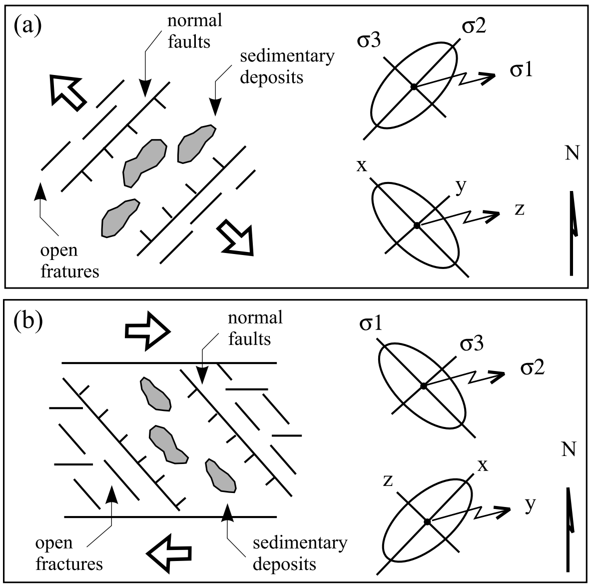

Fig. 3 – Regional tectonic movements with the principal structures that arisen out and the tension and deformation ellipsoids of (a) the extensional regime, that acted from Upper Cretaceous up to the Paleogene and (b) the dextral transcurrent regime, initiated on Neogene.

VARIATION OF WELL PRODUCTIVITY IN REGIONAL SCALE

Superposition of the lineament and structural maps and the residual maps of specific capacity were done separately to wells that exploit the Crystalline Aquifer System, the Tubarão Aquifer System and both systems. The positive residuals show places that correspond to more productive wells, that are detached relating to others, i.e., they indicate productivity anomalies.

PRODUCTIVITY AND LINEAMENTS

In the Crystalline Aquifer System, association between productivity anomalies and lineament density is not observable, neither to that traced in regional scale nor to that traced in more detailed scale (Figure 4). The same occur with the wells that exploit the Tubarão Aquifer System and with the wells that exploit both the aquifers (Figure 5).

In those areas with low lineaments density, the sedimentary covers generally are present and the weathering layer tends to be thicker. Thus, the lineaments become disguised and cannot be observed in the remote sensing images. However, where the fracture density is greater, the rocks are easily attacked by weathering and, depending on their original composition, highly permeable material can be formed. Therefore, one could expect the presence of positive residuals in locations where low lineaments density occur.

PRODUCTIVITY AND REGIONAL STRUCTURES

The superposition of specific capacity residual maps and the map of faults and shear zones show close associative relations between some productivity anomalies and the structural traces (Figure 6).

The most prominent point with positive residual value occurs close to the Cachoeira Fault. Similarly, there are points of positive anomalies throughout the Valinhos Shear Zone, in its intersection with the Cururu Fault, in the Campinas Shear Zone and next the Itu Fault. Between the faults with NW–SE direction that control the scarps of the Jardim Mountain Range, and throughout there, points with high positive residuals can also be seen.

Points with high productivity unlinked to the trace of regional structures exist only in two regions. One of them is the central portion of the area and the other is southward to the Jundiuvira Shear Zone. The last one is associated to the presence of the carbonatic metassediments of the São Roque Domain, which have an important hole in high well yields (Neves 2005). On the other hand, the positive anomalies located in the central

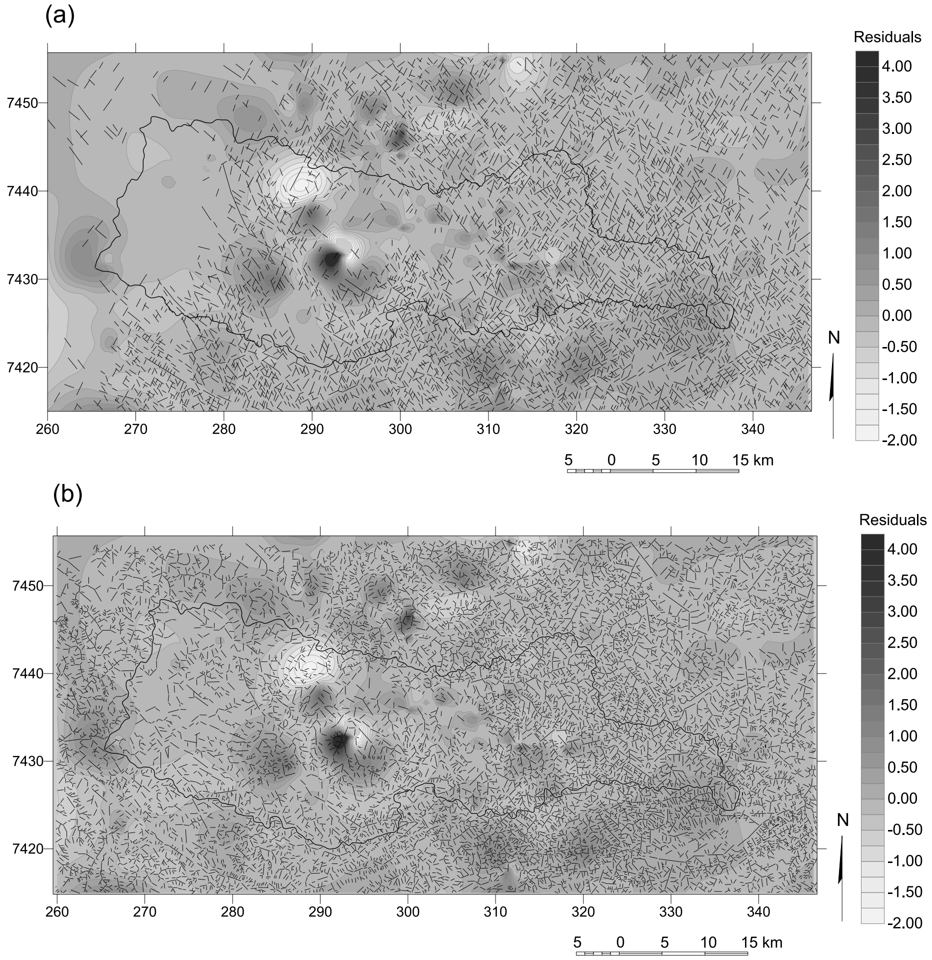

Fig. 4 – Residual maps of specific capacity of wells that exploit the Crystalline Aquifer System with the lineaments traced from (a) the radar images in 1:250.000 scale and (b) the aerial photography in 1:60.000 scale.

region are due to the morphostructural compartments. Central region is relatively depressed and surrounded by the mountains that delimitate the Jundiaí River Catchment and by the structural barrier of Itu granitic massive (Neves et al. 2003).

The positive productivity anomalies of wells that exploit the Tubarão Aquifer System and that exploit both aquifers also have a notable association with the regional structures (Figure 7). The points with high positive residuals are associated to the Campinas Shear Zone, which crosses the area in NNE–SSW direction. Although the Tubarão Aquifer System is a porous aquifer, the structural control also plays an important hole. Indeed, springs were detected along joints that affect sandstones of the Tubarão Group (Neves 2005).

VARIATION OF WELL PRODUCTIVITY IN LOCAL SCALE

Although there is a close association between the regional geologic structures and the presence of highly productive wells, the analysis in local scale (1:50,000 or more) show that even in the areas where highly productive wells occur, other wells with low productivity also exist. The heterogeneity of the fractured rock gives rise to situations where one well cross a productive fractured zone meanwhile other, next to it, cross the massive rock.

Several similar cases were identified in the studied area. In most of them the median specific capacity (considering all wells) is superior to the median calculated for the sample that exploit the Crystalline Aquifer System of the area as a whole ($Q/s_{med} = 0.07\ m^3/h/m$). In

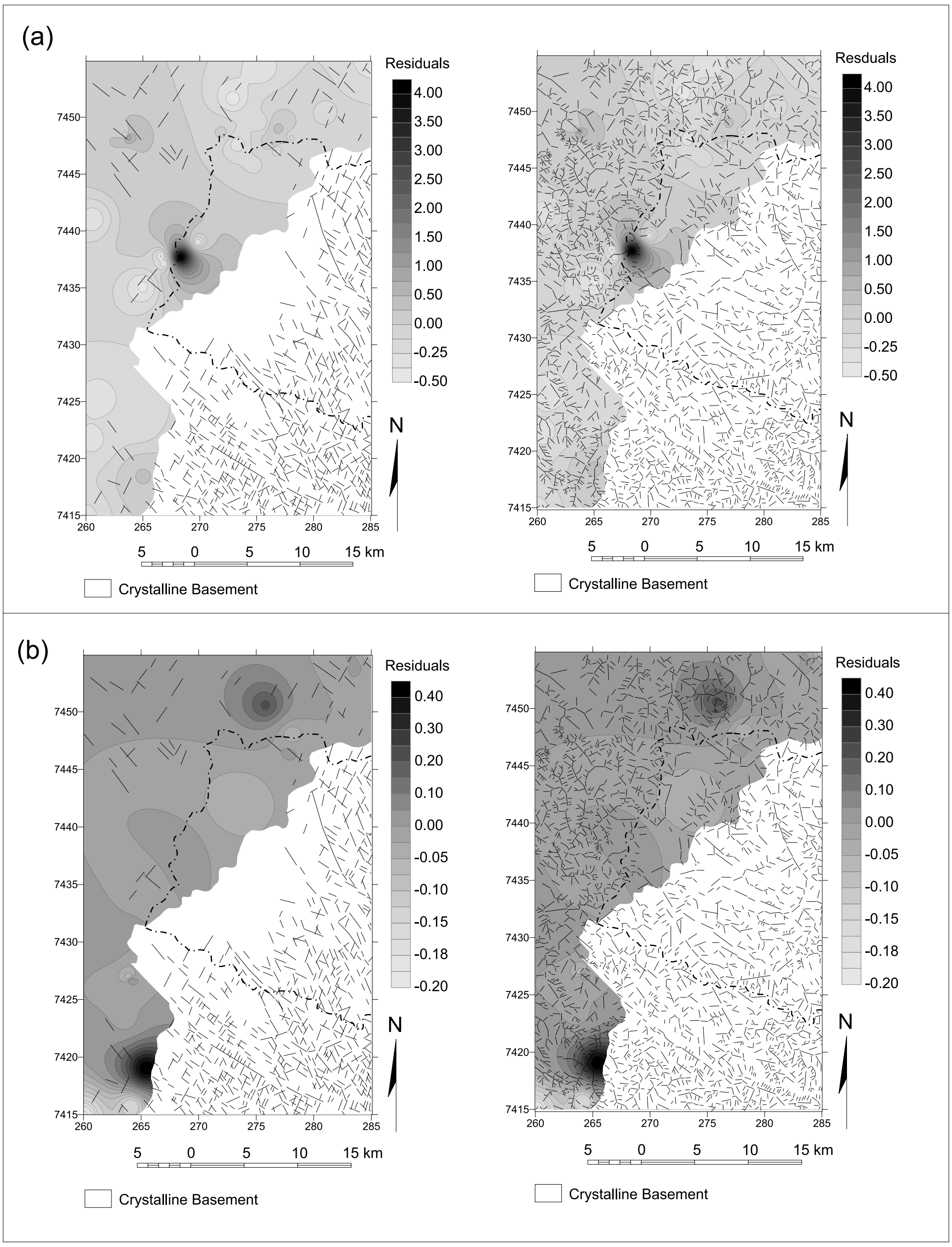

Fig. 5 – Residual maps of specific capacity of wells that exploit (a) the Tubarão Aquifer System and (b) both aquifers, besides the lineaments traced from the radar images in 1:250.000 scale and the aerial photography in 1:60.000 scale.

all of these areas, the presence of lineaments and structures with NW–SE and E–W directions is striking. Three typical examples are presented below.

Highly Productive Wells from Cabreúva

In the Cabreúva region, there are gneisses, migmatites, quartizites and granites of the crystalline basement, as well as Cenozoic colluvial-elluvial and alluvial deposits (Figure 8). The Piraí Fault, in the NW–SE direction and other structures in E–W and N–S directions cut this area. Although the Piraí fault appears as a simple trace, it is, in fact, a fault zone of changeable thickness, dipping with high angle towards southwest. The structures with E–W directions also have high dip angle and form fracture

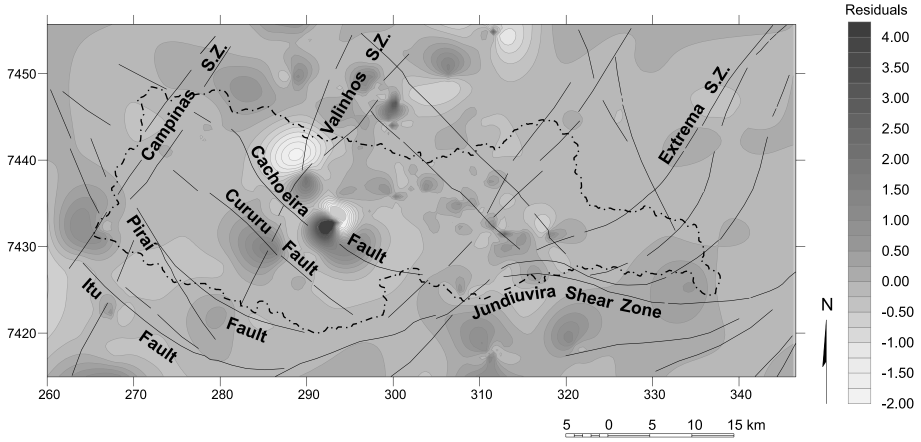

Fig. 6 – Specific capacity residual map of wells that exploit the Crystalline Aquifer System and its relation with shear zones and regional faults.

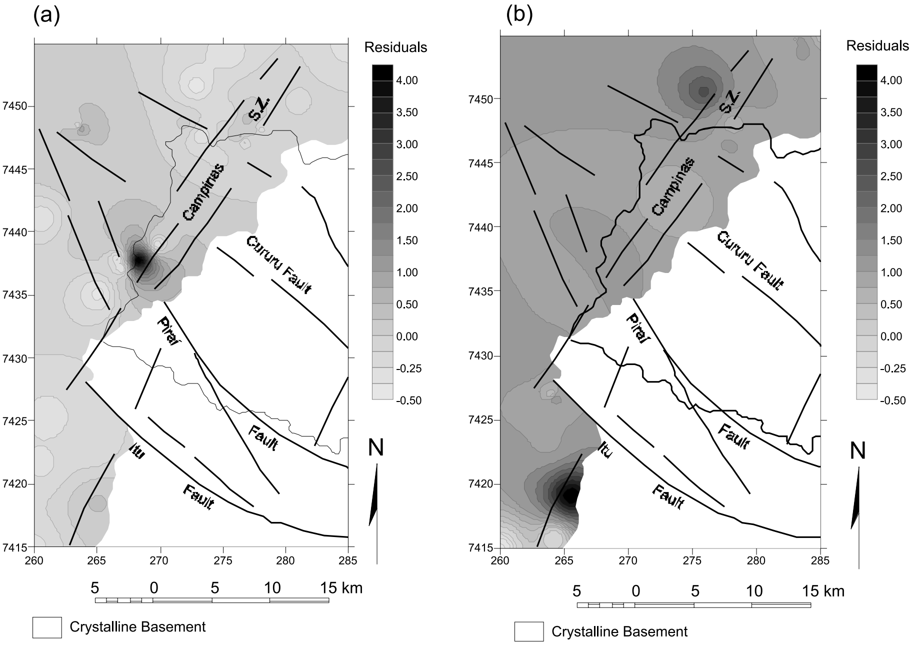

Fig. 7 – Residual map of specific capacity of wells that exploit (a) the Tubarão Aquifer System and (b) the wells that exploit both aquifers and the shear zones and regional faults.

zones that intercept the NW–SE and N–S discontinuities in sites where accumulation of alluvial sediments occur.

The median specific capacity of wells in this area is equal to 0.08 $m^3/h/m$, greater than the median specific capacity calculated to the area as a whole by one order of magnitude. To analyze the structural influence in the spatial variation of productivity, the wells number 626, 630 and 2580/99 were selected, the first one with specific capacity equal to 0.56 $m^3/h/m$ and the two others with specific capacity of 0.05 and 0.04 $m^3/h/m$, respectively. The geological sections illustrated in the Figure 8 show the 626 well crossing, in subsurface, the structures with NW–SE and E–W directions, which provide the high productivity to the well. The wells number 630 and

2580/99 are located near the same structures, but do not intercept the main structures in depth and, consequently, their productivities are low.

HIGHLY PRODUCTIVE WELLS FROM JACARÉ DISTRICT

Another similar case was identified in the Jacaré District, near the Marechal Rondon Highway (Figure 9). Two important structures cross this area: the Cururu Fault, with NW–SE direction and high dip to SW, and the Valinhos Shear Zone, with NNE–SSW direction and also high dip to ESE. There are E–W structures, which control Cenozoic deposits occurrences, as well as N–S structures that control the relief dissection giving rise to ravines with the same direction.

In this place, the median specific capacity of wells is equal to 0.05 m^3/h/m, minor than the median specific capacity of wells in the crystalline. But one of the wells has high productivity: the well number 301/48, with specific capacity equal to 1.61 m^3/h/m. The other two selected wells have low productivity: the well number 81, with 0.03 m^3/h/m and the well number 44, with 0.04 m^3/h/m. The geological sections (Figure 9) show that, even located near similar lineaments, the productivity are very different depending on the location relating to the geologic structures in subsurface.

HIGHLY PRODUCTIVE WELLS FROM LOUVEIRA

The third case involves the Louveira County, where granites and gneisses of Amparo Complex, alluvial deposits in the Capivari river alluvial plain and colluvial-elluvial deposits along of its margins coexist (Figure 10). A high number of wells exist in this area, whose median specific capacity is equal to 0.15 m^3/h/m, almost two times the median of the Crystalline System of the whole area. This case stands out by the presence of E–W and NW–SE lineaments and, furthermore, a ramification of the Valinhos Shear Zone crossing the area in NNE–SSW direction.

Geological sections were constructed in two locations where four wells in situations clearly controlled by structures are present (Figure 10). The wells number 711 and 727 have productivity considered high (specific capacities of 1.22 and 1.17 m^3/h/m, respectively) and the wells number 737 and 6570 demonstrate low productivity (0.17 and 0.02 m^3/h/m).

DISCUSSION

Statistic correlations between productivity of wells and their distance to lineaments, length of lineaments, density of lineaments or number of lineament intersections is a common method used to evaluate the chances of finding groundwater in crystalline terrains (e.g. Hardcastle 1995, Loiselle and Evans 1995, Mayer and Sharp 1998). However, some authors emphasize that an intrinsic subjectivity of lineament tracing does exist (Wise 1982, Tam et al. 2004). Others suggest applying "reproducibility tests" by selecting just the traces that two or more professionals consider as lineaments (Mabee et al. 1994, Sander et al. 1997).

In addition, the structural characterization of the features that are revealed in the lineaments, such as their typology, the dip angle and other particular characteristics is of fundamental importance. In the studied area, the simple superposition of maps was capable to show that correlations between positive productivity anomalies and the density of lineaments do not exist in both of the applied scales (Figures 4 and 5). The reason for this is that the sedimentary covering and the thick weathering layer can mask the geologic structures of the underlying basement and, consequently, the different lineament densities that one observe in the remote sensing imagery do not necessarily reflect the fracturing rate of the geologic substratum. Otherwise, one important characteristics of this area is the conspicuous contrast between landforms with sedimentary cover and pediments beside of others with exposed rocks and rough relief. The first ones tend to show low lineament density and, according to Singhal and Gupta (1999), greater capacity for groundwater supplying.

The study in regional scale show that the specific capacity anomalies tend to occur besides the regional structures represented by the shear zones and the fault zones that delineate the morphostructural compartments. One fact that reaffirms the influence of these structures in the groundwater flow at relatively high depths is the presence of thermal water springs along the Valinhos Shear Zone registered by Hasui et al. (1989). The association between highly productive wells and regional structures that are similar to the ones that occur in the studied area (NW–SE and NNE–SSW directions) was also identified in the Campinas region by Fernandes and

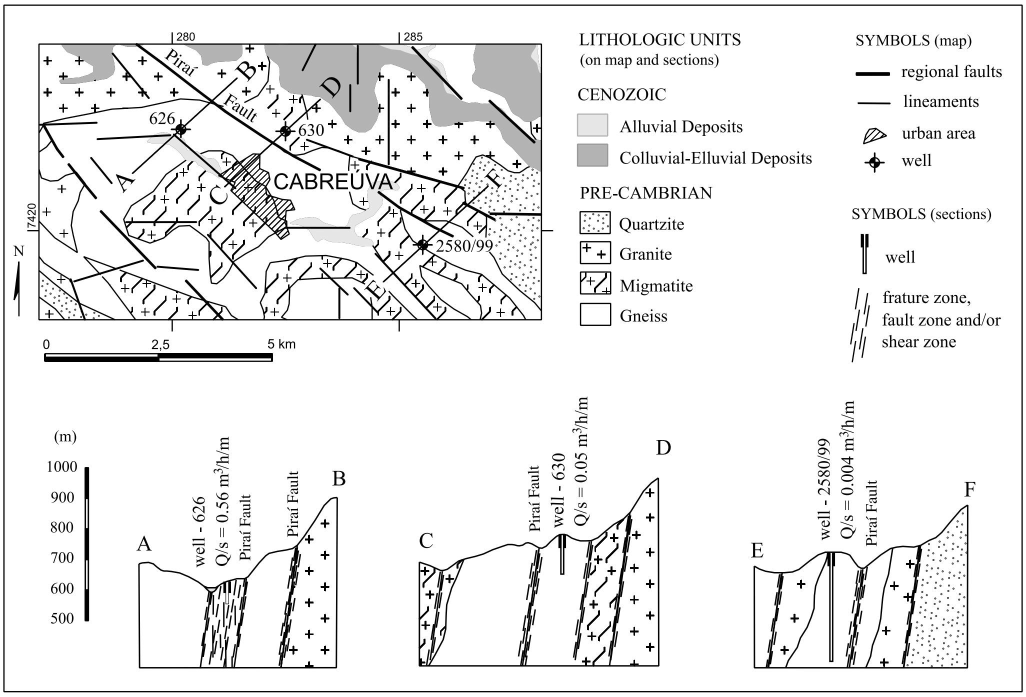

Fig. 8 – The case study of Cabreúva County, where there is control by NW–SE and E–W structures in well productivity.

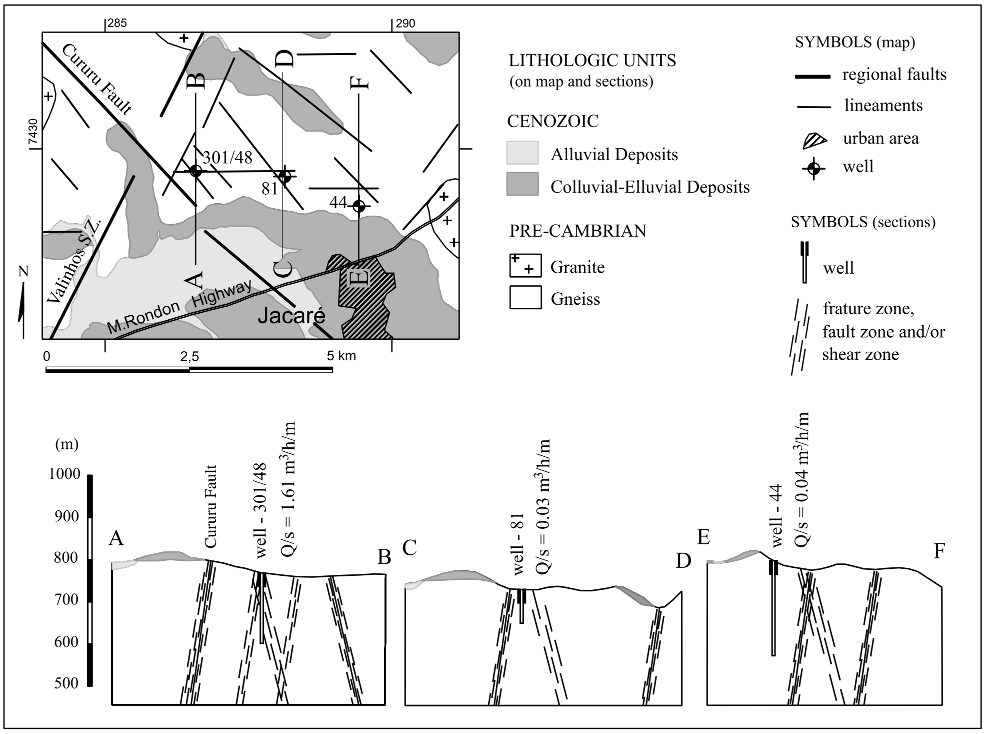

Fig. 9 – The second case study, in the neighborhood of Jacaré District. The high productivity of one well is associated with NW–SE and E–W lineaments.

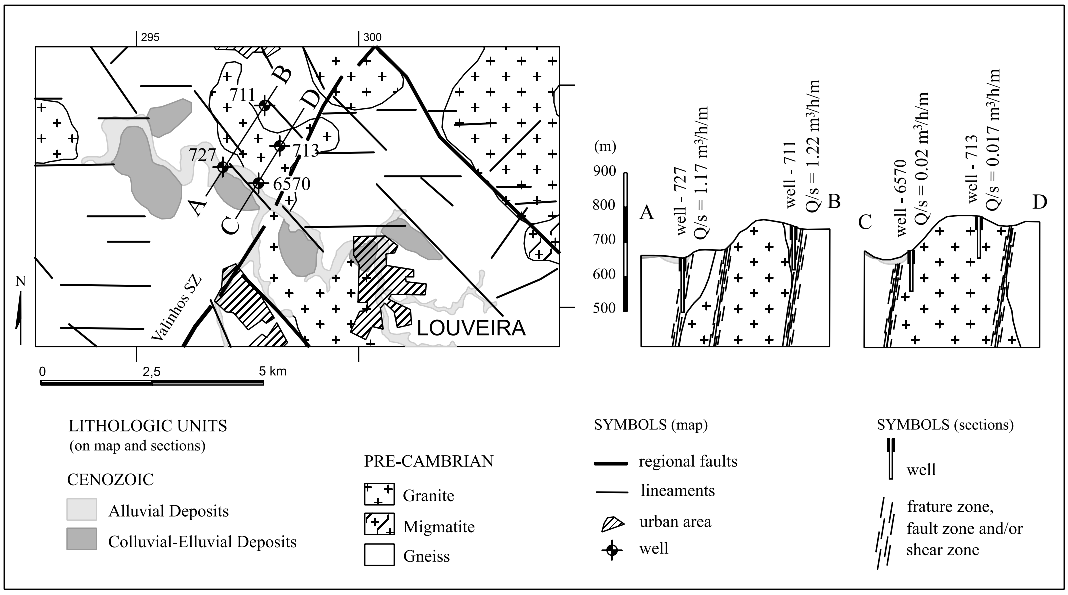

Fig. 10 – The third case study, in the proximities of Louveira, where wells with high productivity are associated to structural sheaves with NW–SE and E–W directions.

Rudolph (2001), who considered them as opened by neotectonic events.

Gustafsson and Krásn (1994) affirm that intensively fractured zones, with dozens kilometers in extension, can form great hydraulic conductors, meanwhile other authors call attention to the fact that not always regional structures are in fact the most productive (e.g. Banks et al. 1992, Nilsen 1998). The discontinuity filling would be an important factor in this case, because the major fractured zones tend to develop clayey filling by the alteration of fragmented material. But the kind of filling depends on the original material and, if the rock is rich in quartz, as granites, gneiss and quartzites, which are abundant in the studied area, the altered material can be highly permeable (Davis and Turk 1964, Singhal and Gupta 1999, Neves 2005).

Although the existence of fractures is a fundamental factor to defining well productivity in crystalline terrain, certain characteristics such as their aperture should be favorable to groundwater flow (Lachassagne et al. 2001, Banks et al. 1996, Banks and Robins 2002). The formation of open discontinuities and/or the opening of pre-existent discontinuities occur according to the orientation of the major horizontal tectonic tension. In this way, the effects of the extensional tectonic in NE–SW structures and the transtensional effects of the transcurrent tectonic in NW–SE structures are of a prime importance to groundwater flow in the fractured rock, mainly if they are associated to others of E–W directions.

However, the fact that one structure is favorable to percolation of water does not indicate that it is related to neotectonic tension action. Older structures can also remain opened through geologic time, especially in intraplate setting, where tectonic tensions are smaller than in plate borders.

CONCLUSIONS

The morphostructural compartment limits, marked by shear zones and regional faults, are favorable sites to obtain productive wells. Nevertheless, the wells should be located favorably to the structural dip and, further, the structures should be originally opened or submitted to extensional tensions during tectonic reactivations.

According to the fracturing analysis and the definition of geologic evolution, the geological structures potentially opened have NE–SW direction (fracture zones associated to the extensional tectonic that worked from the final of Mesozoic to the beginning of Tertiary), NW–SE direction (normal faults and open fractures formed or reactivated by the neotectonic event) and E–W direction (very important when associated to the NW–SE structures, that characterize transtensional zones).

Associated to the geologic evolution study, the structural analysis can be used to indicate the structures or the areas that provide higher chances of obtaining productive wells. For a precise location of wells, the studies in regional scale are necessary and are as important as the study in detailed scale.

ACKNOWLEDGMENTS

The financial support for this research was given by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). The authors thank Jundsondas Poços Artesianos for the furnishing of well data, Prof. Dr. Yociteru Hasui for the initial revision of this paper and the anonymous reviewers of the journal Anais da Academia Brasileira de Ciências for the valorous suggestions.

RESUMO

A produtividade dos poços tubulares profundos em terrenos cristalinos é extremamente variável e depende, além das propriedades intrínsecas da rocha, de fatores externos a ela. Na bacia do rio Jundiaí, Região Sudeste do Brasil, a existência de descontinuidades abertas em situações geológicas favoráveis à recarga constitui o principal fator que influencia a produtividade dos poços. Nesta área, zonas de cisalhamento e zonas de falhas pré-cambrianas reativadas ao longo do tempo geológico controlam a compartimentação morfoestrutural e a deposição de sedimentos cenozóicos. O cruzamento do mapa estrutural com os dados dos poços que explotam o Sistema Aqüífero Cristalino mostrou que poços com produtividade elevada em relação aos demais concentram-se ao longo das estruturas regionais. O forte controle estrutural sobre a produtividade dos poços também é notável em escala de detalhe. Nesta escala, constatou-se que os poços mais produtivos situam-se em áreas onde estruturas rúpteis de direção NW–SE e E–W denotam a ação de esforços transtrativos neotectônicos. A compreensão da história evolutiva aliada à análise do fraturamento mostrou ser uma técnica eficiente e de baixo custo, conveniente para ser utilizada na seleção de áreas onde, posteriormente, métodos mais dispendiosos poderão ser aplicados.

Palavras-chave: água subterrânea, rochas cristalinas, tectônica, Jundiaí, Sudeste do Brasil.

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