From SE Paraná to Pelotas Basin, a geophysical-geological transect traversing two of the world's largest igneous provinces in South America

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This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Abstract

The transition from the southeast Paraná Basin onshore to the Pelotas Basin offshore in southeast Brazil constitute a world class area to understand the relationships between the tectono-magmatic events that preceded and continued during the Gondwana breakup, which resulted in the development of continental margin rift basins and the formation of the South Atlantic Ocean. This work presents a regional geological-geophysical cross-section of approximately 1100 km long, traversing two of the world's largest igneous provinces. Seismic, gravity, magnetic, wellbore and geochronological information has been compiled along the transect to contribute to a better understanding of the complex processes that took place in the transition from the prerift continental flood basalts to the postrift oceanic magmatic events during the evolution of this segment of the South Atlantic passive margin.

Introduction

The continuous processes related to continental break-up and the onset of a new ocean have been thoroughly discussed over the last 5 decades in the geological literature. Pioneering ideas about this fundamental geological process were introduced in the 1970's (e.g., Morgan, 1971), when the closer temporal relationship between the extrusion of flood basalts followed by a continental break up was reported. Courtillot et al (1999) analyzed the close relationship between the major continental flood basalt provinces and the continental rifting produced in the last 300 Ma. The geological mechanisms are complex and comprise several stages such as:1) the probable initial impact of a thermal anomaly in a continental lithosphere, 2) intense magmatic activity in the form of flood basalts, 3) initiation of continental rifting, 4) large extrusions of seaward dipping reflectors (SDRs), and 5) inception of a true oceanic crust and onset of the seafloor spreading. These authors recognized that the Atlantic Ocean is the best example where this connection can be studied, emphasizing that at least three large ocean basins were created by the impact of three mantle plumes (Courtillot et al, 1999).

In this work we focus on the geological and geophysical changes observed along a regional transect that extends for approximately 1100 km from the Paraná continental flood basalt province (Paraná CFB) to the Pelotas Basin rifted margin in southeast Brazil (Figure 1 The regional transect connects two of the world's largest igneous provinces: the Paraná CBF province and the southwestern branch of the South Atlantic, which is characterized by the SDRs province in the Pelotas Basin (Figure 1). Both provinces are related to the complex processes that operated from the rifting of the Gondwana supercontinent to the opening of the South Atlantic Ocean with the development of a passive continental margin after breakup (Gladczenko et al., 1997).

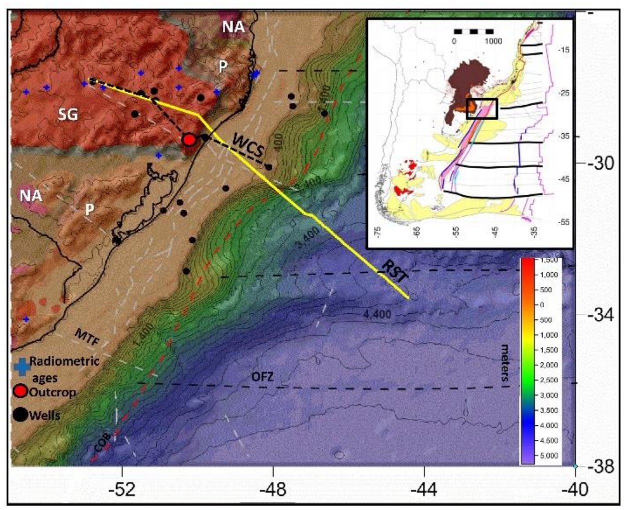

Figure 1: Geology, topography/bathymetry and location map. (References: COB (continental/oceanic crust boundary); OFZ (oceanic fracture zones); MTF (major tectonic feature); RST (regional seismic transect); WCS (well and outcrop cross section); NA (Neo Archean rocks); P (Paleoproterozoic rocks); SG (Serra Geral volcanic rocks)

Database and methods

This study was conducted using selected reflection seismic profiles, gravity, magnetic and borehole information (courtesy of the Agência Nacional de Petróleo), as well as published information of the Brazilian Geological Survey (CPRM), and public domain dasets (e.g,, Sandwell and Smith, 2009; Maus et al., 2009; Waichel et al, 2012).

Parana and Pelotas basins geological setting

The Paraná Basin is a large intracratonic basin extending from central Brazil to Argentina, Paraguay and Uruguay (Figure 1). The Paraná Basin stratigraphy comprises Paleozoic to Mesozoic sediments and magmatic rocks that reach a maximum thickness in the order of 7 km (Milani et al., 2007).Basin development started at the end of the Brazilian orogeny, which was responsible for the amalgamation of the Gondwana supercontinent along the Neoproterozoic. The Paraná Basin evolved from confined rift systems, to a foreland basin tectonic setting from xxxx to the Neo Triassic (CITA). During this phase, the evolution of the basin was strongly controlled by the subduction of the oceanic Phantalassa plate, and by a series of collisional events along the southwestern margin of the paleocontinent (Milani and Ramos, 1998).

According to Milani et al. (2007), the regional stratigraphy of the basin includes six second-order super sequences, known as: 1) Rio Avaí (Ordovician to Silurian); 2) Paraná (Devonian); 3) Gondwana I (Carboniferous to Eo Triassic); 4) Gondwana II (Neo Triassic); 5) Gondwana III (Neo Jurassic to Eo Cretaceous) that includes the important magmatism of Serra Geral; and 6) Bauru (Neo Cretaceous).

The Pelotas Basin is the southernmost Atlantic passive margin basin offshore Brazil, extending from the southern coast of Brazil to the northern coast of Uruguay (Figure 1). To the west, the Pelotas Basin is limited by the Paleozoic-Mesozoic sediments of the Paraná Basin and by the Don Feliciano Precambrian belt (Figure 1). The basin has a limited development onshore and a maximum expansion offshore, with Tertiary sediments reaching bathymetries in the order of 4600 meters (Bueno et al, 2007; Figure 1).

The Pelotas Basin exhibits distinctive features such as the presence of a volumetrically expressive synrift/postrift volcanism, a subordinate presence of terrigenous synrift deposits, a scarcity of evaporites, and an important marine sediment accumulation depocenter, mainly located at the Rio Grande Cone area (Bueno et al., 2007; Figure 1).

The crystalline basement offshore is probably composed by the Dom Feliciano mobile belt, which extends to the west underneath the present eastern edge of the Paleozoic Paraná Basin (Figure 1). The Dom Feliciano mobile belt comprises igneous and high-grade metamorphic poly-orogenic rocks developed from Neoproterozoic to Ordovician times (Heilbron et al., 2004 and references therein).

The sedimentary record of the Pelotas Basin includes the prerift, rift, transitional, and postrift mega sequences which are mainly developed in the offshore area (Dias et al.,1994; Bueno et al., 2007).

The prerift mega sequence is composed of Paleozoic and Mesozoic sediments and volcanic rocks from de Paraná Basin. Outcrops from this mega sequence are recognized in the Torres syncline area (Dias et al., 1994; Figure 1). The Neocomian-Barremian rift sequence is characterized by antithetic faults and half grabens filled by proximal deposits and lavas (Dias et al.,1994; Bueno et al., 2007). The transitional mega sequence, composed of only anhydrite, exhibits a very restricted distribution and is found only in the Florianópolis Platform region (Figure 1). The marine deposits of the postrift mega sequence include five stratigraphic sequences ranging in age from Albian to Holocene (Bueno et al., 2007).

The southeast Paraná to Pelotas basins regional transect

The main tectono-magmatic units of Paraná and Pelotas basins are illustrated by sets of magnetic lineaments with orientation NE and E/NE onshore, and NNE offshore in the airborne (CPRM) and satellite (EMAG) magnetic maps of Figures 2a and b.

The onshore NE magnetic lineament (lineament 1 in Figure 2a) is probably associated with the contact of the sedimentary section and the crystalline basement. The E/NE lineament is interpreted to be related to the main foliation of the crystalline basement of the Dom Feliciano mobile belt (lineament 2 in Figure 2a). The prerift lavas of Paraná Basin exhibit less organized and negative magnetic values as seen in the magnetic area 4 in the map of Figure 2b, and in the magnetic profile of Figure 3 (section 0 to 320 Km). Near Torres city, in the transition between these two provinces (at the distance of approximately 390 km in the regional transect of Figure 3), the magnetic response begins to increase to positive values, probably reflecting the proximity of the crystalline basement. Eastward, the volcanism of the Pelotas Basin is expressed by NNE lineaments (lineament 3 in Figure 2b), corresponding to the average response of a series of SDRs. In map view, the magnetic lineament 3 displays variations along the strike. In the southwest segment of the basin this lineament is represented by two separated magnetic belts that merge into one belt towards the northeast. In deep water, the oceanic crust displays a set of organized magnetic strips (lineaments 5 in Figure 2b).

The Bouguer gravity profile (Figure 3) shows a contrasting change from strong negative gravity anomalies in the Parana Basin sector to high positive gravity anomalies in the Pelotas Basin sector. The gravity profile reflects the important crustal thinning that occurs in the transition from the Parana to the Pelotas basins, associated with an expressive mantle rise (Figures 3 and 6).

The regional wellbore cross section (Figure 4) is composed of the Paraná wells (2RD-1RS, 2LV-1RS, 1MC_1RS, 2TO_1RS) and by the Pelotas well (2-BPS-6BP), drilled nearby the regional transect (Figure 1). This transect provides detailed geological information of the regional variation of the sedimentary and volcanic records in both basins. The Paraná wells documented deposits of the Gondwana I and III supersequences on top of the crystalline basement (Figure 4). The four wells in the Paraná Basin reached and sampled between 15 to 32 m of the crystalline basement with typical P wave velocities of 6000 m/sec and densities of about 2.7 gr/cm^3. The descriptions of the well cores indicate the presence of porphyritic granites, biotite/muscovite and granitic gneisses, and migmatites with a K/Ar 547 ±7 Ma muscovite age (2RD-1RS ANP well file). Structurally, the crystalline basement displays a relief dipping towards the northwest, controlling the deposition of the Gonwana I and Gondwana III sedimentary cycles as well as the deposition of the lavas of the Serra Geral volcanism (Figure 4).

The Paraná prerift magmatism (Serra Geral Fm.) is composed of lava and dike outcrops and subsurface dikes and sills that have been dated as late Jurassic/Early Cretaceous (Almeida et al., 2013). The lava thickness varies considerably, from 150 meters near the coast (well 2-TO-1RS) to close to 1200 meters inland in the northwest (well 2-RD-1RS; Figure 4). The proposed volcano stratigraphy of the Torres Syncline area (Waichel et al, 2012) comprises five volcanic episodes summing up to 1000 meters of volcanic flows (outcrop RS 486, Figure 4). Waichel (*op. cit*.) recognized several alternations of basic and acid magmatic episodes indicating changes in the magma supply and effusion rates. The smooth contact among the volcanic facies and the absence of paleosoils development suggest a short time eruption interval (Waichel et al, 2012).

The Serra Geral subsurface sill complexes are quite extensive bodies, distinctive in seismic profiles due to the high acoustic impedance contrast (Figure 5). The intrusions appear to be continuous but they are affected by a normal fault system. In general, they exhibit a tendency to intrude and concentrate in the upper Irati Fm. and in the lower part of Rio do Rasto Fm. In the studied area, the sills are more frequent and thickest to northwest of the transect (summing up to 400 meters of diabases) as can be observed in the diabase total isochore map of Figure 4.

The well 2-BPS-6BP, documented the total stratigraphic record of Pelotas Basin. From bottom to top, the stratigraphy is composed of 800 meters of basalts (units “C” and “H", Gordon and Mohriak, 2015), 500 meters of a sandy/limestone shallow marine section (Portobello Fm.), and 4500 meters of deep marine shales, marls and siltstones known as Atlantida and Imbê formations (Bueno et al., 2007; Figures 4).

The duration of the Paraná CFB volcanism has been under a long dispute in the geological community. The large dispersion observed in the compilation of age histograms explains the different opinions related to the tempo-geographical evolution of this province and reflects the analytical difficulties of dating basalts. Basically, the geochronological discussion focuses on the duration the volcanism of the Paraná CFB province, with interpretations of a short or a long time span process.

Thiede and Vasconcelos (2010), summarized the disputes about the age of the Paraná CFB province generated by a conflicting 40Ar/39Ar. These authors revisited the oldest and youngest reported ages of the province, proposing a short time span hypothesis for the main lava flows of the Paraná CFB volcanism at ca 134.7 ±1 Ma age.

A compilation of published radiometric 39K/40Ar and 40Ar/39A ages of volcanic rocks from the southern Paraná and Pelotas basins published in Gordon and Mohriak, 2015, exhibits bimodality where the principal mode (131-135 Ma) corresponds to the main Parana CFB lavas, and the secondary mode (117-127 Ma) corresponds to the Pelotas Basin volcanism. The same behavior is also observed in the compilation of radiometric ages in the Florianopolis dyke swarm (FDS; Almeida et al, 2013). The same bimodal signature is presented in the FDS, with two peaks at approximately 119-127 Ma and 131-141 Ma intervals, in good agreement with the Pelotas and Serra Geral volcanisms.

The geochemical and geochronological similarities between the oldest FDS dikes (131-141 Ma) and the Paraná CFB lavas allowed the interpretation that this dike swam could be the feeder system of the voluminous Southern Paraná volcanism (Almeida et al, 2013). The set of younger FDS dikes (119-127 Ma) led also some authors to interpret them as representatives of the feeder system of a younger magmatic episode, related to extension of the continental crust and the formation of the offshore basins (Raposo et al.,1998). The hypothesis of two cycles of magmatic feeder system episodes can be sustained by field work evidences. The existence of older dikes cross cut by younger dikes; composite dikes with central to border variations in both age and composition; and finally, by sets of dikes with different strike orientation, support the idea of different generation ages of dike swarms (Almeida et al, 2013 and references therein).

The volcano-stratigraphy of the Paraná CFB province and the FDS has been approached mainly by geochemical analysis of minor, trace and isotope elements. Peate et al (1992) identified high and low TiO_2 suites, although the Paraná magma types cannot be considered as chronostratigraphic units (Turner et al.,1994). The magmatic suites seem to reflect different compositional sources (Mantovani et al, 1985). The presence of the high and low TiO_2 suites has also been recognized in the Pelotas Basin by Lobo, 2007.

The volcano-stratigraphy of the Pelotas Basin is based in the interpretation of seismic and wellbores (Gordon and Mohriak, 2015), and by published geochemical and geochronological analysis (Lobo, 2007).

The initial infill of the Neocomian-Barremian rift half grabens, in shallow waters, correspond to alkaline basalt of the volcanic unit “A” (~125 Ma) and minor proximal siliciclastic deposits (Dias et al.,1994). Towards deep waters the basin developed an important synrift volcanism, in the form of SDRs (Units "B" to "F") and volcanic mounded features (Units "G1" and "G2") as displayed in Figure 6 (Gordon and Mohriak, 2015). The unit “C” volcanic sequence has been analyzed by Lobo, 2007 and it is composed of high TiO_2 tholeiitic basalt. The SDR wedges display an oceanward evolution, younging basin wards and developing unconformities between the different wedges. This geometry reflects changes in the structural configuration of the basin during the late rift/early postrift transition

The volcanic activity at the postrift stage is represented by trachy-andesite lavas (Unit “H”, ~113/118 Ma) that display a flat-lying configuration over the transitional extended crust with a low TiO_2 tholeiitic basalt composition (Lobo, 2007), and by seamount and volcanic cones (unit “I”) in oceanic crust (Figure 3).

Conclusions

The magmatic cycle that starts prior and along with the Gondwana breakup displays two major magmatic sub-cycles: the prerift Paraná CFB and the syn/postrift volcanic successions of Pelotas Basin. The transition between both large igneous provinces can be described along the geophysical and geological transect of Figures 3 and 4.The Valanginian to Barremian prerift magmatism of the Paraná CFB may reach a maximum thickness of about 2 km in the central part of the Paraná Basin. However, these lavaflows pinch-out towards the continental margin of the Santos and Pelotas basins, where Precambrian rocks crop out near the coastline. There are several magma types in the Paraná CFB and they have been grouped into high and low TiO_2 suites, which are related to melting of different mantle sources. During Barremian to Aptian times, the Pelotas Basin developed narrow troughs during the main extensional phase and subsequently the magmatism shifted the main locus from inland to oceanward. The Pelotas Basin volcanic rocks display a sequential geochemical and temporal evolution from alkaline to tholeiitic affinities and from high to low TiO_2 basalts (Lobo, 2007, Gordon and Mohriak, 2015). The evolution of the volcanism of the Pelotas Basin agrees with the increase in the lithospheric thinning during the rifting process.

Finally in southeast Brazil, from our point of view, there was a long-lived magmatic cycle with a clear association with the impact of the Tristão da Cunha plume, which shifted from an onshore to an offshore position between the prerift and the synrift stages. The effect of the plume appears to be, more thermal than compositional, as the melting a heterogeneous subcontinental lithospheric mantle source is suggested by the shifting in the basaltic composition. This huge magmatism triggered the lithospheric thinning during the rift phase and resulted in inception of oceanic crust in a rather short time span.

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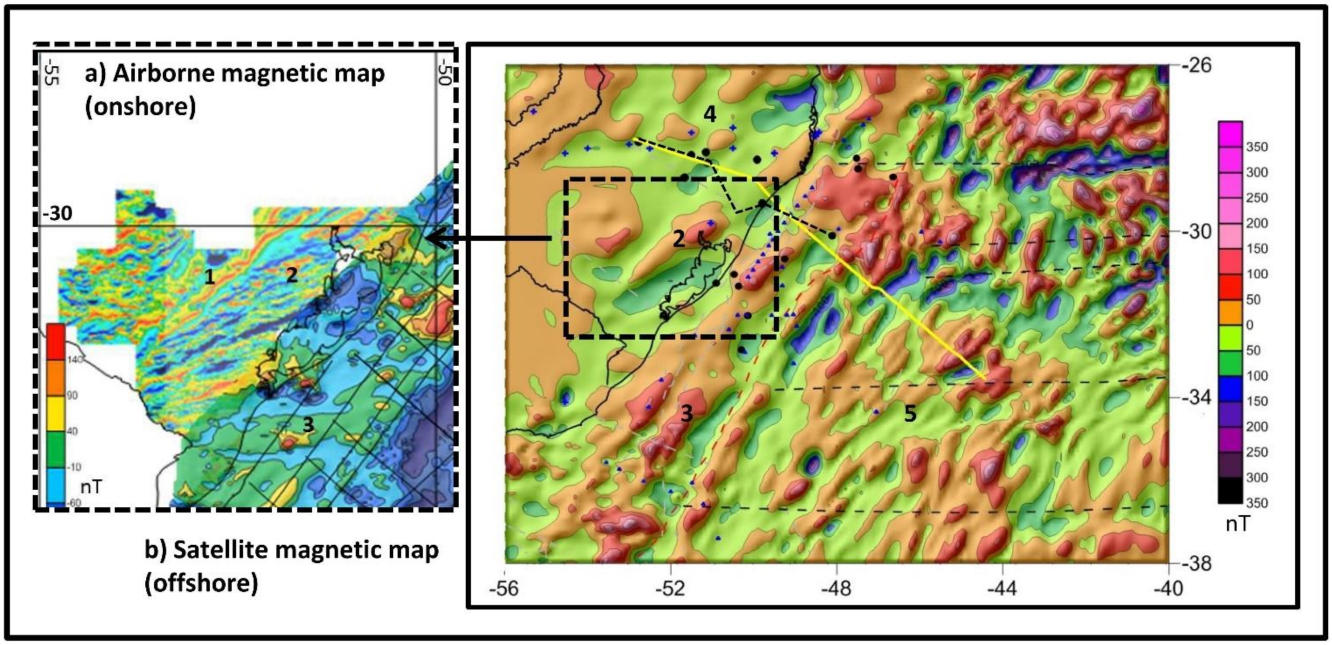


Figures 2 a and b: Onshore and offshore magnetics maps.

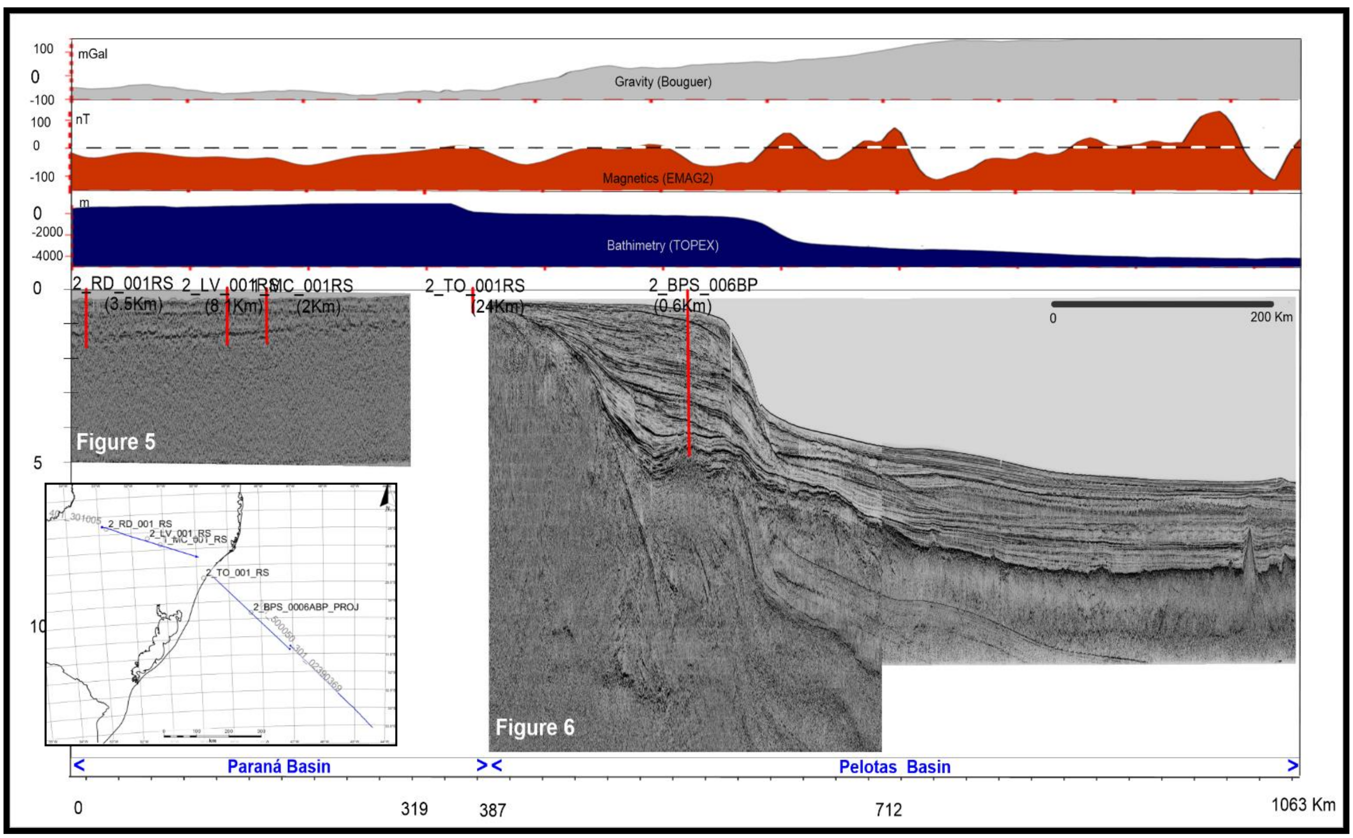


Figure 3, Regional seismic transect from Paraná to Pelotas basins

Figure 4, Well and outcrop cross section .

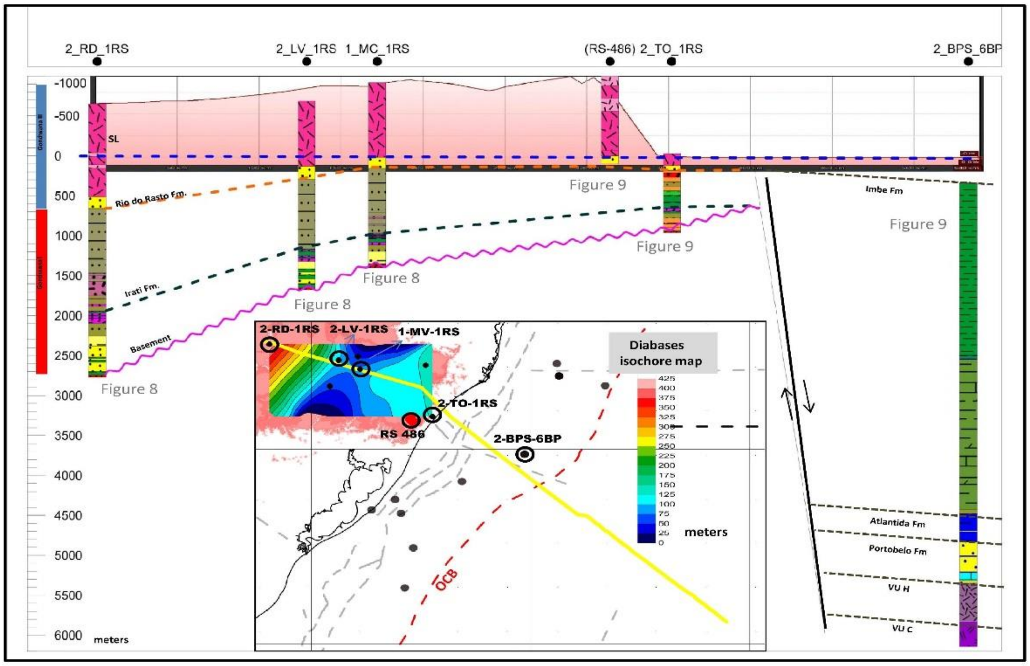
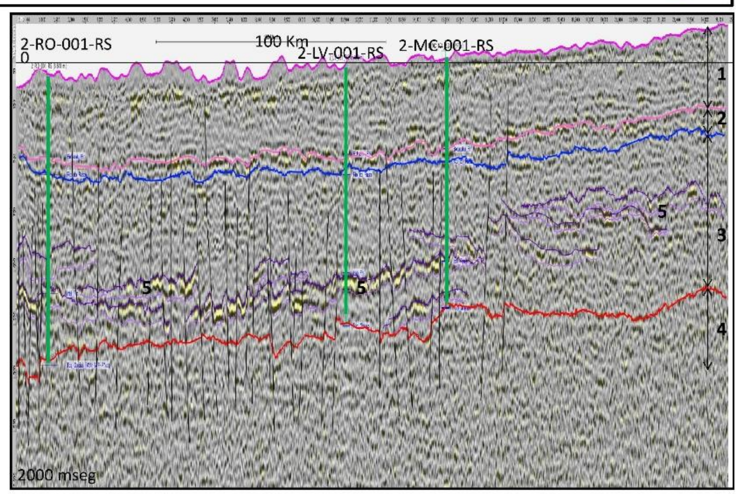


Figure 5, Parana Basin seismic line

(References: 1- Serra Geral Lavas; 2-Botucatu sandstones ; 3- Gondwana I sedimentary cycle ; 4- Crystalline basement ; 5-Serra Geral sill complex)



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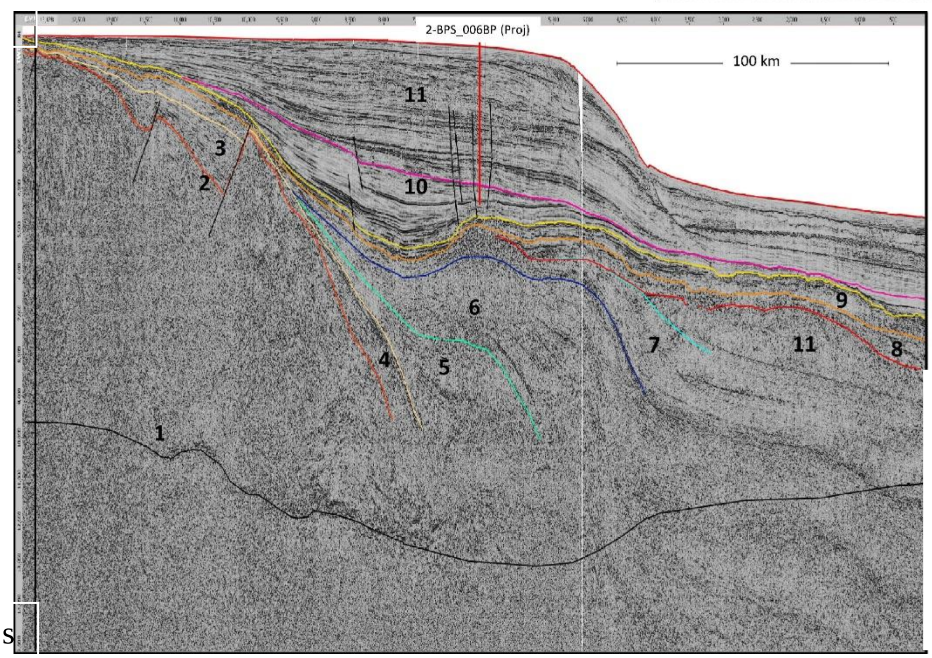

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Figure 6, Pelotas Basin seismic line

(References: 1- Reflection Moho,

2-Top crystalline basement,3-synrift sequence, 4-volcanic unit A 5 to 8- volcanic units B to F (main SDRs),

9- Volcanic unit H, 10-Cretaceous sediments, 11- Tertiary sediments