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ARTICLE

Analysis of the geometry of diabase sills of the Serra Geral magmatism, by 2D seismic interpretation, in Guareí region, São Paulo, Paraná basin, Brazil

Análise da geometria de soleiras de diabásio do magmatismo Serra Geral, por interpretação sísmica 2D, na região de Guareí, São Paulo, Bacia do Paraná, Brasil

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ABSTRACT: The Paraná Basin holds in its stratigraphic record a thick layer of volcanic rocks related to the opening of the Gondwana Supercontinent, which occurred during the Eocretaceous. Based on the interpretation of three two-dimensional (2D) seismic lines in the region of Guareí, East-Central São Paulo state, in the Southeast of Brazil, the subsurface geometries of these volcanic rocks were identified. Since the original seismic resolution quality was low, alternative techniques were utilized to improve the seismic imaging, such as isolating maximum and minimum amplitude values by manipulating the color scale, and using the root mean square (RMS) attribute and the Amplitude Volume technique (tecVA), which emphasize the seismic signature of igneous rocks in relation to sedimentary layers. The use of such techniques allowed the identification of different geometries of diabase sills and showed a relationship between these intrusive and organic matter maturation of the source rock.

KEYWORDS: Geometry of sills; Serra Geral magmatism; Amplitude analysis.

RESUMO: *A Bacia do Paraná possui em seu registro estratigráfico uma espessa camada de rochas vulcânicas relacionadas à abertura do Supercontinente Gondwana, ocorrida durante o Eocretáceo. Por meio da interpretação de três linhas sísmicas em duas dimensões (2D), localizadas na região de Guareí, centro-leste do estado de São Paulo, Sudeste do Brasil, foram identificadas as geometrias dessas rochas vulcânicas em subsuperfície. Como a qualidade da resolução sísmica original era baixa, foram utilizadas técnicas alternativas para melhorar o imageamento sísmico, como o isolamento de valores máximos e mínimos de amplitude pela manipulação da escala de cores, mediante o uso do atributo root meansquare (RMS) e a técnica Volume de Amplitude (tecVA), as quais enfatizaram as rochas ígenas em relação às camadas sedimentares. A utilização dessas técnicas permitiu a identificação de diferentes tipos de soleiras de diabásio, além de sua relação com a maturação da matéria orgânica nas rochas geradoras.*

PALAVRAS-CHAVE: *Geometria de soleiras; Magmatismo Serra Geral; Análise de amplitude.*

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INTRODUCTION

Regardless of the tectonic context of a sedimentary basin, the presence of magmatic rocks in its stratigraphic record is recurring. It is very important to understand the origin, the structure and the geometry of magmatic intrusions, when trying to assess the economic impact of those occurrences in sedimentary basins with hydrocarbon exploration potential.

In some sedimentary basins, igneous rocks can be classified as elements of the petroleum system, as reservoir rocks and seals, or as forming structural traps which hold the oil. In addition, the heat from magmatic rocks can help in the maturation of the organic matter contained in hydrocarbon source rocks (Magoon & Dow 1994).

Reservoir rocks of magmatic origin occur in several oilfields in the Liaohe Basin, China (Chen *et al.* 1999). In the Neuqén Basin, Argentina, oil and gas are found in the fractures of diabase sills intruded in the source rocks (Schiuma 1988). In Brazil, the oilfields of Badejo and Linguado, located in the southern portion of the Campos Basin, produce oil from fractured basalt.

Diabase dikes and sills, as well as basalt flows, can act as effective sealing rocks, especially when not altered or fractured. Basaltic flows and dikes occur as vertical and lateral seals, respectively, in the oil and gas fields of Dapingfang and Huangjindai, Liaohe Basin, China. Diabase sills act as sealing rocks in the Barra Bonita gas field, Paraná Basin (Eiras & Filho 2003).

Conceição *et al.* (1993) studied and classified the structures induced by magmatic intrusions in the Brazilian intracratonic basins, on the basis of the igneous bodies, and the structural elements present in the enveloping rock.

In intracratonic basins with low heat flow, such as the Brazilian Paleozoic syneclises, several authors studied how magmatic intrusions helped in the maturation of the organic matter, as Rodrigues *et al.* (1990) in the Solimões Basin, Rodrigues (1995) in the Parnaíba Basin, Alves & Rodrigues (2002) in the Amazonas Basin, and De Souza *et al.* (2005) in the Paraná Basin.

Given those prior studies, this work sought to characterize the geometry of the diabase sills of the Serra Geral Formation, Early Cretaceous age, which occur in the stratigraphic record of the Paraná Basin, specifically in the region of Guareí, East-Central São Paulo state, in southeastern Brazil, based on patterns observed in two-dimensional (2D) seismic lines, since those magmatic rocks may be directly related to the development of the petroleum systems of the basin.

PARANÁ BASIN

The area of study is within the tectonic and stratigraphic context of the Paraná Basin, a Paleozoic syneclise composed of magmatic and sedimentary rocks with ages from the Ordovician to the Cretaceous (Zalan *et al.* 1991), which cover the meridional portions of Brazil and part of Paraguay, Argentina and Uruguay, with a total area of approximately 1.4 million km^2 (Fig. 1).

According to Milani *et al.* (2007), the stratigraphic record of the basin is divided into six tectonic sequences separated by interregional unconformities: the Ivaí River (Ordovician-Silurian), Paraná (Devonian), Gondwana I (Carboniferous-Lower Triassic), Gondwana II (Middle to Upper Triassic), Gondwana III (Upper Jurassic-Lower Cretaceous), and Bauru (Upper Cretaceous).

The igneous rocks present in the stratigraphic record of the Paraná Basin are related to the Gondwana Supercontinent rupture (200 Ma), which resulted in the opening of the Atlantic Ocean, at about 120 Ma (Mizusaki & Thomaz-Filho 2004). This major geodynamic episode was registered in the Paraná Basin during the Early Cretaceous as a magmatism of tholeiitic and calc-alkaline basalts, with subordinate rhyolites and rhyodacites, which characterize the Serra Geral Formation (Peate *et al.* 1992).

The Serra Geral Formation is constituted by a thick pile of lava flows, which can reach thicknesses of 2.000 m in some regions (Fig. 1). It is characterized by a network of dikes, cutting the entire Paleozoic-Mesozoic sedimentary succession, and multiple diabase sills that intrude into the stratification planes of Paleozoic sediments, preferentially along Irati Formation horizons (Mizusaki & Thomaz-Filho 2004).

Considering the basin scale, several authors (Milani 1997, Milani & Zalán 1999, Araújo *et al.* 2000, Correa & Pereira 2005) emphasize the heat deriving from the diabase sills directly influenced the maturation of the organic matter present in the shales of Irati Formation. In this way, the main petroleum system of the Parana Basin — Irati–Rio Bonito/Piramboia(!) — is defined as a non-conventional petroleum system, according to Magoon & Dow (1994).

Loutfi (2011) analyzed biomarker and isotope data on oil samples found in Rio Bonito Formation and associated them to the Assistência Member of Irati Formation. Other authors (Cabral 2006, Serafim 2011, Vital 2012) also ratified the oil found in the sandstones of Piramboia Formation is related to organic matter generated in the shales of Irati Formation.

Thomaz Filho (1982), in reference to Quadros (1981), suggests that the intense fracturing caused by Serra Geral magmatism during the Early Cretaceous initially contributed to the migration of oil generated in Irati Formation towards the intercalated limestones, which acted as a sort of intermediate reservoir, from where, in a subsequent stage, the oil migrated to the eolian sandstones of Piramboia Formation (Fig. 2). In that same model, the author also associates the structural control caused by the diabase dikes to the horizontal entrapment of oil accumulations.

Considering the local scale context, Araújo *et al.* (2005) emphasize the main control for trap formation, maturation of organic matter, and migration pathways for oil, is the structural network dominated by NW and NE lineaments that arose during the tectonic episode in the Juro-Cretaceous.

The geologic map of the study area allows the visualization of the main lineaments described by Araújo *et al.* (2005), confirming there is a structural control, imposed by faults, in the contact between Piramboia Formation (Triassic) and Teresina Formations (Permian), as well as in Irati Formation, encircled by the younger Teresina and Serra Alta Formations (Fig. 3).

MATERIALS AND METHODS

The data used in this work are located in the township of Guareí, East-Central São Paulo state, in southeastern Brazil. The region was studied in the past due to the occurrence of oil sands, which led to an interest in seismic surveys and exploratory wells in the region. The present project included the interpretation of three 2D post-stack seismic on time domain (0240-0025, 0240-0026 and 0240-0027), from the acquisition 0240_PARANÁ_51 made by Petróleo Brasileiro S.A. (Petrobras) in 1992, in addition to the analysis of two wells (1-GU-4-SP and 1-CP-1-SP), which intercept those lines (Fig. 3).

There is no information on the acquisition and processing of these lines besides the dates they occurred: 1992 and 2000, respectively. The data does not include any embedded information in its language that could assist interpretation, only the basic parameters to visualize the seismic stack such as number of samples, samples interval in ms for each trace and the navigation file.

Therefore, the phase and polarity of the seismic was established using subsurface features that can generate high amplitude reflections (Brown 2011) such as igneous intrusions in contrast to the enveloping sediment. This relationship was observed in the well 1-CP-01-SP, where the transition from the sediments to a diabase sill with 110 m thick shows a decreasing of slowness (sonic log) and increasing of density log. It is also observed in the amplitude of the seismic reflectors, where the entrance of the sill is reflected by a peak in the seismic amplitude (from sediments to igneous) while the exit shows the opposite behavior, configuring a trough (Fig. 4).

Araújo *et al.* (2005) report some troubles with seismic surveys of Paraná Basin, because of the thick volcanic rock packages hamper seismic imaging. Thus, the use of filters, seeking to minimize noise and consequently improve imaging, was one of the most important stages of the processing adopted in this work. The methodology also involved the calibration of seismic lines with synthetic seismograms

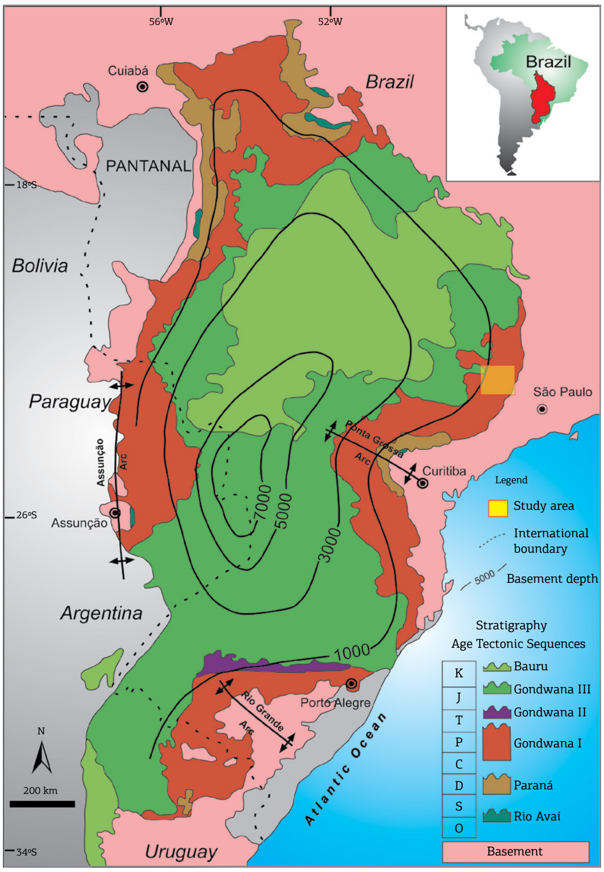

Figure 1. Location and simplified geological map of Paraná Basin. Modified from Zalán (1991).

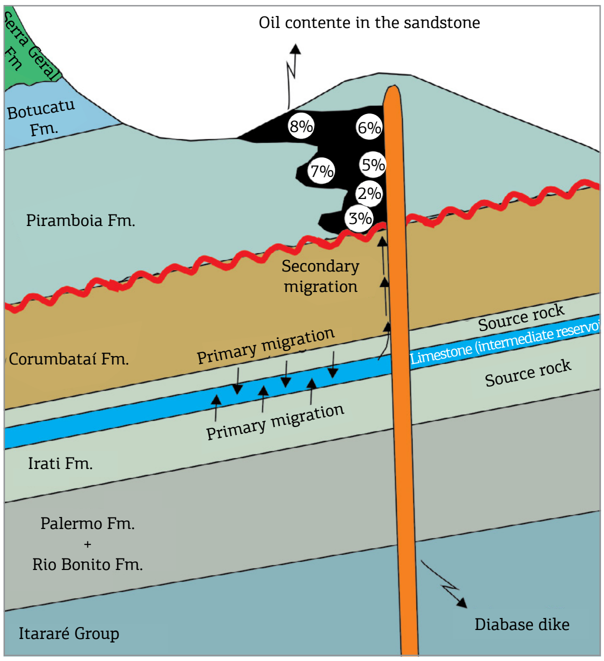

Figure 2. Oil migration scheme in petroleum system Irati-Piramboia(!), adapted from Thomaz Filho 1982.

based on the well logs, extraction of seismic attributes, seismic-stratigraphic analysis of the main horizons, and, finally, interpretation of the main faults and diabase sills.

It is important to emphasize that, with a poor seismic resolution, the main ally in interpretation was the condition that the petroleum system is outcropping, which provides direct analogues and subsurface indicators.

The techniques used were: isolation of maximum and minimum amplitude values by manipulating the color chart; the root mean square (RMS) attribute; and the Amplitude Volume technique (tecVA).

The isolation of the maximum (10,000 to 25,000) as well as the minimum (-10,000 to -25,000) absolute amplitudes by choosing green and yellow colors — over a grayscale for low and medium amplitudes —, emphasized great impedance contrasts associated with igneous bodies in contact with sedimentary rocks, as in the works of Porto (2013) and Costa (2015).

Even with this approach, the seismic imaging showed many colored points related to noise, so that it was necessary to extract RMS attributes, and subsequently use tecVA in order to isolate only the amplitude anomalies with geological significance.

The RMS attribute measures the reflectivity along a time window using the square root of the sum of the square of amplitudes, divided by the number of samples. As a result, both positive and negative maximum amplitudes are emphasized in relation to minimum amplitudes.

The RMS is used as input data to extract tecVA, a technique initially used to emphasize faciological variation and highlight layers. It is calculated empirically using high impedance contrast through the rotation of the zero phase to -90º. As a result, shales signatures are considered background and sandstones, conglomerates, volcanics, intrusives, source rocks, limestones, among others, are the emphasized layers (Bulhões & Amorim 2005).

The output data obtained with the technique comprises amplitude data and the fluctuations of the seismic fundamental frequency (amplitude, frequency and modulated phase). Thus, this technique has the potential to show that small fluctuations can reveal features such as faults and channels (Bulhões & Amorim 2005). Due to the high density of intrusive rocks in the stratigraphic record of Paraná Basin, these seismic discontinuities can also indicate dikes and sills.

Applying this attribute to the data points where the main contrasts are given by the presence of intrusive rocks, the tecVA allowed to identify sills, the pattern of their geometry, their relation with the enveloping rocks, and their association with other structures, such as possibly smaller feeding dikes. The same technique was successfully used by Oreiro *et al.* (2008) when studying the Upper Cretaceous and Paleogene magmatism at the border between Campos and Santos Basins.

THEORETICAL FOUNDATIONS

The migration and storage of magma in Earth's crust represent very important geological processes. Neumann *et al.* (2003) believe that the understanding of

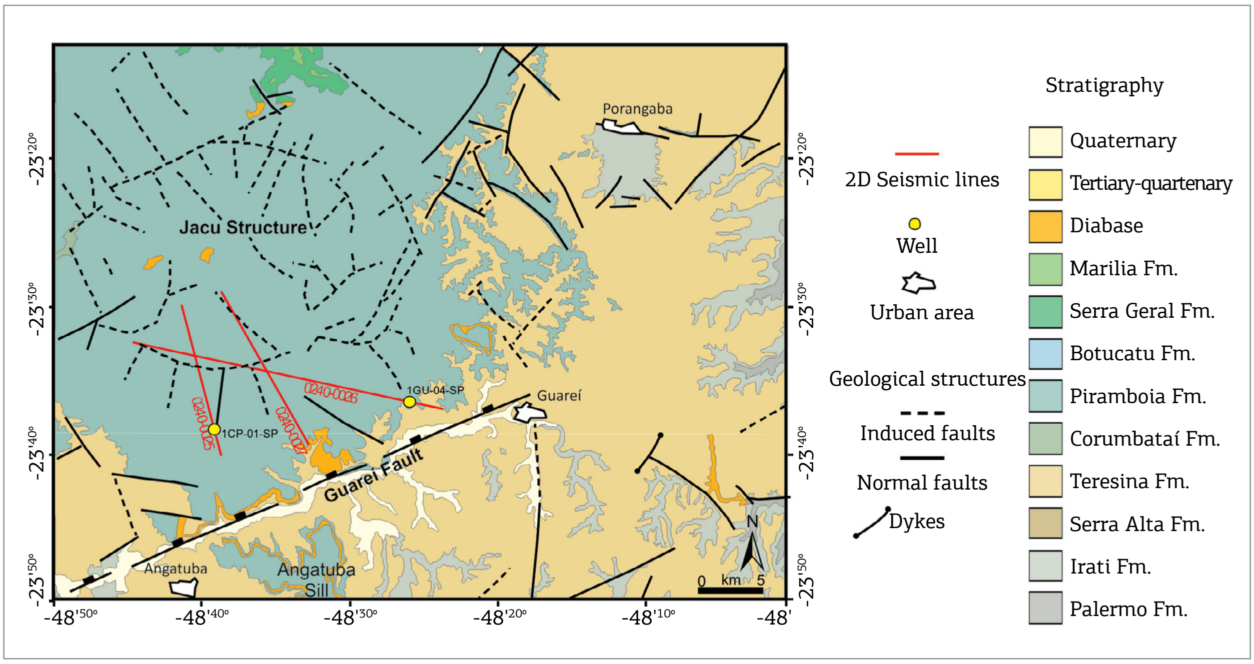

Figure 3. Geologic map of the study area and location of seismic and well data.

these processes has important implications in the comprehension of the evolutionary dynamics of a volcano-sedimentary basin. Thus, it is necessary to recognize the different forms in which magmatism may manifest itself.

Tabular or sheet intrusions, such as dikes, sills and laccoliths are the most common types of magmatic bodies included in Earth's crust. Dikes are vertical to subvertical magma fill along fractures, mainly controlled by magma buoyancy properties at high temperatures. Sills, on the other hand, while also tabular, are predominantly parallel to the bedding of the host rock. Laccoliths, while also parallel to the bedding of the enveloping rock, differ from sills due

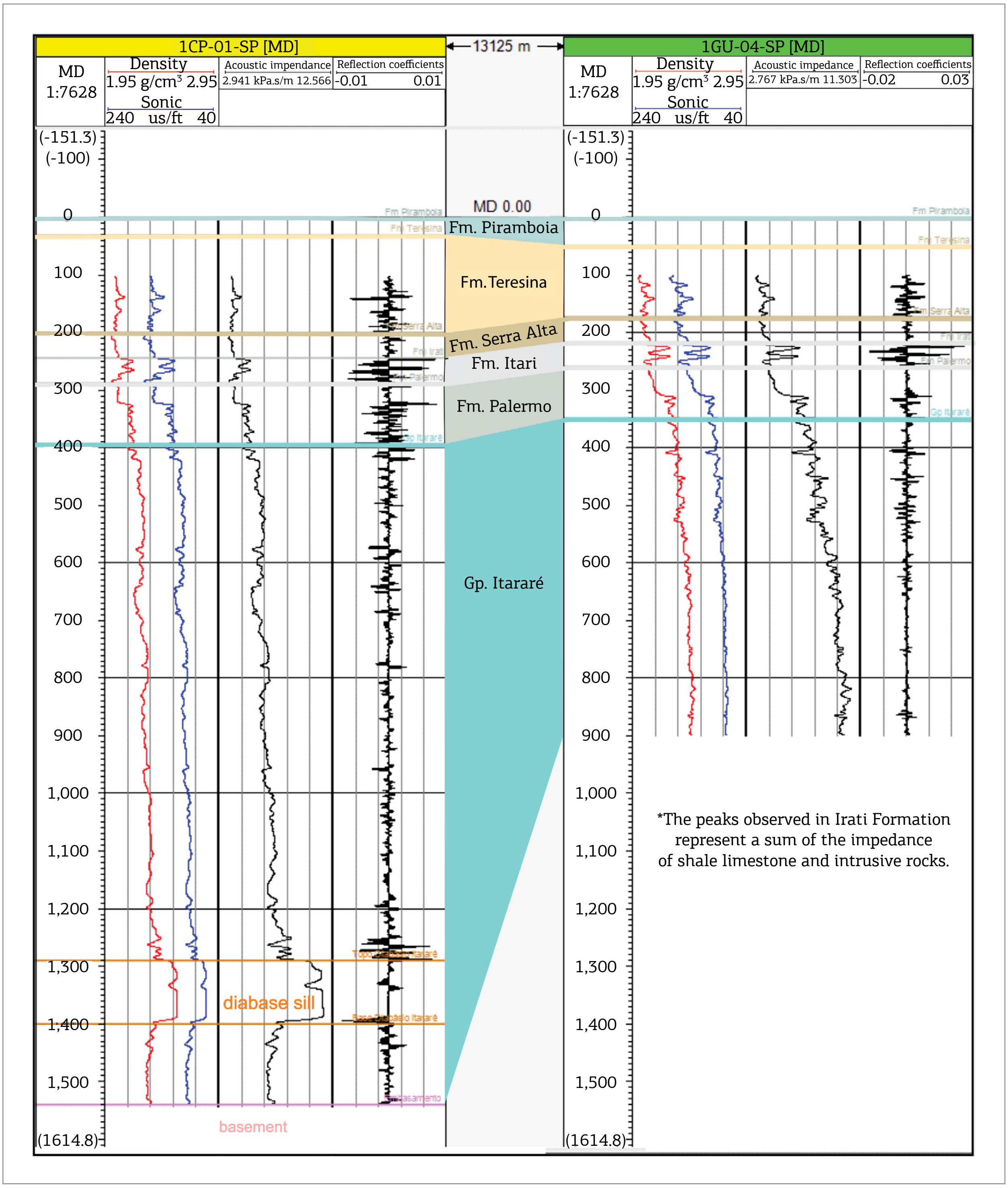

Figure 4. Well log correlation showing reflectivity pattern from stratigraphic marks (formation tops) and intrusive rocks.

to their geometry, since their base is flat and their tops are dome-shaped (Malthe-Sørenssen *et al.* 2004).

Regarding the seismic imaging of intrusive bodies, sills have a high seismic velocity (Vp ~ 5–7 km/s), and are frequently imaged as high amplitude reflections when intruded in sedimentary strata (Neumann *et al.* 2003). Dikes, on the other hand, represent blind points or pitfalls in the seismic image, like the majority of vertical bodies. Since these vertical bodies fill fractures, and because they are the means by which sills are fed, seismically mapped vertical discontinuities are often associated with dikes in regions marked by intense intrusive igneous.

Among the many parameters that contribute and control the development of a sill, the work of Neumann *et al.* (2003) compiles interpretations from various authors and lists the following factors: the density of the magma and the pressure applied in relation to the regional stress field (Anderson 1951); the thickness of the overburden package (Mudge 1968); the presence of wet sediments that interact with the magma, forming barriers and producing water vapor (Mudge 1968); mechanical discontinuities, such as the bedding of sedimentary rocks (Mudge 1968, Gretener 1969); the petrophysical properties contrast between different lithological units, inducing horizontal tension between the strata (Gretener 1969); the existence of fractures (Leaman 1975) or faults (Liss *et al.* 2002); and the level of density inversion between the magma and the host rock (Francis 1982).

Studies at the seismic and field scale, such as those of Neumann *et al.* (2003) and Planke *et al.* (2005), found that the fundamental geometry of a sill is saucer-shaped. This form and some of its sub-classifications were clearly recognized based on the seismic interpretation performed in this work.

Since the Paraná Basin exhibits a large volume of volcanic rocks, it is common to find a dense and entangled network of intrusive rocks, such as compound sills and even sill complexes. Thus, in order to determine the geometry of the sills observed in the present work, the analysis proposed by Hansen *et al.* (2004), which consider junctions of two or more sills forming compound and complex sills, was followed.

RESULTS AND DISCUSSION

Line 0240-0025

Line 0240-0025, oriented NNW-SSE, was interpreted using the stratigraphy of the well located along the line (1-CP-01-SP).

Due to the loss of lateral continuity of the reflectors and high noise of the seismic data, it was made a seismic well tie extracting three wavelets (multi-wavelet calibration), according the seismic domains. The first wavelet was extracted between 240–600 ms, which includes the first reflectors of the seismic to the top of Itararé Group. The intermediate wavelet was extracted from 600–940 ms, which includes younger reflections of the Itararé Group, which does not show high contrast impedance. Finally, the last wavelet was extracted from 940–1,340 ms, which corresponds to shales and shaly tillites, including 110 m of diabase (registered in the well) near the contact with the basement.

After the seismic well tie, the locations where the largest drifts between the input and output interval velocities occurred are related to the proximity of diabase sills in the extraction window.

In this line, important normal faults can be recognized near the Guareí Fault Zone. The increase in the noise level of the seismic signal suggests that there are intrusive rocks associated with the fault zone, and that they may represent as conduits for magmatic activity. The proximity with the Angatuba sill (5 km to the south) and with the Jacu structure contributes to the hypothesis that there is a local preferential spot for magma migration in that fault zone.

The following sill facies were identified: smooth layer parallel; saucer-shaped rough; climbing saucer-shaped; and fault block. Among those, the facies fault block stands out in the seismic line, emphasizing the importance of faults in that local context (Fig. 5).

Line 0240-0026

Line 0240-0026, oriented NWW-SEE, was interpreted using the stratigraphy of the well 1-GU-04-SP, located in the southeast portion of the line. It cuts across the extreme south of the Jacu structure. Based on the analysis of the interpreted geological section (Fig. 6), the presence of local folds can be observed, evidenced by alternating of anticlines and synclines compartmentalized in faulted blocks.

Sill geometries corresponding to the following seismic facies were recognized in the subsurface: smooth layer parallel; slightly saucer-shaped; saucer-shaped rough; climbing saucer-shaped; and fault block shape.

Below the anticline that defines the Jacu structure, two important layer-parallel rough sill levels can be recognized. In a hypothetical three-dimensional (3D) interpretation associated to surface geology (see geological map on Fig. 3), such levels could represent a sill complex under the dome structure, which could explain the prominence of that feature, with a major axis diameter of 20 km.

Line 0240-0027

Line 0240-0027, oriented NNW-SSE, also cuts across the extreme south of the Jacu structure, and what was hypothesized for line 0240-0026 can be observed in subsurface (the possibility of the presence of sill complex), in this section. Right below the structure, a sill complex was interpreted, evidenced by two saucer-shaped rough sills and a climbing saucer-shaped sill, connected by a junction of the type confinement of one sill against another. The sills also seem to control the shallower faults and fractures that stretch from the strata of Teresina Formation (reflectors above Serra Alta Formation) to the top of the Itararé Group (Fig. 7).

Besides the saucer-shaped rough sill facies and the climbing saucer-shaped sill facies, which join the mapped sill complex, sill facies of smooth layer parallel, slightly saucer-shaped and of fault block shape were recognized.

The seismic interpretation identified different sill geometries, sill complex and diabase dikes, which intrude preferentially the Itararé Group strata and subordinately the seismic interface Palermo-Irati-Serra Alta.

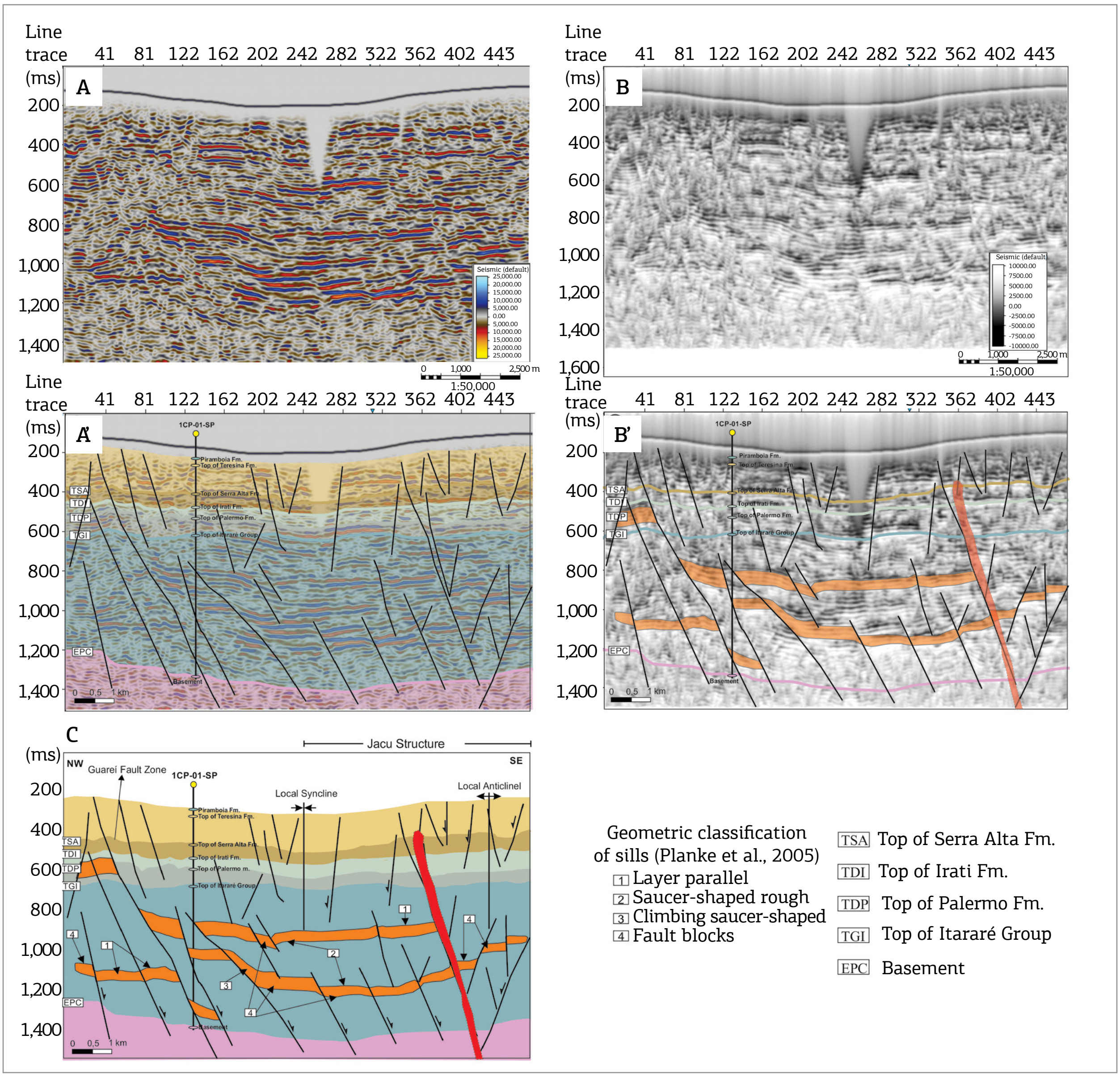

Figure 5. Seismic interpretation of line 0240-0025. In (A): filtered data without interpretation; in (A'): filtered data with superimposed horizons and mapped faults; in (B): tecVA attribute; in (B') interpretation of the diabase sills and dikes superimposed on the tecVA attribute; in (C): schematic geological section.

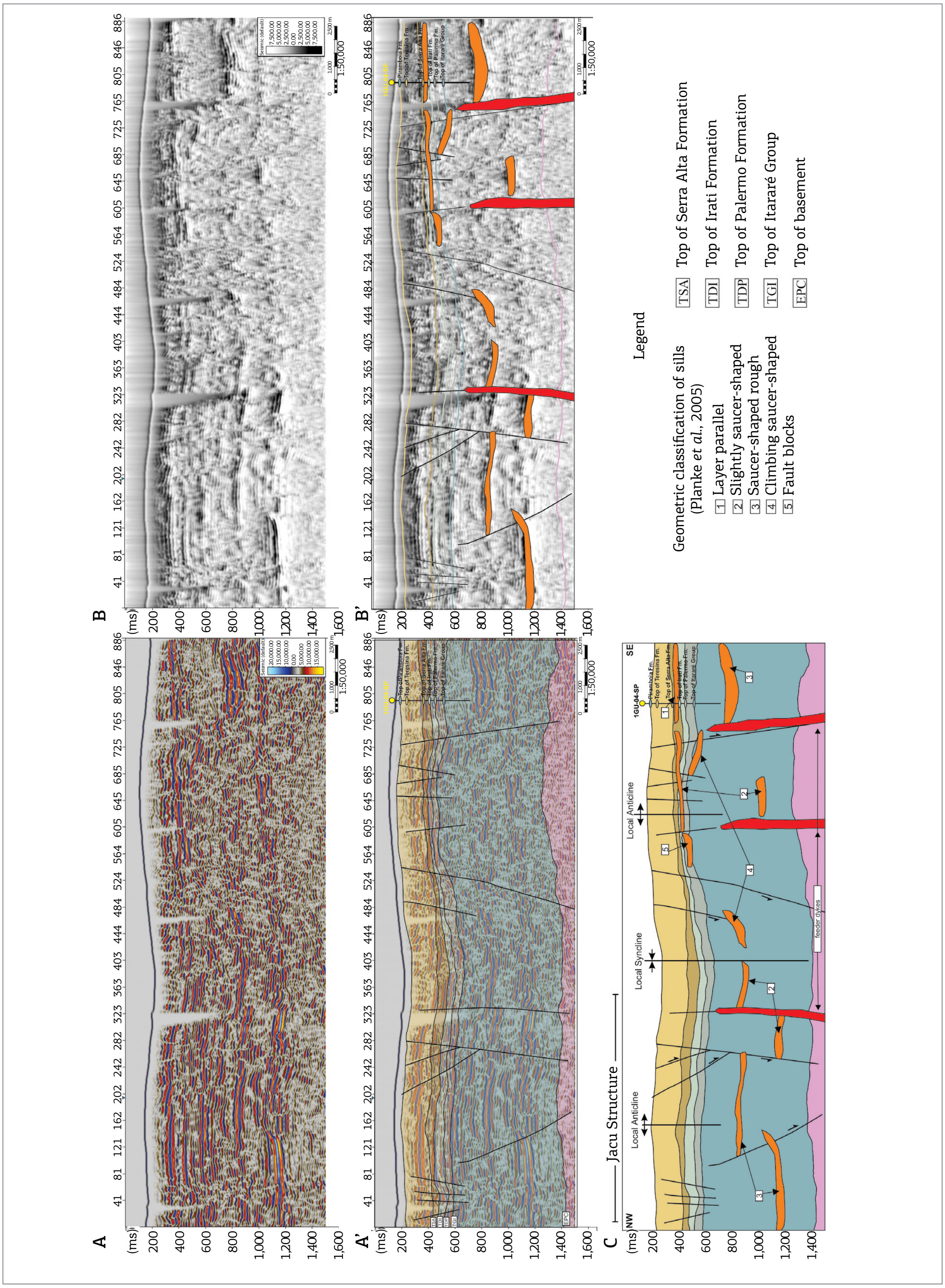

Figure 6. Seismic interpretation of Line 0240-0026. (A): filtered data without interpretation; (A'): filtered data with superimposed horizons and mapped faults; (B): tecVA attribute; (B') interpretation of the diabase sills and dikes superimposed on the tecVA attribute; (C): schematic geological section.

The direct contact of the interpreted magmatic features in Figures 5, 6 and 7 with Irati Formation (black shales) would have contributed to the thermal maturation of the organic matter, since it is known that, in normal burial conditions, the source rock did not reach the window of hydrocarbon generation, featuring an unconventional generation model.

CONCLUSIONS

Despite the low signal/noise ratio, the methodology used in the treatment of the original seismic trace satisfactorily allowed the mapping and characterization of the geometries of the diabase sills, as well as their relation with the enveloping rocks.

Five sill geometries were recognized in the study area, according to the classification of Planke *et al.* (2005): smooth layer parallel; slightly saucer-shaped; saucer-shaped rough; climbing saucer-shaped; and fault block shape. The sills preferentially occurred intruding the Itararé Group and the interface of Palermo/Irati Formations.

Since 2D lines were involved, it was not possible to define the size of the sills in relation to their diameter and thickness. However, the crosscuts of the mapped sills vary from a little more than 1 km to a little more than 10 km in width, and the thickest sills are recognizable intruding the Itararé Group.

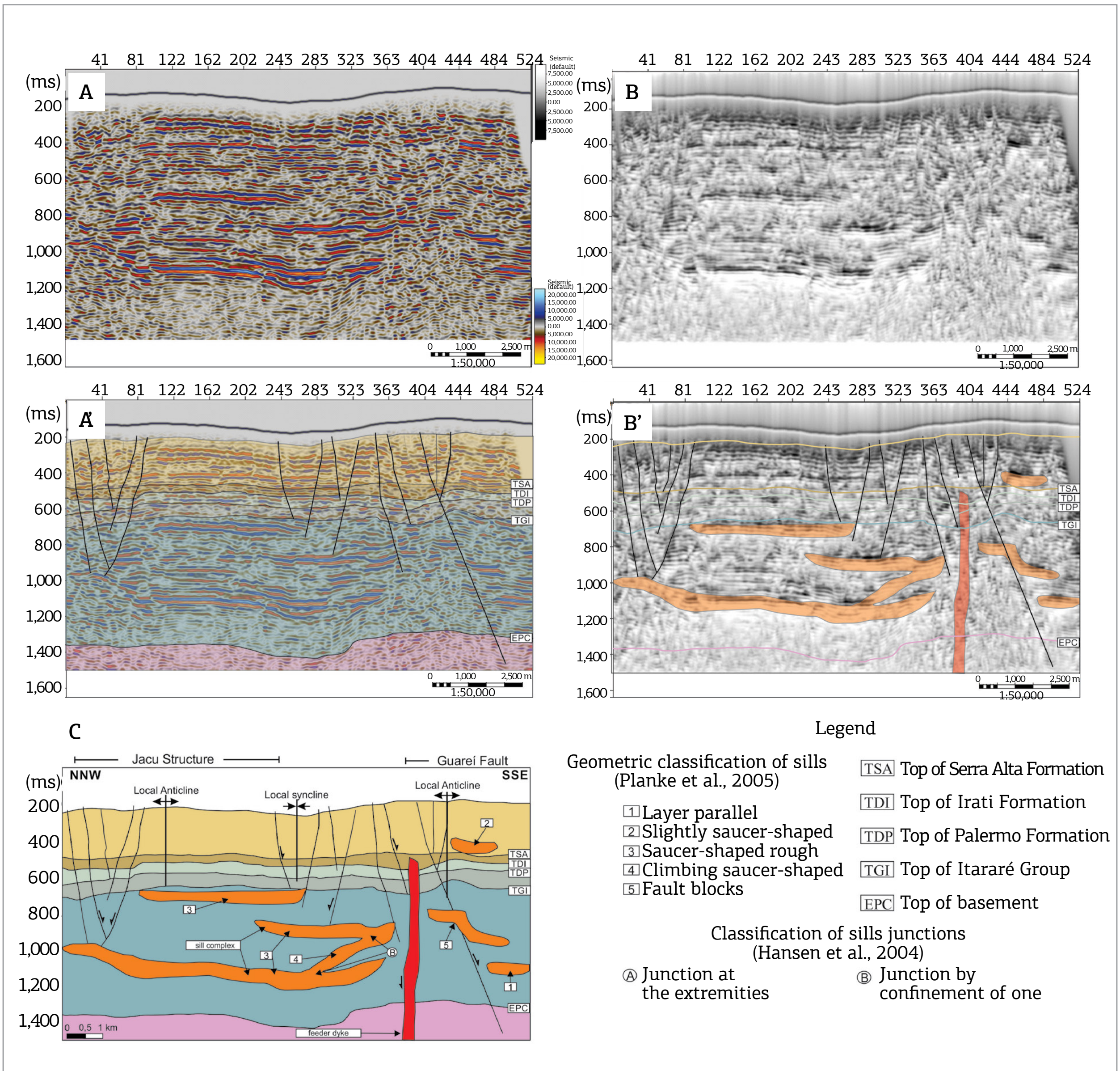

Figure 7. Seismic interpretation of Line 0240-0027. (A): filtered data without interpretation; (A'): filtered data with superimposed horizons and mapped faults; (B): tecVA attribute; (B') interpretation of the diabase sills and dikes superimposed on the tecVA attribute; (C): schematic geological section.

This is corroborated at the well scale, where the 1-CP-01-SP well has a 110-meter-thick sill in the basal package of the Itararé Group, while the sills that intrude Irati and Palermo Formations have a thickness varying from 2 to 9 m (1-GU-04-SP well).

Compound sills and sill complexes formed by the junction of the extremities, or by confinement of one sill against another, were also observed, underscoring the dense and entangled network of sills and dikes, that is common in a magmatic province such as the Paraná Basin.

The seismic interpretation allowed associating the maturation of organic matter with igneous intrusions, performing an unconventional petroleum system.

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