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PIMENTEIRA FORMATION (DEVONIAN, PARNAÍBA BASIN): A NEW PROSPECT FOR HYDROCARBON RESERVOIRS

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Resumo – O registro sedimentar de regressões forçadas consiste freqüentemente em um pacote de sedimentos marinhos macroclásticos, limitado acima e abaixo por lutitos. O conceito de regressão forçada trata de uma queda relativa do nível do mar, associada à migração da linha de costa bacia adentro, com subseqüente progradação da linha de praia, seguido de transgressão marinha. Tal mecanismo é de grande importância por posicionar potenciais rochas-reservatório em direto contato com as rochas geradoras. A Formação Pimenteira (Devoniano) é entendida pela literatura como tendo sido depositada em uma paleoplataforma marinha, com eventual aporte de areias por processos induzidos por tempestade. Durante estudo estratigráfico de testemunhos de sondagem dessa formação, foi observado um intervalo arenoso com características de rocha-reservatório, lateralmente contínuo (>140 km), formando um pacote com cerca de 20 m de espessura em contato brusco com os siltitos e folhelhos sobrejacentes e subjacentes. Entretanto, o pacote observado é aqui interpretado como resultante de uma regressão forçada, fato este nunca discutido na literatura. Esta observação permite interpretar novos prospectos para possível acumulação de hidrocarbonetos na bacia do Parnaíba, visto que os folhelhos orgânicos desta formação são considerados os principais geradores da bacia e que tais arenitos constituir-se-iam potenciais reservatórios.

Palavras-Chave: Bacia do Parnaíba; Sistemas Petrolíferos; Regressão Forçada; Devoniano; Geologia de Reservatórios

Abstract – The sedimentary record of forced regressions often consists of a package of macroclastic marine sediments limited, above and below, by mudstones. The concept of forced regression involves a relative sea-level fall, which results in a basin ward migration of the coastline with subsequent shoreline progradation, followed by a marine transgression. Such mechanism is of great importance since it places potential reservoir rocks in direct contact with source rocks. The Pimenteira Formation (Devonian) is considered by the literature as deposited in an ancient marine shelf, with eventual sand transport by storm induced processes. During a stratigraphic study of cores from this formation, a laterally continuous (>140 km) sandstone package with reservoir rock characteristics was observed, with average 20 m of thickness, sharply overlying siltstones and shales. Such sandstone package is here interpreted as resultant of a forced regression, a fact never mentioned before by the literature. This observation allows the interpretation of new prospects for possible hydrocarbon accumulations in the Parnaíba Basin, since the organic shales of this formation are the main source rocks of this basin and such sandstone packages would constitute potential reservoir rocks.

Keywords: Parnaíba Basin; Petroleum Systems; Forced Regression; Devonian; Reservoir Geology

1. Introduction

The Parnaíba Basin is a large (600.000 km^2) Paleozoic intracratonic basin located in Northeast Brazil (Figure 1). The basin was prospected for oil and gas until the early 90s, but was abandoned after that due to the lack of commercial findings. The petroleum system of the basin, according to Milani & Zalán (1998), is the Pimenteira–Cabeças (!). Nowadays the Brazilian National Petroleum Agency (ANP) classifies the Parnaíba Basin as a frontier basin.

The Pimenteira Formation, of Devonian age (Givetian–Frasnian), is composed mainly of shales with subordinate sandstones, and is interpreted as deposited in an ancient storm dominated interior sea or "shelf" (Della Fávera, 1990). The thick shale intervals of the Pimenteira Formation, especially those of Frasnian age, are considered the main source rocks of the basin (Rodrigues, 1995).

Young (2003), during a stratigraphic analysis of the Pimenteira Formation using cores and well logs from the projects *São Miguel do Tapuio* (Albuquerque *et al.,* 1972) and *Fosfato de São Miguel do Tapuio* (Oliveira & Barros, 1976) – both executed in the East border of the basin (Figure 1) – described a thick (20 m), sharp-based, and laterally continuous (>140 km) sandstone interval encased in offshore siltstones and shales (Figure 2). This sandstone interval was previously identified by Oliveira & Barros (1976), but a detailed evaluation of its facies, spatial distribution and stratigraphic significance was not carried by these authors. This interval was informally named "B" sandstone (*sensu* Oliveira & Barros, 1976) and was interpreted by Young (2003) as the result of an event of forced regression (*sensu* Posamentier *et al.*, 1992).

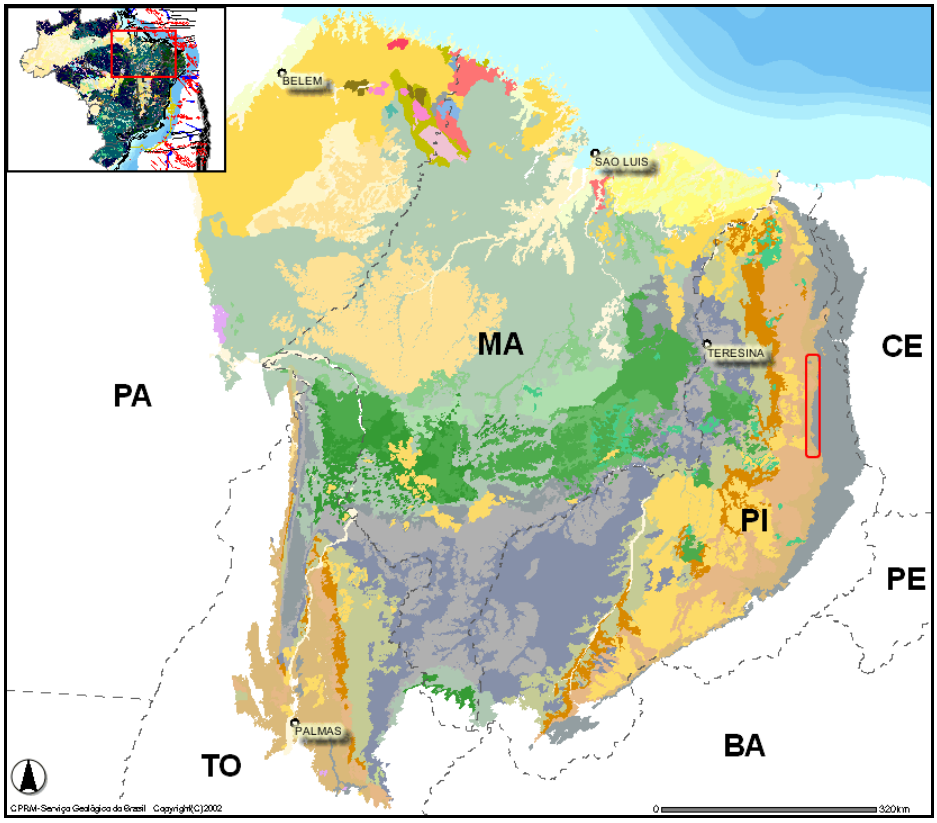

Figure 1. Location map of the Parnaíba Basin. The basin is located in Northeast Brazil, mainly in the states of Piauí (PI) and Maranhão (MA). The red rectangle delineates the studied area, where the gray color represents the Serra Grande Group and the Itaim Formation, the beige color the Pimenteira and Cabeças formations, and other colors represent units above the Cabeças Formation (modified from CPRM, 2002, used with permission).

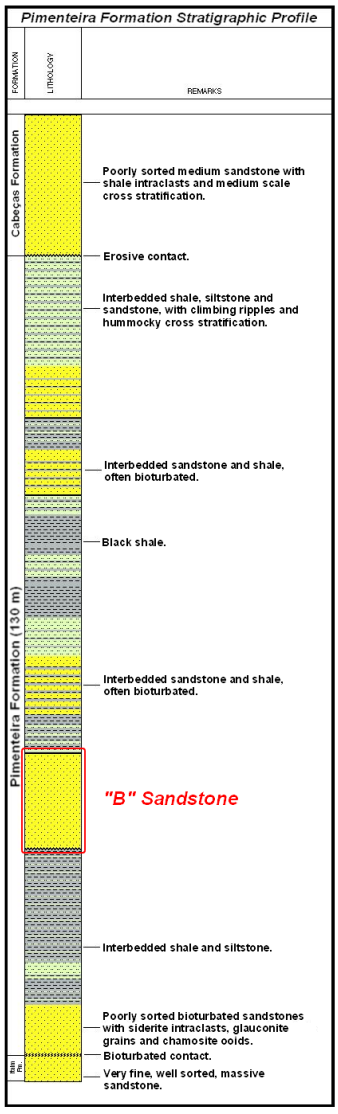

Figure 2. Stratigraphic profile of the Pimenteira Formation in the studied area. The "B" sandstone is highlighted in red.

2. Forced regressions: stratigraphic significance and petroleum exploration importance

Forced regressions are basin wide events. Such events produce sharp-based, narrow (<12 km) and relatively coarse-grained proximal deposits encased in distal, offshore mudstones (Posamentier *et al.*, 1992). These detached sandstone bodies in

the shelf are of great importance for petroleum exploration due to their potential as reservoir rocks within source rocks (offshore mudstones). This setting is of extreme value in the Alberta Basin, Canada, where it has resulted in considerable oil accumulations (*q.v.* Krause *et al.*, 1987).

The Parnaíba Basin has a complex petroleum system, due to the fact that the main source rocks of the basin, the Pimenteira Formation shales, have not reached thermal maturity to generate oil due to its shallow burial depths (Rodrigues, 1995). This fact restricts oil generation to the thermal effect of intrusive diabase sills and dikes, a situation that requires very favorable conditions for oil migration and accumulation so as to generate commercial oil fields. In this situation, sandstone bodies deposited by events of forced regression could potentially work as preferred paths for migration and accumulation of oil and gas due to their direct contact with the source rocks.

3. Facies and petrophysics of the "B" sandstone

The "B" sandstone is composed of three sedimentary facies, and it sharply overlies (Figure 3A) the shales and siltstones. Facies 1 (Figure 3B) consists of massive, very fine sandstones with occasional shale or siderite intraclasts. It has porosity (ϕ) of 23% and permeability (k) of 65 mD, and is interpreted as the deposit of high density turbidity currents. Facies 2 (Figure 3C) represents very fine sandstones with hummocky cross stratification, with ϕ = 21% and k = 8 mD. This facies is interpreted as the result of the reworking of bottom sands by storm waves. Facies 3

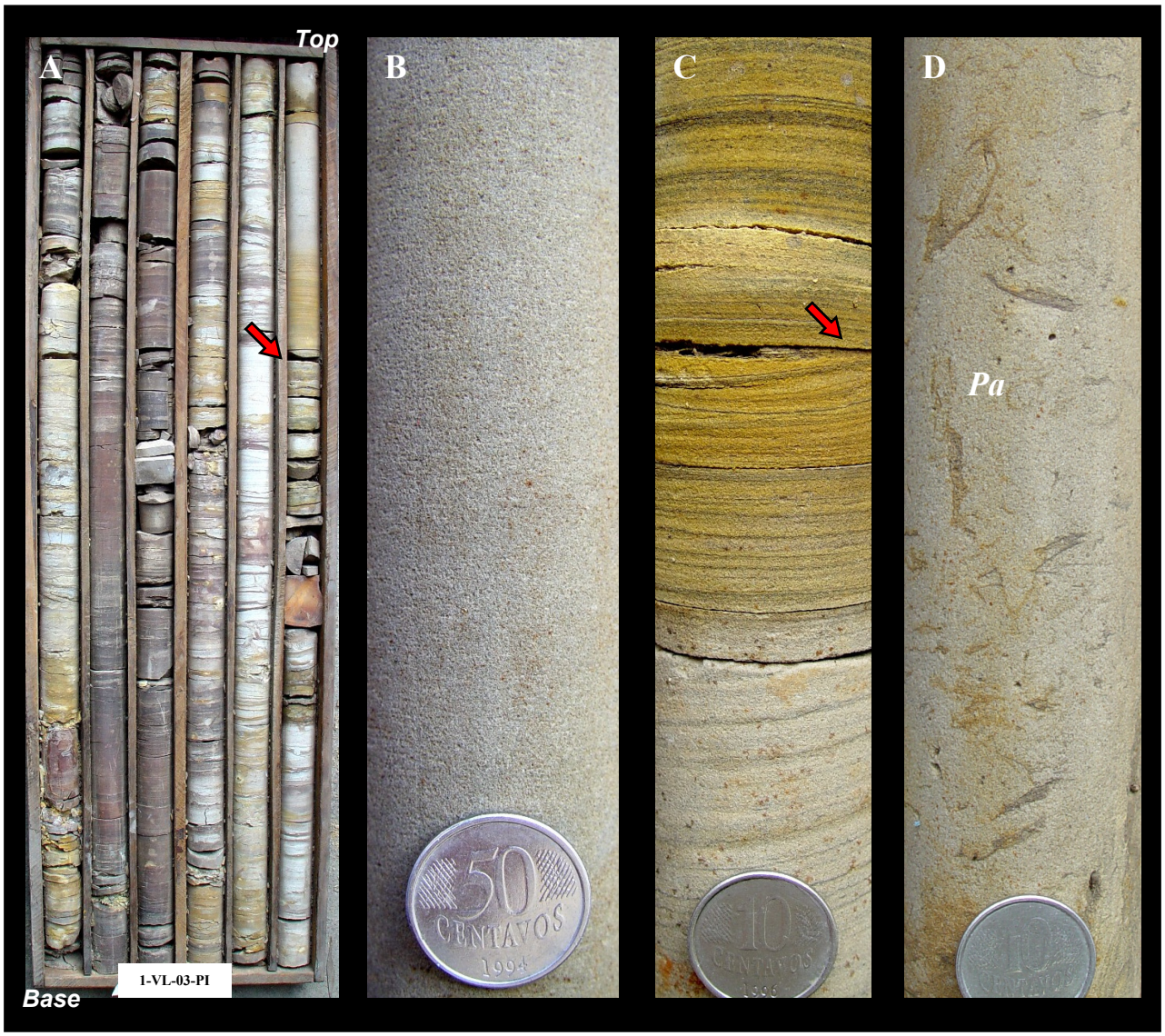

Figure 3. A) Well 1-VL-03-PI, interval 46.1–52.1 m, illustrating the sharp base of the "B" sandstone (arrow) and the underlying siltstones and shales; box height is 1 m. B) Facies 1, massive very fine sandstone. C) Facies 2, very fine sandstone, showing normal grading and hummocky cross stratification; note the truncating laminae (arrow). D) Facies 3, bioturbated very fine sandstone with *Palaeophycus* isp. (Pa) burrows. 50¢ coin has diameter of 2,2 centimeters; 10¢ coin has diameter of 2 centimeters.

(Figure 3D) consists of very fine sandstones, extremely bioturbated (*Asterosoma* isp., *Cylindrichnus* isp., *Palaeophycus* isp., *Planolites* isp., *Rosselia* isp., *Skolithos* isp. and *Teichichnus* isp.) with $\phi = 20\%$ and k = 0,1 mD, and represents the burrowing activity of benthic organisms in yet unconsolidated sediments during fair-weather. The usual cyclic facies succession consists of facies 1, followed by facies 2 and finally by facies 3, although facies 1 may occur truncating facies 2 or even amalgamated with another facies 1. The "B" sandstone belongs to the *Cruziana* ichnofacies whereas the encasing siltstones and shales belong to the *Zoophycos* ichnofacies.

4. Spatial distribution and structural characteristics of the "B" sandstone

Figure 4 is a North–South cross section with selected wells which illustrates the "B" sandstone and its encasing siltstones and shales. It shows that the "B" sandstone has a tendency to thicken northwards, and that its maximum (24 m) and minimum (13 m) thicknesses are observed in wells 1-CT-01-PI and 1-VL-03-PI, respectively. Nevertheless, its northern and southern limits are currently unknown. The thickening-northwards tendency is further emphasized in its isopach map (Figure 5A), which shows all wells that drilled through the entire section of the "B" sandstone in the study area.

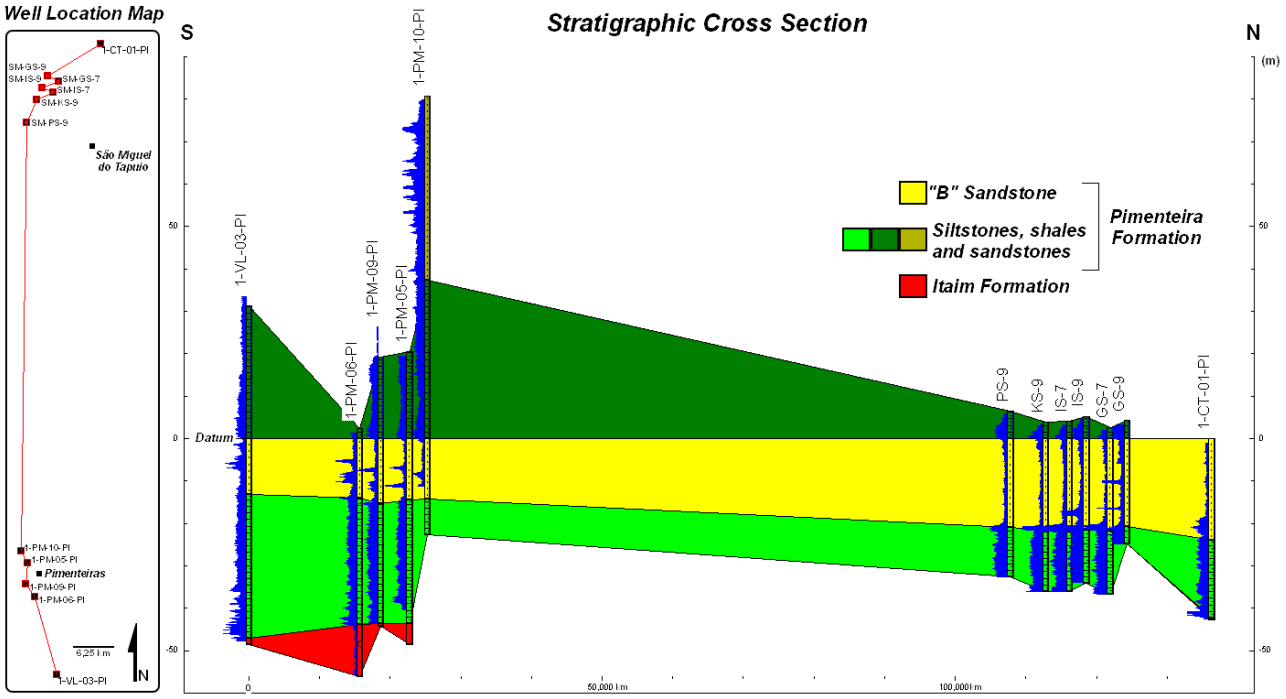

Figure 4. Stratigraphic cross section with well location map, illustrating the "B" sandstone, its encasing siltstones and shales, and the Itaim Formation. The "B" sandstone shows a tendency to thicken northwards. Correlation datum is the top of the "B" sandstone. The blue curve is the Gamma Ray log, which increases to the left.

Figure 5B is a structural contour map of the top of the "B" sandstone. It shows that the "B" sandstone presently occurs in a segmented form due to post depositional tectonics, with apparent graben-like structures. The contour map in Figure 5C has the same data set of Figure 6 but was built using a different method of interpolation, with directional weighting to the NW direction. This NW direction corresponds to the main tectonic pattern in the area, as reported by Oliveira & Barros (1976). It also corresponds to one of the main tectonic lineaments of the whole basin, the Picos–Santa Inês Lineament (Cunha, 1986). In this new map, the structural style of the area is more clearly observed, showing graben and horst structures controlling the depth to the top of the "B" sandstone.

5. Final remarks

Since forced regression are basin wide events, the identification of such event in the East border of the basin could lead to the reinterpretation of other sandstone bodies in the Pimenteira Formation as genetically similar, such as the Carolina Member of Carozzi *et al.* (1975). This creates potentially new exploration prospects, with source and reservoir rocks in the Pimenteira Formation, differently from the one commonly used, which consider the Cabeças Formation (Frasnian–Famenian age) the main reservoir. Also, the forced regression stratigraphic model used in this

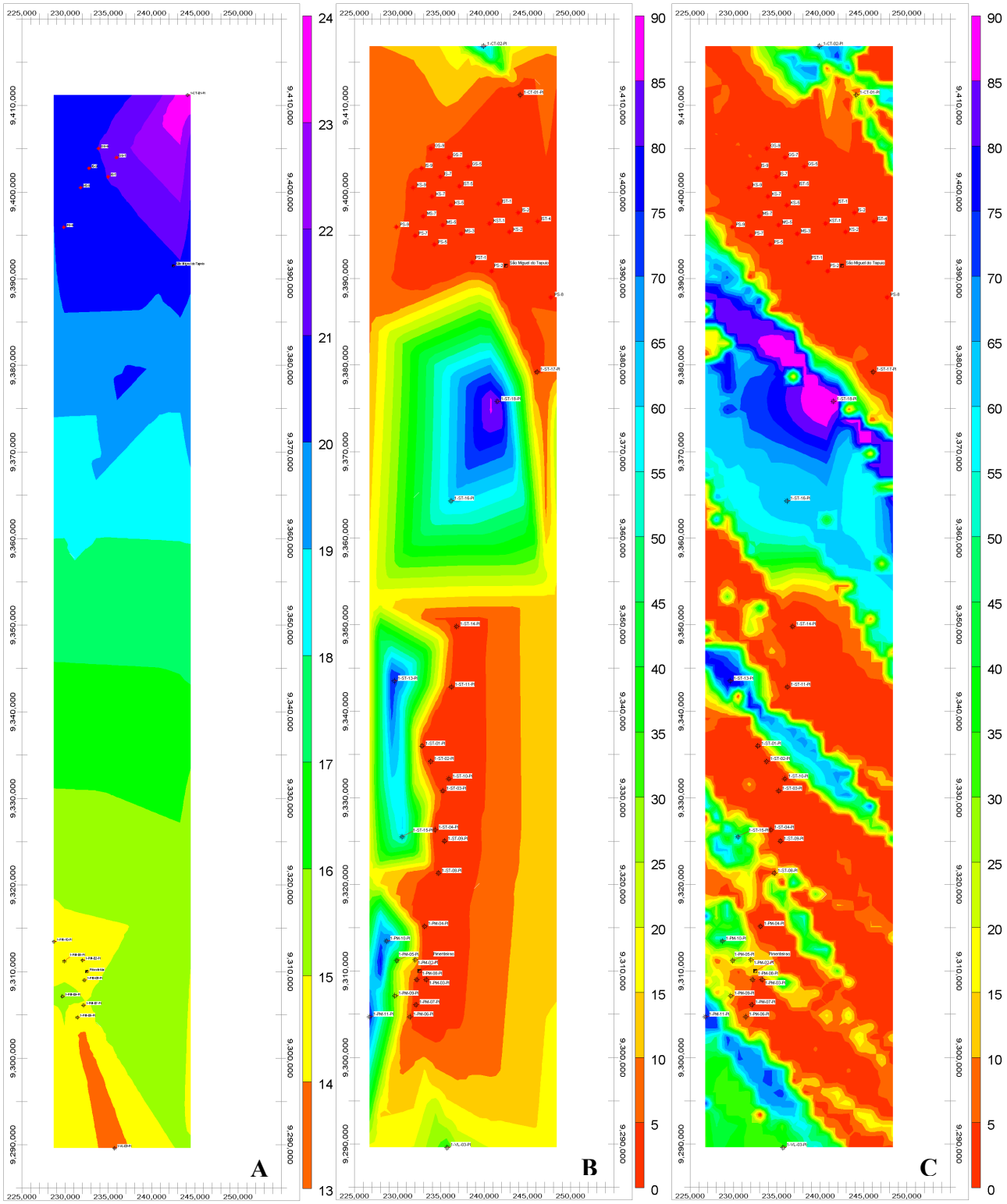

Figure 5. A) Isopach map of the "B" sandstone, showing its tendency to thicken northwards. B) Structural contour map of the top of the "B" sandstone, which shows highs and lows with depth differences of up to 80 m. C) Structural contour map of the top of the "B" sandstone built with a NW-SE directional weighting; this map shows strong NW-SE oriented graben-like structures. All maps use UTM (m) unit. Thicknesses (Figure 5A) and depths (Figures 5B and 5C) are in meters.

study differs fundamentally from the one proposed and used by Della Fávera (1990) and Albuquerque (2000), which consider all sandstones intervals of the Pimenteira Formation as resultant of deltaic progradational events.

Further, depending on spatial distribution of the "B" sandstone, such beds could be used as an excellent stratigraphic marker for long-range correlations.

Structurally, the pattern observed in the stratigraphic maps roughly corresponds to the basin's structural pattern, which means that eventual production from a reservoir with such characteristics must take into consideration its probable compartmentalization.

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