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THE PARANÁ MAGMATIC PROVINCE STATE-OF-THE-ART IN THE GEOPHYSICAL AND GEOCHEMICAL INVESTIGATIONS

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ABSTRACT. This paper presents an overview of the present knowledge on the Paraná magmatism and the lithospheric structure under the Paraná Basin. The genesis and diversity of the flood basalt types are linked to the structure and tectonic processes that have affected the crust and upper mantle since the Western Gondwana amalgamation until subsequent rupture. It focuses mainly on the work developed at the Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG), Universidade de São Paulo (USP), during five decades, starting from the first detailed paleomagnetic data acquisition along vertical profiles and then associated with the chemical data, a pioneering initiative in the world. Chemical and isotope data were then acquired substantially, allowing advanced knowledge of the sources and genesis of the different magma types. The geophysical studies, including gravity, seismology and electromagnetic induction methods, allowed the recognition of crustal and lithospheric structures and rheology below the sedimentary basin, giving evidence for the magma generation models. Although the aspects addressed here do not run out the subject, it summarizes essential aspects of the present knowledge of the Paraná Magmatic Province.

Keywords: Paraná flood basalts; magma genesis; lithospheric structure; emplacement time.

INTRODUCTION

The first mention of the volcanic rocks of the Paraná Basin appears in White (1908), describing outcrop 17, the endpoint of his famous description of the Serra do Rio do Rastro geological column (the White Column; in Orlandi Filho et al., 2006). Later, Guimarães (1933) described the Paraná magmatism naming it the Magmatic Province of Southern Brazil. Leinz (1949) studied the flows in the White column and established what would be classical within flow structure, with vitreous character in the bottom and vesicular texture in the top. The name Serra Geral Formation is due to Gordon Jr. (1947), who described the lithological sequence made mainly of basic-type lavas on the base and showing intermediate to acid types to the top. Nowadays, it is referred to as the Serra Geral Group. Intrusive rocks are frequent in the Paraná sedimentary rocks. Based on the Presidente Epitácio electrical well log, Leinz et al. (1966) evaluated a volume of 6.50x10^5 km^3 for the entire magmatic province. The authors counted 32 lava flows in that well, reaching 1,800 m. Despite the massive expression of this magmatism, affecting all the southern Brazil and extrapolating the geographic borders, few authors dedicated attention to studying the Paraná igneous rocks. Until the 70s, most of the works referred to local basaltic/ dolerite occurrences or attempts to date the rocks by the K/Ar radiometric method (Sanford and Lange, 1960; Schneider, 1964; Creer et al., 1965; Rüegg and Dutra, 1965; Amaral et al., 1966; McDougall and Rüegg, 1966; Melfi, 1967; Cordani and Vandoros, 1967; Minioli et al., 1971), despite the massive expression of the magmatism, affecting all the southern Brazil and extrapolating the geographic borders.

In the Department of Geophysics of IAG/USP, interest in Paraná magmatism was launched by the paleomagnetic works of Pacca and Hiodo (1976) and Ernesto et al. (1979). Since then, thorough and continuous research has been developed, concentrating on geological/geochemical and paleomagnetic studies and extending to other branches of geophysics, counting on international collaboration.

The first compilation of the Paraná igneous rocks knowledge came out in a book organized by Piccirillo and Melfi (1988). In this volume, the authors showed that the lava flows and intrusive rocks in the form of dykes and sills were all related to the same geodynamic events that resulted in the breakup of Western Gondwana during the Early Cretaceous. During this process, about 10% of the total volume of the magmatic rocks was emplaced on the formely contiguous African side (Etendeka, Namibia). The Paraná-Etendeka Magmatic Province is one of the world's largest magmatic provinces.

In Brazil, the basalts of the Paraná Magmatic Province (PMP) are best exposed on the eastern border of the Rio Grande do Sul and the Santa Catarina States, where the flow sequences may reach more than 1,000 m. To the north, outcrops are sparse, and the flatter relief exposes only part of the sequences, although one drill core near the Paraná River showed ~1,700 m of basalts (Almeida, 1986). The PMP also comprises an expressive number of intrusive rocks in the form of outcropping sills, particularly in the northeast part of the province, and less frequent in the northwest portion. They intrude the Late Paleozoic sedimentary column and, to a lesser extent, the Jurassic/ Cretaceous layers (Melfi and Girardi, 1962; Davino et al., 1982; Machado et al., 2007; 2015). Dyke swarms are relevant features in the PMP. They occur along the eastern Brazilian coast (Piccirillo and Melfi, 1988; Peate, 1997). The Ponta Grossa dyke swarm is the most impressive, occupying a large area from south São Paulo to the Paraná States. Dykes are up to 100 m thick and trend mainly NW contrasting to the other swarms of NE preferential orientation (Piccirillo and Melfi, 1988).

Magmatic events of the magnitude of the PMP cause significant changes in the structure and composition of the lithosphere throughout geological time. In the abundant international literature, different models are proposed to explain the origin of large continental basaltic provinces. Mantle plumes (Richards et al., 1989) were widely used to describe the source of several basaltic provinces despite the chemical and isotopic composition of the involved magmas suggesting other geneses. Sheth (2005) and Anderson (2005) demonstrated that the model could not be generalized. Regarding the PMP, the plume model was frequently invoked, and the magma origin was linked to the Tristan da Cunha (TC) plume (e.g. Marsh et al., 2001; Ewart et al., 1998, 2004). However, the attempts to place the PMP over the TC plume without any physical constraints proved unrealistic when the calculated paleolatitudes (Ernesto et al., 2002) evidenced that the PMP was about 5° to the north of the present TC position at the time of the magma emplacement.

As the knowledge of the PMP magma chemistry and spatial distribution advanced, the proposition that the plume represented only a source of heat to melt the lithospheric mantle gained strength (e.g. Peate et al., 1999; Marques et al., 1999). It should be noted that there is no unequivocal evidence for a high-temperature source for the Paraná magmatism, since picritic glass samples were never found in the PMP, nor in lavas from Tristan da Cunha archipelago and the surrounding Guyot Province (Foulger, 2012). Note that picritic glasses are used to represent uncontaminated original melt compositions of a magma generated under high-temperature conditions, as predicted by the mantle plume model. The possible involvement of depleted asthenospheric mantle of the N-MORB type in the last phases of extrusive activity (Peate and Hawkesworth, 1996) has also been suggested. Since then, much more information was accumulated on the magmatism itself, the genesis and ages of the magmatic rocks, and the lithospheric structure beneath the Paraná Basin and adjacent areas.

In this paper, we will review the contributions of the geophysical and geochemical data to the knowledge of the genesis and evolution of the PMP. We will focus mainly on the work developed in IAG, although the aspects addressed here do not include all the contributions produced by the research groups in this Institution.

GEOLOGICAL BACKGROUND

The intracratonic Paraná Basin (Figure 1) developed over Precambrian igneous and metamorphic rocks within the Brazilian Shield comprising Rio de la Plata, Mantiqueira, Luis Alves craton fragment, the Tocantins Province, and the Paranapanema block. The sedimentary infilling started in the Ordovician and now

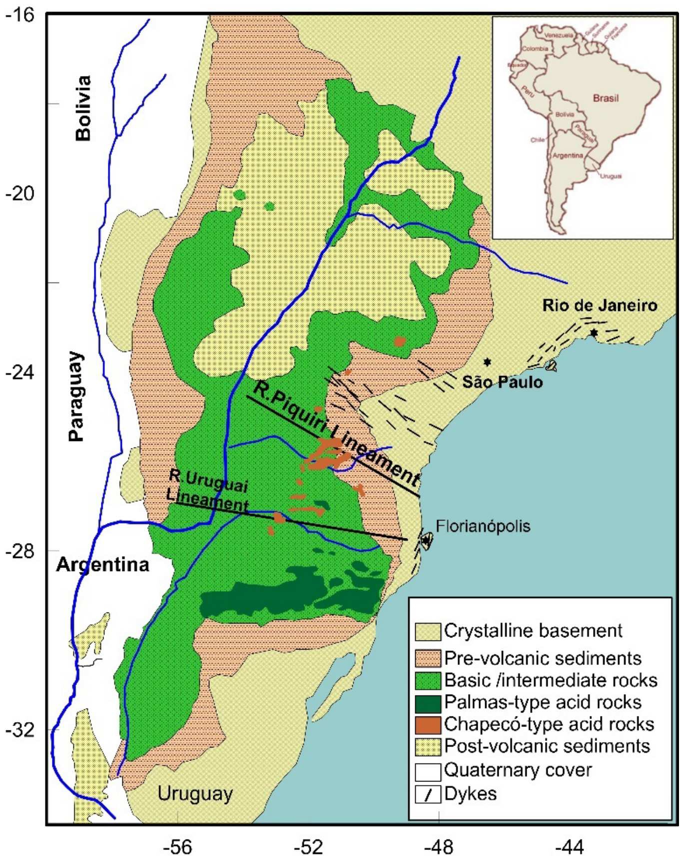

Figure 1: Simplified geological map showing the location of the Paraná Magmatic Province, the main tectonic structures, and the occurrences of the basic and acid rock types.

covers ~10^6 km², mainly in Brazil, extending into Argentina, Paraguay, and Uruguay. The sedimentation ended in the Late Jurassic/Early Cretaceous with the formation of large dune fields due to the desertification processes in the Western Gondwana supercontinent. The dunes gave rise to the Botucatu Formation that the Serra Geral traps covered in the Early Cretaceous (Assine et al., 2004)

The PMP is mainly composed of volcanic rocks of a bimodal nature since they are predominantly composed of a succession of tholeiitic basalts and basaltic andesites (< 60 wt.% SiO_2), accompanied by subordinated rhyolites and rhyodacites (> 64 wt.% SiO_2), with an absence of samples with 60-64 wt.% SiO_2 (Piccirillo and Melfi, 1988; Peate, 1997; Nardy et al., 2002; Marques et al., 2018). Intrusive rocks, most basic in composition, are also present, either as sills intruded in Paraná Basin sedimentary rocks (Ernesto et al., 1999; Machado et al., 2007) or dykes. The latter are concentrated in three swarms, which are referred as Ponta Grossa, Florianópolis, and Serra do Mar (Almeida, 1986; Piccirillo et al., 1990; Raposo et al., 1998; Déckart et al., 1998; Marques and Ernesto, 2004; Guedes et al., 2005; Valente et al., 2007; Guedes et al., 2016). Some dykes are also found in Southern Espinhaço, located at the border of São Francisco Craton (Rosset et al., 2007; Marques et al., 2016).

As is common in many large igneous province, the PMP and Etendeka lavas include both high- and low-TiO_2 compositional types. The first extensive work (Comin-Chiaramonti et al., 1988) on the volcanic and intrusive rocks made clear that the southern part of the PMP (South of the Uruguai Lineament) differs substantially from the northern one (North of the Piqueri Lineament). The occurrence of tholeiitic basalts with low-TiO_2 (Gramado and Esmeralda types; $TiO_2 \leq 2$ wt.%) and low contents of incompatible elements, such as P, Ba, Sr, Zr, Hf, Ta, Y, and light rare earth elements (LREE) dominates the southern PMP (Figure 2). In the northern PMP, the tholeiitic basalts are mainly of high TiO_2 concentration (Pitanga and Paranapanema formations; $TiO_2 > 2$ wt.%) and incompatible elements (Bellieni et al., 1984; Piccirillo et al., 1989; Peate et al., 1992; Peate, 1997; Rocha-Júnior et al., 2013). Scarce low-TiO_2 (Ribeira Formation) and high-TiO_2 (Urubici Formation) rocks are found in the northern and southern PMP, respectively. These basic rocks (extrusive and intrusive) underwent extensive fractional crystallization (Mg# < 0.56).

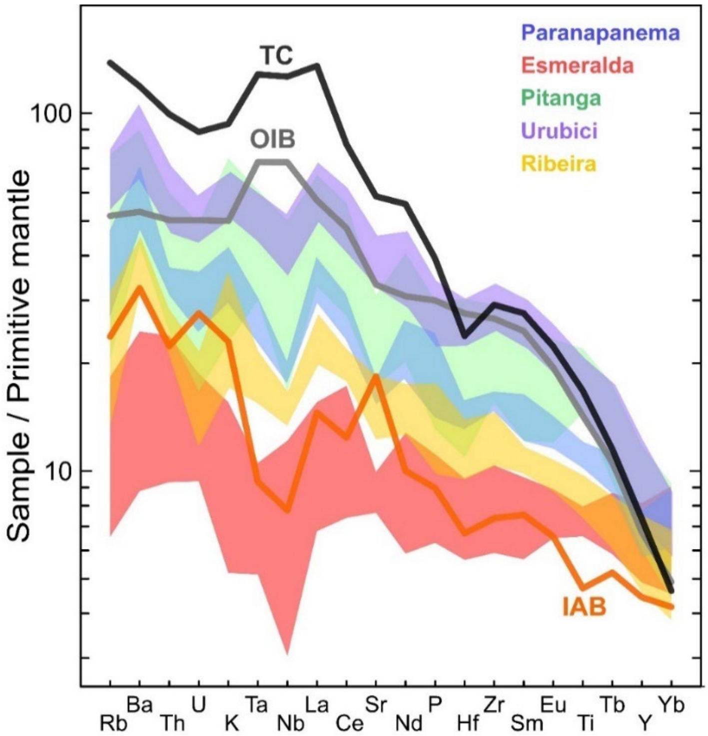

Figure 2: Primitive mantle-normalized (McDonough and Sun, 1995) lithophile trace element distribution patterns for low-Ti and high-Ti tholeiites. In contrast to the PMP basalts, the trace element pattern of the OIBs (in particular, Tristan da Cunha volcanic rocks) shows a distinctive Nb-Ta positive anomaly. Data sources: OIB (Sun and McDonough, 1989), Island Arc Basalts (IAB; Kelemen et al., 2014), and Tristan da Cunha are based on data from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc).

This provinciality was ascribed to geochemical heterogeneity of the subcontinental lithospheric mantle (SCLM) beneath the Paraná sedimentary Basin (Bellieni et al., 1984; Peate et al., 1992; Marques et al., 1999), the concentric zonation of the Tristan da Cunha plume (White and McKenzie, 1989; Gibson et al., 1999) or the bilateral asymmetry of the Tristan da Cunha plume (Hoernle et al., 2015).

The acid rocks may also be divided into two groups with distinct geochemical characteristics (Bellieni et al., 1986; Piccirillo et al., 1987, 1988; Garland et al., 1995; Nardy et al., 2008). The acid volcanics of the Chapecó Formation, which are spatially associated with the Pitanga basalts, have higher contents of TiO_2, Na_2O, K_2O, P_2O_5, and incompatible trace elements (Sr, Ba, Zr, Hf, Ta and REE) about the Palmas Formation, genetically related to Esmeralda and Gramado basalts, as well as to the low-Ti tholeiitic andesites.

Tectonic Framework

The Paraná Basin is located on terrains of the South American platform, which were extensively affected by the tectonic, metamorphic, and magmatic events of the Brasiliano/Pan-African orogenic cycle. Such heterogeneous crust was formed by the successive accretion of different geotectonic domains, as well as Neoproterozoic-Cambrian mobile belts related to the Brasiliano - Pan African Orogeny (1000-630 Ma) and Clymene Ocean closure (560-500 Ma) that were responsible for the assemblage of Western Gondwana (Holz et al., 2006; McGee et al., 2018).

The configuration of the crystalline basement of the basin is still a matter of debate. Radiometric dating from two basement samples inferred a Proterozoic cratonic nucleus beneath the central axis of the Paraná Basin unaffected by the Brasiliano orogen (Cordani et al., 1984). Another single cratonic core (Paranapanema Block; Mantovani et al., 2005) has been proposed with a basis mainly on residual gravity data. In contrast, using basement samples from several drill cores (including the Paleozoic Três Lagoas basalts), Milani and Ramos (1998) proposed a basement configuration consisting of a collage of several cratonic blocks separated by several interposed suture zones (Figure 3).

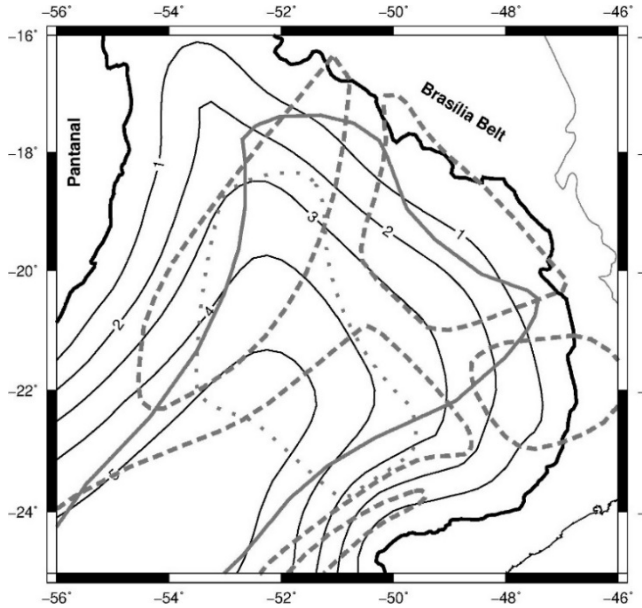

Figure 3: The Paraná Basin (thick black line) and three different cratonic basement models: cratonic nucleus of Cordani et al. (1984) (gray dotted lines), the fragmented basement model of Milani and Ramos (1998) (gray dashed lines), and the Paranapanema Block of Mantovani et al. (2005) (continuous gray lines). The map also shows the depth of the crystalline basement in kilometers.

The Neoproterozoic-Cambrian mobile belts developed in response to the collision between the Amazonian and other adjoining cratons (Congo – São Francisco – Rio de la Plata – Paranapanema fragments) that were separated from proto-Gondwana by the Clymene Ocean, thus marking the final suture of Western Gondwana (Tohver et al., 2010, 2012; McGee et al., 2018). The Clymene Ocean closure resulted in the Araguaia, Paraguay, and Pampean belts, located on the western part of the Paraná Basin (São Francisco/Amazonian craton). Recently, a continental-scale gravity gradient (Western Paraná Suture/Shear zone; Dragone et al., 2017) flanking the Western Paraná Basin was interpreted as a crustal discontinuity separating the Paranapanema, and smaller blocks, from the Rio Tebicuary and Rio de la Plata cratons, which was also associated with ocean closure on the western border of the Paranapanema fragments. The closure of the Goiás and Adamastor oceans formed the Brasília, Ribeira, and Dom Feliciano mobile belts during Neoproterozoic and are associated with the Brasiliano - Pan African orogenic cycle, which borders the northeastern and southeastern of the Paraná Basin. The Brasília belt corresponds to the closure of the Goiás Ocean (~ 630 Ma), which is located between the Goiás magmatic arc and the São Francisco craton (northeastern border of the Paraná Basin). The closure of the Adamastor Ocean involved the interaction among the São Francisco, Paranapanema fragments, Congo, and Kalahari cratons, resulting in the formation of the Mantiqueira Province, which includes the Araçuaí, Ribeira, and Dom Feliciano fold belts (eastern border of the Paraná Basin). It is worth noting that the geological character, age, and composition of the oldest basement rocks below the Paraná Basin are mostly unknown.

ISOTOPIC SYSTEMATICS OF PMP THOLEIITIC BASALTS

The Sr-Nd-Pb isotope compositions of the PMP tholeiites are essential to the inferences of the genesis of these magmas. Until the end of the last century, isotope determinations were relatively scarce. Still, they gave evidence that the low-TiO_2 rock types show crustal contamination in southern PMP but not in northern PMP (e.g. Piccirrillo et al., 1989; Peate and Hawkesworth, 1996, Marques et al., 1999). Since then, much more data has been acquired, allowing the discrimination of the compositional types that underwent crustal contamination. The lithophile-element-based isotope compositions ($^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$) are not homogeneous for the low-TiO_2 and high-TiO_2 basalts (Marques et al., 1999, 2016, 2018; Rocha-Júnior et al., 2012, 2013, 2020) as seen in Table 1. They show moderate variations in Sr and Nd isotope ratios for southern low-TiO_2 and northern high-TiO_2.

Table 1: Isotope ratios for the magma types from southern and northern PMP. The values in each cell are the minimum and maximum variation limits.

Magma type	$^{87}Sr/^{86}Sr_i$	Initial $\varepsilon^{143}Nd$	$^{206}Pb/^{204}Pb_i$	$^{207}Pb/^{204}Pb_i$	$^{208}Pb/^{204}Pb_i$
Esmeralda	0.70460	-1.0	18.09	15.60	38.19
(southern low-TiO_2)	0.70601	+2.6	18.42	15.65	38.46
Pitanga and Paranapanema	0.70538	-5.6	17.62	15.50	37.95
(northern high-TiO_2)	0.70642	-1.8	17.83	15.55	38.11
Urubici flows	0.70452	-5.7	17.14	15.47	37.75
(rare southern high-TiO_2)	0.70641	-1.6	17.94	15.56	38.15
Ribeira basalts	0.70546	-4.2	17.63	15.50	37.86
	0.70593	-2.0	17.81	15.54	38.15
Gramado	0.70640	-8.0	18.20	15.60	38.42
Rb/Ba > 0.04	0.71350	-1.5	18.57	15.67	38.69

The Esmeralda basalts show a slight variation in initial Pb isotope compositions; comparatively, the northern high-TiO_2 (NHT) basalts have less radiogenic Pb. The Urubici flows present some distinct geochemical characeristics compared to the NHT basalts. The Ribeira basalts have $^{87}Sr/^{86}Sr_i$ and $^{143}Nd/^{144}Nd_i$, varying in a narrow range overlapping with those of the NHT rocks. The Ribeira basalts are similar to those of the NHT rocks. It is worth mentioning that the geochemical and isotope signatures of the Gramado magma-type demonstrate that these rocks were severely affected by crustal contamination.

Regarding Sr-Nd-Pb isotope compositions, PMP tholeiites are radiogenic, plotting far from a depleted mantle source (Figures 4 and 9). More striking information came from the first study on the osmium isotopes (Rocha-Júnior et al., 2012), showing that the basalts display a homogeneous composition regardless of their TiO_2 contents (Figure 4). Initial $\gamma^{187}Os$ in PMP range from -0.8 to +3.0 (Rocha-Júnior et al., 2012), overlapping the fertile mantle compositions (primitive upper mantle: $\gamma^{187}Os = +2.0$; Meisel et al., 2001). Such osmium isotope study was restricted to the magma-types that were not contaminated by continental crust, which are NHT ($\gamma^{187}Os_i$ = +0.1 to +1.4), Esmeralda ($\gamma^{187}Os_i$ = -0.8 to +3.0), and Urubici ($\gamma^{187}Os_i$ = -0.3 to +0.6). The Ribeira-type magma was recently investigated (Rocha-Júnior et al., 2020), revealing an osmium isotopic signature surprisingly typical of the Archean lithospheric mantle. The $^{187}Os/^{188}Os$ signatures ($\gamma^{187}Os_i$ range from -15.5 to -0.3) for Ribeira basalts are more unradiogenic than the other magma types of the PMP, as well as the estimates for the contemporary depleted mantle. They are lower than any osmium isotopic ratio yet reported for CFB, requiring the participation of old lithosphere portions. The initial Os isotope compositions of the Ribeira rocks overlap with those of the peridotite xenoliths from on-cratonic SCLM, which is typified by very unradiogenic Os isotope compositions with strongly negative frequency distributions (e.g. mean $\gamma^{187}Os$ = -10.3; Pearson and Nowell, 2002).

THE LITHOSPHERIC STRUCTURE UNDER THE PARANÁ BASIN

Knowing the structure and nature of the lithosphere under the PMP is crucial for understanding the geodynamic processes involved in continental basaltic volcanism, the rupture of the continental lithosphere, and the opening of the South Atlantic Ocean. The initial knowledge was achieved mainly from sparse drillings of the volcano-sedimentary package (e.g. Cordani et al., 1984) and few geophysical surveys in the northern half of the Paraná Basin, including seismic reflection (Marques et al., 1993), potential methods (Ferreira et al., 1982; Molina et al., 1989) and magnetotellurics (Stanley et al., 1985). Results from these studies allowed discussions on three principal themes: (i) the existence of a weakness zone (central rift) that controlled the subsidence of the basin and later facilitated the extrusion of basalts; (ii) magmatic underplating, promoted from the discovery of a positive Bouguer anomaly (25-30 mGal) along the axis of the northern Paraná Basin, which was modeled by Molina et al. (1989) as due to the intrusion of high-density mantle-derived material into the lower-middle crust; (iii) configuration of the crystalline basement.

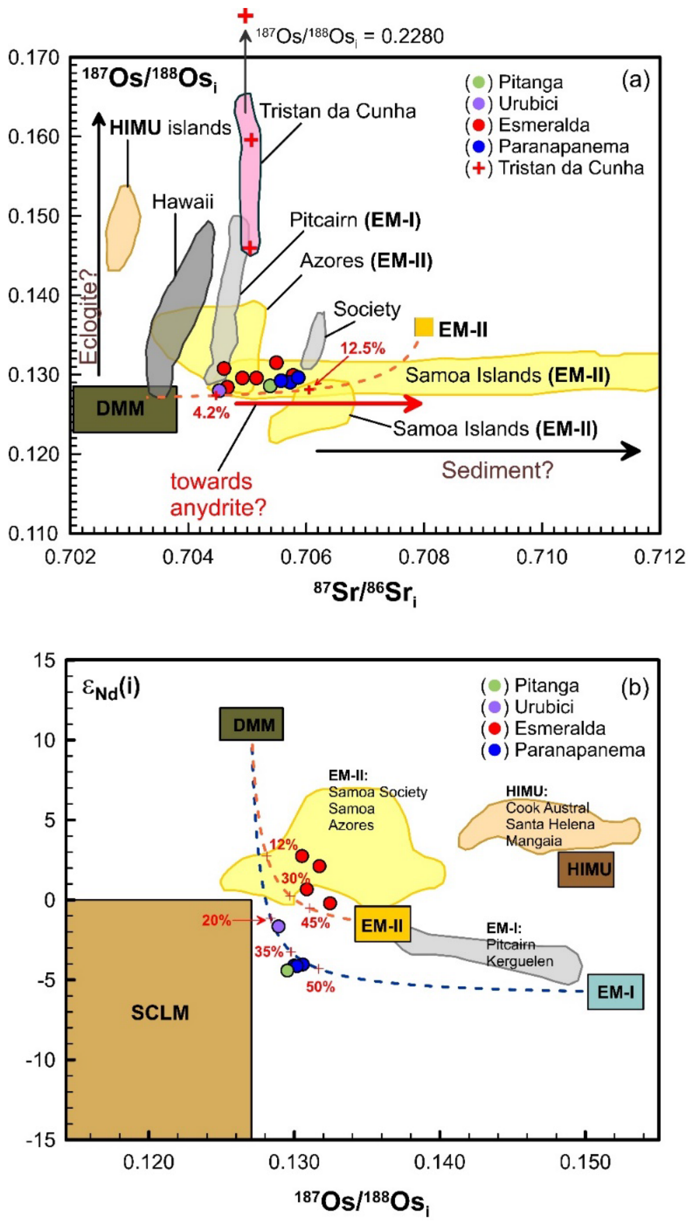

Figure 4: (a) Initial $^{187}Os/^{188}Os$ plotted against initial $^{87}Sr/^{86}Sr$. Modeling assumes two-component mixing between the sublithospheric mantle (represented by arc-mantle peridotite) and two enriched components. Model (1) is EM-I (blue curve). Model (2) is EM-II (orange curve). (b) Initial $^{143}Nd/^{144}Nd$ plotted against initial $^{187}Os/^{188}Os$. Modeling assumes two-component mixing between depleted mantle-derived melts (represented by arc-mantle peridotite) and two enriched components. Model (1) is EM-I (blue curve). Model (2) is EM-II (orange curve). The parameters used for modeling are found in Rocha-Júnior et al. (2012).

Systematic teleseismic studies started in 1992 under the Brazilian Lithopsheric Seismic Project (BLSP) (James et al., 1993; Snoke and James, 1997), with a portable array of 14 three-component broadband seismograph systems deployed in a roughly east-west arrangement along 20°S latitude, encompassing the area previously studied by Molina et al. (1989) (indicated in Figure 5). Several teleseismic techniques were used to estimate the deep structure beneath the network, including surface-wave inversion, body wave traveltime tomography, receiver-function analysis, and S-wave splitting. Some results and conclusions of the initial studies involving (but not limited to) these data are summarized in the following paragraphs.

Using receiver functions analyses, James et al. (1993) obtained preliminary results of crustal thickness for the eastern Paraná Basin. They observed high values (43-45 km) relative to the São Francisco craton (40-42 km), a fact that has been confirmed by subsequent teleseismic studies using larger data sets (e.g. Julià et al., 2008; Rivadeneyra-Vera et al., 2019). Using data from additional stations, Assumpção et al. (2002) confirmed this contrast, suggesting two hypotheses to explain the data: (i) The lithospheric mantle under the São Francisco craton has low density, which would be compatible with a depleted (low FeO) composition. (ii) Alternatively, the crust beneath the Paraná Basin is denser than that of the craton. Together with the measured high Poisson's ratio, this later hypothesis would be consistent with magmatic underplating, as proposed previously by Molina et al. (1989). However, widespread magmatic underplating has been refuted by subsequent teleseismic studies. An and Assumpção (2006), for example, observed low S-wave velocities and normal Vp/Vs in the northeastern Paraná Basin. These results led the authors to infer that underplating is not widespread in the basin and to defend a different source for the gravity high near the basin axis. Alternatively, they suggest a higher density lithospheric mantle, as indicated by a Rayleigh-wave group velocity tomography (Feng et al., 2004). Julià et al. (2008), using receiver function analysis, observe responses compatible with underplating only in some particular stations (red triangles in Figure 5), approximately along the inferred sutures of the fragmented craton model of Milani and Ramos (1998).

Travel time inversion of teleseismic body waves (VanDecar et al., 1995; Schimmel et al., 2003) revealed a large-scale low-velocity structure shaped roughly like a vertical cylinder in the upper mantle below about 200 km in the northeastern Paraná Basin (see Figure 5). This negative seismic anomaly was interpreted as a fossil plume (Tristan da Cunha) head conduit for the Paraná flood basalts, implying that all the upper mantle has moved coherently with the lithosphere since the opening of the South Atlantic Ocean at corresponding latitudes. However, the presence of a plume in the northern Paraná has been questioned by Molina et al. (1989), arguing that no geoid anomaly or topographical expression of the presence of a thermal anomaly is recognized in the region, and by Ernesto et al. (2002), based on paleomagnetic reconstructions, who argue that the Tristan da Cunha plume was located about 1000 km south of the Paraná Basin at the time of the magma eruptions. In addition, the contribution of asthenospheric sources has been ruled out, given the isotopic and geochemical signatures typical of the lithospheric mantle for the Serra Geral basalts (Comin-Chiaramonti et al., 1997; Marques et al., 1999; Rocha-Júnior et al., 2020).

Snoke and James (1997) used surface wave dispersion to estimate the average lithospheric structure. Two station phase velocity inversion of Rayleigh and Love waves revealed high S-wave velocities (4.6-4.7 km/s) in the upper 200 km of the mantle under the entire region of study. This result led the authors to support the proposal of Cordani et al. (1984) for a cratonic nucleus beneath the central axis of the Paraná Basin. Subsequent surface wave studies in the part north of the Paraná Basin corroborate such a cratonic signature beneath the Paraná Basin, showing that the mantle up to 150 km deep characterizes by mean S-wave velocities (~4.65 km/s) typical of cold platforms (An and Assumpção, 2006; Feng et al. 2007). Similar high velocities in this region are observed in the global model of Schaeffer and Lebedev (2014) and recent continental-scale tomographies (Celli et al., 2020; Finger et al., 2021; Nascimento et al., 2022).

More recently, Padilha et al. (2015) questioned the cratonic nature of the lithosphere under the Paraná Basin. Using magnetotelluric data from a west-east profile between the Rio Apa Block and Ponta Grossa arch (profile 1 in Figure 5), they argue that the electrical resistivity values (<500 ohm-m) in a wide range of the lithosphere around the central axis of the basin are lower than expected for Archean and Proterozoic cratons. But, using additional magnetotelluric data from three small intersecting profiles, Maurya et al. (2018) observed high resistivities at lithospheric depths just north of Padilha et al.'s (2015) profile, leading the authors to support the seismic models of cratonic lithosphere.

New seismic and magnetotelluric data acquired recently in the PMP have improved the geophysical knowledge of its lithosphere. In the southwest part of the PMP, new areas mapped with high seismic velocities below about 200 km (e.g. Rocha et al., 2019; Nascimento et al., 2022) coincides partially with deep resistive roots mapped from magnetotelluric profiles across northern Argentina and Uruguay (Bologna et al., 2019; Dragone et al., 2021). These results indicate the existence of a relatively cold and dry lithosphere (cratonic?). In contrast, upper mantle with low seismic velocities, also seen in continental-scale tomographic models (e.g. Celli et al., 2020; Finger et al., 2021), and low resistivities have been found principally in the southeastern PMP, close to the continental margin. Such results may indicate the presence of a relatively hot upper mantle.

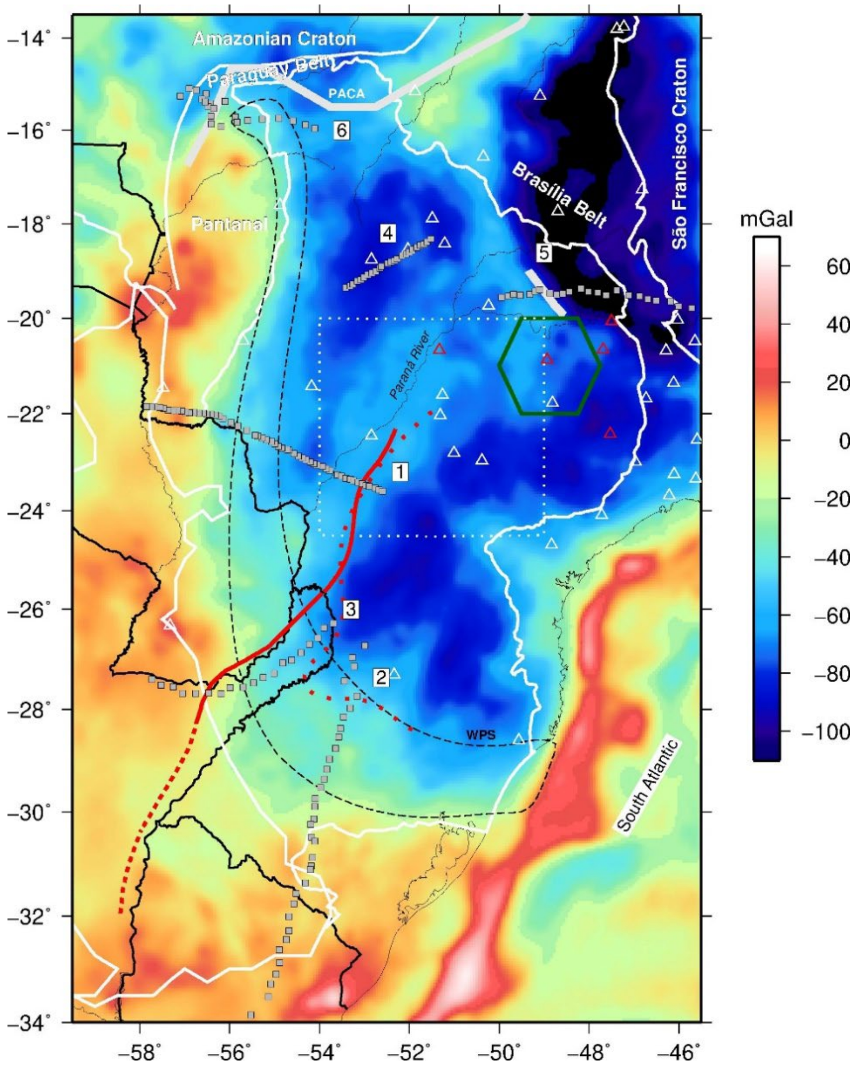

Figure 5: Tectonic provinces (continue white lines) showing the location of the Paraná Basin, over the Bouguer anomaly map (Sá, 2004) upward- continued to the height of 10 km. The black dotted rectangle indicates the studied area of Molina et al. (1989). Teleseismic stations from the Brazilian Lithosphere Seismic Project (BLSP; James et al., 1993; Snoke and James, 1997) are indicated by white and red triangles. The red ones are the stations with evidence of mafic underplating in the lower crust, according to Julià et al. (2008). The green hexagon represents the horizontal position of the fossil conduit mapped by VanDecar et al. (1995). Gray squares are magnetotelluric sites along linear profiles (labeled from 1 to 6). Thick white lines are sutures inferred from magnetotelluric surveys, including the Paraguay-Araguaia conductivity anomaly (Bologna et al., 2014). Thin dashed black lines are the gravity feature Western Paraná Suture/Shear zone (Dragone et al., 2017). MT profiles: (1) Padilha et al. (2015), (2) Bologna et al. (2019), (3) Dragone et al. (2021), (4) Bologna et al. (2013), (5) Bologna et al. (2011), (6) Bologna et al. (2014).

Inversion modelings of GDS and MT data (Padilha et al., 2015, profile 1 in Figure 5; Maurya et al., 2018) confirmed the existence of such linear structure, defined as a middle to lower crustal (15-20 km) feature spatially associated with areas with the thickest basalt accumulation (>1 km). Maurya et al. (2018) named this lineament Paraná Axial Anomaly (PAA) and suggested that the conductive lineament bend to the east towards the Torres syncline following the gravity-defined Western Paraná Suture/Shear zone (WPS; Dragone et al., 2017, see Figure 5). This eastward bending was questioned by Dragone et al. (2021), using results from two MT profiles across the transition between the Paraná and Chaco Paraná basins (profiles 2 and 3 in Figure 5). These authors argue that PAA may continue further to the south inside Argentina. Figure 5 shows the two proposed traces for PAA. The extension of PAA to the north is uncertain, but similar localized conductors at middle to lower crustal depths occur in an MT profile (Bologna et al., 2013, profile 4 in Figure 5) in the Aporé region, northernmost Paraná Basin.

The present-day geophysical data on the deep structure beneath the PMP suggest that the Paraná lithosphere is more likely composed of a mosaic of cratonic blocks and heterogeneous terrains. Enrichment processes in lithospheric mantle minerals associated with ancient subduction zones around the Paraná Basin, as suggested by MT studies across the Brasília and Paraguay belts (profiles 5 and 6 in Figure 5), may have preserved the cratonic characteristics from the seismological point of view (high velocities of the lower crust and upper mantle) but may have altered the electrical conductivity, and perhaps the density (cf. Chaves et al., 2016), relative to a typical Precambrian cratonic lithosphere.

PALEOMAGNETISM AND THE EMPLACEMENT TIME OF THE PMP

Since the pioneering work by Creer et al. (1965), a sizeable paleomagnetic dataset for the Paraná magmatism has been constructed. Most of the data come from the extensive work by Ernesto et al. (1990), with samples covering the entire PMP area. A comprehensive set of the still available samples were recently reanalyzed, and the data was reinterpreted using modern equipment and techniques (Zaffani, 2013). The new results produced negligible differences compared to the old ones. A work by Alva-Valdivia et al. (2003) complemented the database from the central area (between the Rio Uruguay and Rio Piquiri lineaments). In the northern region (north of the Rio Piquiri Lineament), the paleomagnetic work (Ernesto et al., 1990, 1999) was concentrated on the sills, and recently Ernesto et al. (2021) acquired more data from flows and sills in the area. Beyond the Brazilian borders, there are data from Paraguay (Ernesto et al., 1996; Goguitchaichvili et al., 2013), Argentina (Mena et al., 2006), and Uruguay (Cervantes-Solano et al., 2010) are available, and from the African side (Gidskehaug et al., 1975; Dodd et al., 2015; Gidskehaug et al., 1975; Dodd et al., 2015; Owen-Smith et al., 2019). All these data make the Paraná-Etendeka Province very well-known from the paleomagnetic point of view. There is a perfect match between the paleomagnetic poles (Ernesto et al., 2021) from the southern and northern parts of the PMP and the Etendeka poles in pre-drift reconstructions indicating a short time interval for the accumulation of the majority of the PMP flows, as confirmed by the most accurate geochronological data. However, data from the central PMP gives a paleomagnetic pole slightly different from the other areas. Ernesto et al. (2021) attributed this difference to the tectonism that affected the area, leaving a sharp relief. The paleomagnetic difference is compensated by a tilting correction of 3°-5° in a north-south direction.

The first $^{40}Ar/^{39}Ar$ ages for the PMP were published by Renne et al. (1992), placing the beginning of the volcanism at 133±1 Ma and indicating a magmatic duration not greater than one million years, agreeing with the paleomagnetic indications (Ernesto and Pacca, 1988). Since then, many $^{40}Ar/^{39}Ar$ and U-Pb ages have been published. Recently, Gomes and Vasconcelos (2021) compiled the existing $^{40}Ar/^{39}Ar$ step-heating (n = 378) and U-Pb (n = 32) ages. After recalculating the older ages to the current standards and filtering the $^{40}Ar/^{39}Ar$ step-heating data, those authors constrained the results to the 135.5-133.2 Ma interval, with a peak at 134.4 ± 0.1 Ma and an interval of 1.6 to 3.0 Myr for the entire magmatism.

However, Dodd et al. (2015) examined a composite Etendeka (ET; Grootberg and Bergsig) section and claimed that it would be necessary for at least 4 Myr to account for the various geomagnetic polarity reversals recorded in the section. Although there is no indication of such a long period in the PMP data, a new detailed section from the Paraná side (TS, Figure 6) was investigated to check if any polarity interval was skipped in the previous samplings and to produce a better matching with the neighbor sections.

The TS section outcrops along the road between Taquara-São Francisco de Paula in the Rio Grande do Sul State and between PH and BM sections. It starts on the Botucatu sandstones and reaches more than 900 m high. Samples from thirty-three outcrops were submitted to the alternating magnetic field (AF) and thermal treatments (Figure 6a to 6d). Fields not greater than 15 nT removed a soft viscous component. The calculated mean magnetization directions for each sampling site are displayed in Figure 6e and listed in the Appendix. The magnetization is carried by highly oxidized magnetite (Figure 6f) with unblocking temperatures around 580 °C as in most of the already studied PMP rocks (Ernesto et al., 1990, 2021 and references therein).

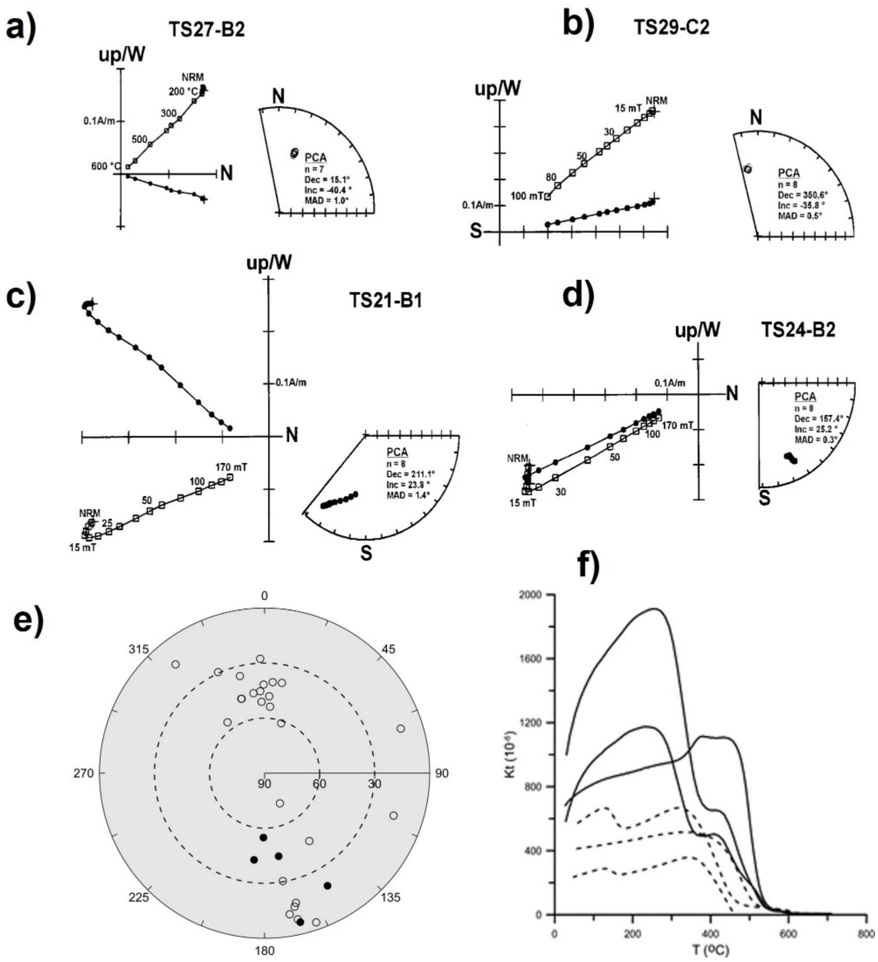

Figure 6: Orthogonal plots and stereographic plots of the magnetization behavior during the demagnetizing processes (a to d). Mean magnetization directions for all sites (e) and examples of thermal magnetic (f).

The mean magnetization of a sampling site corresponds to an instantaneous position of the geomagnetic pole designated as a virtual geomagnetic pole (VGP). The VGP latitude indicates the field polarity - north (south) latitudes correspond to normal (reversed) polarity. The TS polarity column is shown in Figure 7 along with the columns for the other southern sections. Section TS starts in a normal polarity interval followed by four field reversals. This is the same pattern seen in the neighbor BM section but adding more details, except that the TS section seems to have started earlier during a normal polarity chron. Most sections show four to five reversals except for the JS and GB sections with only one reversal (two polarity chrons), and they do not show transitional VGP positions. This is an indication of a rapid accumulation of magma. The VGP paths from one polarity to the other are not fully recorded in the sections because transitions are fast (probably ≤1 kyr), and the magma eruptions are intermittent. Even though mid-latitude VGPs related to a polarity transition, or a geomagnetic field excursion (failed reversal or considerable paleosecular variation of the field), are common in most sections. Another important fact is that the reversed polarity intervals, in the section with more reversals, are generally short, sometimes represented by only one flow. These events may represent subchrons (≤200 kyr) or even cryptochrons (≤30 kyr; Cande and Kent, 1992). Therefore, the relatively high number of reversals recorded by the PMP sections are easily accommodated in a brief time interval.

The Etendeka section fits the area occupied by the BM, TA, and PC sections in a pre-drift reconstruction (Figure 7). ET and PC show impressive correspondence when ET is rotated to South America. Both show three brief reversed polarity intervals; PC ends with an excursion missing in ET but eventually in progress. This is a fantastic match, considering the distance between the two places, even when the continents are juxtaposed.

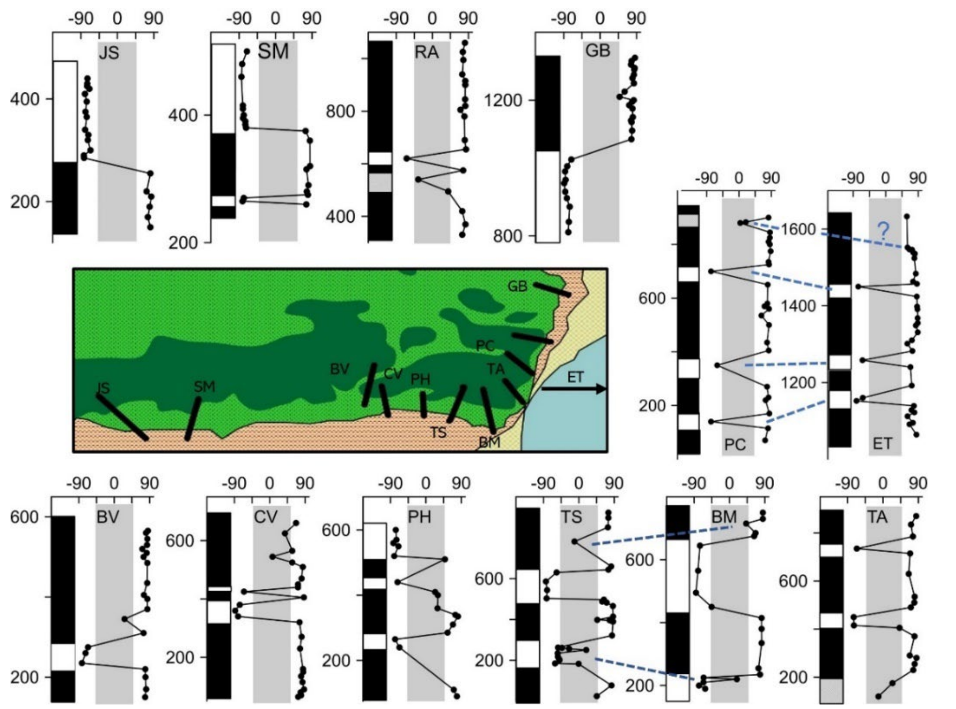

Figure 7: VGP latitude variation recorded by the PMP paleomagnetic sections indicated in the map. The black/white column on the left of each section represents the recorded polarity intervals. Gray stripes mark the latitude interval (45 °S – 45 °N) where the VGPs are transitional, and the reversal is not completed. The ET section is the composed Grootberg-Bergsig section from Etendeka Province, South Africa (Dodd et al., 2015); the plotted latitudes in this section were rotated to South America to show the correspondence better.

Dodd et al. (2015) used the Geomagnetic Polarity Timescale (GPTS) of Gee and Kent (2007) to correlate the reversals found in the Etendeka sections with the GPTS based on oceanic floor anomalies. They concluded that a much longer time would be necessary to accommodate the Etendeka recorded chrons than the ~1 Myr normally postulated. Malinverno et al. (2012) refined the GPTS using a Monte Carlo method to reduce the uncertainties. For the age interval 135-133 Myr, there are eight chrons (Figure 8) with age uncertainty of about 1 Myr and duration uncertainty of ~50-100 kyr. Therefore, it is perfectly possible to accommodate the Paraná-Etendeka sections within that age interval (Figure 8). The PC section apparently shows eight reversals, as does the Etendeka ET section, therefore, covering about two million years, based on the oceanic floor anomalies. However, given the uncertainties in the duration of the chrons and the high probability of the existence of undetected subchrons in the GPTS, the whole time interval could be substantially reduced.

ON THE ORIGIN OF THE PMP THOLEIITIC BASALTS

There are many more difficulties than certainties in models invoking a Tristan da Cunha plume as the source material for PMP (Rocha-Júnior et al., 2012). In that study, the possible influence of an ancient subcontinental lithospheric mantle (SCLM), a Tristan da Cunha plume (OIB - ocean island basalt) or an asthenospheric mantle source (depleted mantle) on the formation of the PMP was investigated based on new Re-Os isotopic data. These showed that exclusive melting of either ancient SCLM or a mantle-plume could not satisfactorily explain the overall chemical and isotopic features of the NHT, Esmeralda and Urubici magma-types of the PMP.

To characterize the mantle sources involved in PMP genesis and account for the chemical and isotopic observations, Marques et al. (1999) and Rocha-Júnior et al. (2012) invoked the involvement of asthenospheric mantle and two enriched components. The asthenospheric component was enriched by fluids and/or magmas related to Neoproterozoic subduction. Based on highly siderophile and lithophile element geochemical data of the PMP, Rocha-Júnior et al. (2012) proposed that the high- and low-TiO_2 basalts were derived from magmas that originated from an asthenosphere-like source (similar to arc-mantle peridotite) variably affected by enriched mantle I (EM-I) and enriched mantle II (EM-II), respectively (Figure 8). EM-I has low $^{87}Sr/^{86}Sr$ (< 0.706) and $^{206}Pb/^{204}Pb$ (< 18), similar to either an ancient,

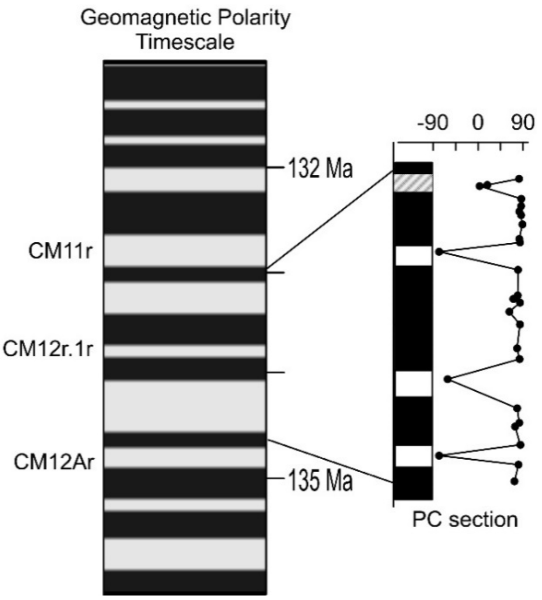

Figure 8: Tentative match between the GPTS and the PC section at the 135-132 Myr interval (Malinverno et al., 2012).

recycled lower continental crustal component or a metasomatized SCLM component. EM-II has more radiogenic Sr ($^{87}Sr/^{86}Sr$ > 0.706), and Pb ($^{206}Pb/^{204}Pb \approx$ 18.8). EM-II ultimately derives from the upper continental crust probably through the subduction and recycling of pelagic sediments or metasomatized (i.e., fluid/melt infiltration) oceanic lithosphere.

Based on osmium isotopes, Rocha-Júnior et al. (2012) verified the possibility of the participation of an asthenospheric component represented by the DMM component. However, Rocha-Júnior et al. (2013) integrated osmium isotopes data with Sr-Nd-Pb isotopes, geochemical and geophysical data and presented a new view on the genesis of the NHT (Pitanga and Paranapanema) of the PMP. The geochemical composition may be explained by fluids and/or small-volume melts related to metasomatic processes. In this context, the source of these magmas was a mixture of asthenospheric peridotite veined and interlayered with mafic components (e.g. pyroxenites or eclogites; Figure 9). An asthenospheric mantle source (dominating the osmium isotopic compositions) that has previously been depleted by a small to moderate degree of melt extraction and a slab-derived hydrous fluid or small-volume melts related to metasomatic processes into the peridotitic mantle wedge source region due to dehydration of oceanic lithosphere subduction. To the northeast of the Paraná Basin, these metasomatic processes are possibly related to the Brasiliano orogeny (Machado et al., 1996; Valeriano et al., 2008; Coelho et al., 2017), which is characterized by complex histories of rifting, ocean opening and closure, and magmatic arcs, while the lithospheric mantle to the west of the Paraná Basin was strongly affected by the closure of the Clymene Ocean, along with suturing processes associated with Western Gondwana assembly (Tohver et al., 2010, 2012; Dragone et al., 2017; McGee et al., 2018).

Furthermore, Rocha-Junior et al. (2013) stated that PMP rocks could be derived from mantle source regions that chemically correspond to the sources of IABs (Figure 2), although caution should be taken for this conclusion. Evidence for the involvement of metasomatic components (possibly related to supra-subduction environments) in the source of the PMP includes (i) enrichment of LREE relative to HREE, (ii) enrichment in mobile large-ion lithophile element (LILE), and (iii) strong negative anomalies of Nb-Ta (Figure 2). The same authors proposed that the NHT source is the asthenospheric mantle affected by fluids and/or magmas related to subduction. This asthenospheric mantle region may have been frozen and coupled to the base of the Paraná Basin lithospheric plate. Note that the sources of the high-Ti basalts of the PMP and alkaline rocks surrounding the Paraná Basin and oceanic basalts with DUPAL signatures appear to be related to EM-I component. Our favored explanation is that the EM-I component associated with these magmatic events in the South American platform derived from mixtures of eclogites or pyroxenite with peridotite, since pyroxenite melts freeze and react entirely with the ambient peridotite.

As discussed previously, the moderately radiogenic Sr and unradiogenic Nd isotopic compositions of the Ribeira mantle source and the NHT basalts appear to have been modified by interaction with a LILE-rich fluid/melt. Note that the NHT, Esmeralda and Urubici basalts are related to two-component sources for the generation of primary mantle-derived basaltic magmas (Figures 2 and 9; Rocha-Júnior et al., 2012, 2013). However, as previously reported, it was not expected similar osmium isotopic signature for the Ribeira basalts and the PMP magma types. To our surprise, a telltale signature of the Archean lithospheric mantle was identified in the petrogenesis of the Ribeira basalts (Rocha-Júnior et al., 2020). The initial $^{187}Os/^{188}Os$ isotopic compositions in Ribeira lavas, ranging from 0.10660 to 0.12575 ($\gamma^{187}Os_i$ range from -15.5 to -0.3; Figure 10), are more unradiogenic than the other magma-types of the PCFB, as well as the estimates of the contemporary

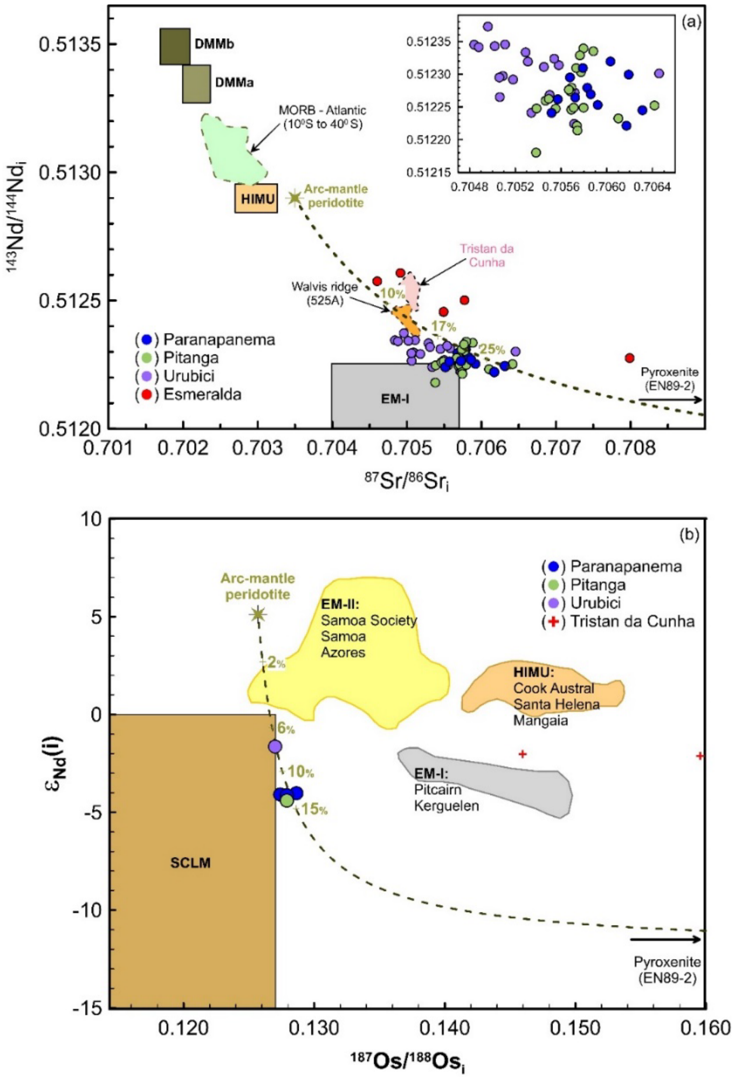

Figure 9: (a) Initial $^{87}Sr/^{86}Sr$ plotted against initial $^{143}Nd/^{144}Nd$. Modeling assumes two-component mixing between the sublithospheric mantle (represented by arc-mantle peridotite) and a hypothetical "mafic vein" material (pyroxenite EN89-2). (b) $^{187}Os/^{188}Os$ plotted against initial εNd. Modeling assumes two-component mixing between the sublithospheric mantle (represented by arc-mantle peridotite) and a hypothetical "mafic vein".

Depleted Mantle and are lower than any osmium isotopic ratio yet reported for continental flood basalts (Rocha-Júnior et al. 2020). These remarkably unradiogenic $^{187}Os/^{188}Os$ ratios preclude significant continental crust contamination and require the involvement of an ancient subcontinental lithospheric mantle source that evolved in a very low Re/Os environment.

The range in $^{187}Os/^{188}Os$ ratios for the Ribeira rocks is similar to that found in on-craton SCLM peridotite, which is characterized by unradiogenic Os isotope compositions, with $\gamma^{187}Os$ values as low as −20 in the most refractory (harzburgitic) Archean cratons (Walker et al., 1989; Pearson and Nowell, 2002). In addition, these latter authors also found that off-cratonic xenoliths are not characterized by such low Os isotope compositions, many of which are within the range of contemporary Primitive Mantle (mean $\gamma^{187}Os$ = -1.5). Some trace element and Sr-Nd isotope studies (e.g. McDonough and McCulloch, 1987) have revealed that neighboring regions of cratons might experience several separate episodes of metasomatism. The unradiogenic $^{187}Os/^{188}Os$ ratios of the Ribeira rocks, along with the occurrence of negative Nb anomalies in these rocks (Figures 2 and 10), low initial $^{87}Sr/^{86}Sr$ ratios between 0.70546 and 0.70593 (related to NHT), and unradiogenic Nd isotope compositions (initial $\varepsilon^{143}Nd$: -3.1 to -4.2) suggest that Archean lithosphere fragments may have contaminated this portion of the PCFB metasomatized mantle source (Figure 10).

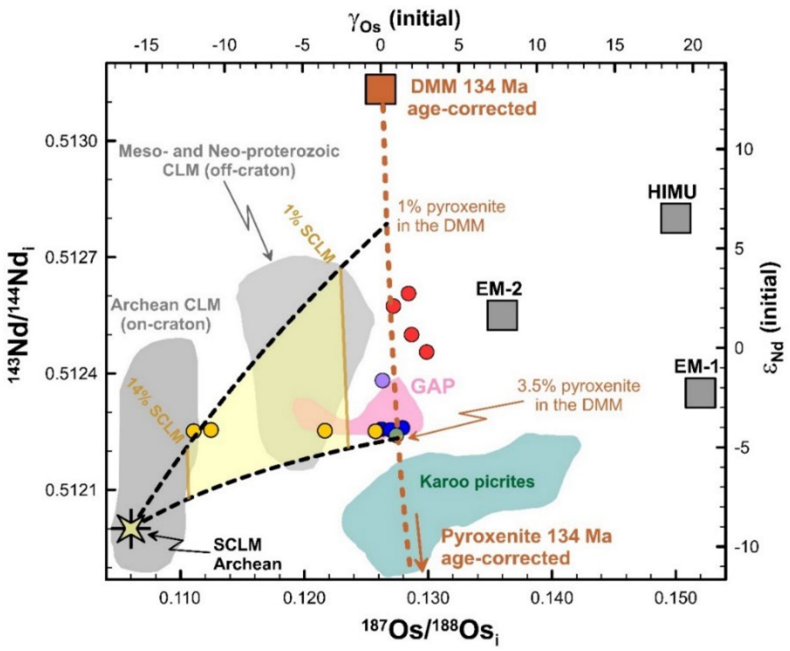

Figure 10: Initial $^{187}Os/^{188}Os$ (at 134 Ma) plotted against initial $^{143}Nd/^{144}Nd$. Modeling assumes three-component mixing between peridotite mantle (represented by DMM), a hypothetical "mafic vein" material (pyroxenite EN89-2) and melts from the on-cratonic Paranapanema SCLM (represented by mafic-alkalic rocks from APAP). Symbols: yellow circles = Ribeira type; blue circles = Paranapanema type; green circles = Pitanga type; purple circles = Urubici type; red circles = Esmeralda type. The parameters used for modeling are found in Rocha-Júnior et al. (2020).

The fact that the Ribeira rocks occur on a peculiar lithospheric geophysical structure and have a unique unradiogenic osmium isotope signature revealed the existence of an Archean lithosphere for the first time concealed by the Paraná Basin, inserted in the Paranapanema fragmented lithosphere. On the other hand, the other magma types of the PMP, whose osmium isotopic signature is similar to the modern fertile mantle, occur close to more electrically conductive lithospheric structures. Thus, osmium isotopic information integrated with recent crustal and upper mantle geophysical soundings provides crucial information about the PMP mantle sources.

Based on geochemical and isotope data from Ribeira basalts, it seems likely that the on-cratonic PFL has contaminated these rocks. As pointed out above, the Ribeira basalts have lithophile-element-based isotope compositions similar to those observed in NHT rocks, so we can assume that all these volcanic rocks have a common metasomatized mantle source component (Rocha-Júnior et al., 2020). This model agrees with Carlson et al. (2007) for lithospheric evolution under the Goiás alkaline province (GAP), which suggested that the old refractory lithospheric mantle was replaced by young fertile compositions or underwent a process of compositional transformation (refertilization). According to Rocha-Júnior et al. (2020), the interaction between the peridotite and slab-derived silicic melts during Neoproterozoic-Cambrian led to the formation of the young fertile lithospheric mantle under part of the Paraná Basin and GAP from which NHT, Esmeralda, and Urubici were derived, while the Ribeira basalts may also have been influenced by the PFL (refractory lithosphere). This interpretation is invoked because the unradiogenic $^{187}Os/^{188}Os$ ratios are exclusively documented in fragments of on-cratonic SCLM brought to the surface as xenoliths are characterized by Re-poor compositions combined with a low $\gamma^{187}Os$, low $\varepsilon^{143}Nd$ signature, and lithophile element enrichment (Pearson and Nowell, 2002).

Our latest findings suggest that the Paraná flood basalts originated from a laterally and vertically heterogeneous lithospheric mantle that was variably hybridized by pyroxenites related to multiple Neoproterozoic-Cambrian suture zone and subduction processes (Rocha-Júnior et al., 2020). It is argued that the pronounced heterogeneity of the PMP province is a direct result of the complex long-term evolution of the West Gondwana amalgamation involving the collision among the Rio Apa/Amazon, São Francisco, and Rio de La Plata cratons (including PFL and Goiás blocks). This tectonism may have changed the stability of the lithospheric mantle, leading to thermal and mechanical erosion at the base of the lithosphere by the upwelling of the hot asthenosphere. The compositional diversity of magmas in the PMP is also associated with the formation of separate plumbing systems and magma production from different parts of such heterogeneous lithosphere in age, thickness, and stress, which plays a vital role in the magmatism location. The occurrence of isotopically enriched mafic rocks, carbonatitic complexes, and alkaline magmatism of the Cretaceous age in central/southern South America demonstrates that subducted material significantly contributed to generating enriched lithospheric mantle in this region. The involvement of Archean lithosphere in the genesis of Ribeira basalts, as strongly evidenced by unradiogenic Os isotope compositions, agrees with several geophysical data, which also point to significant compositional lithospheric heterogeneities under the Paraná Basin.

CONCLUDING REMARKS

What was the Triggering Mechanism for Mantle Melting?

Ernesto et al. (2002) proposed a non-plume model using geochemical, isotope, paleomagnetic, and geoid anomaly data. In this model, magmatism was triggered by a large thermal anomaly located at the coast of Western Africa, over which Paraná Basin remained almost stationary for about 50 Ma. In addition, an upper mantle three-dimensional structure adjacent to Tristan da Cunha Island imaged by marine magnetotelluric and seismological surveys (Baba et al., 2017) did not support the idea of a vertical conduit rising from the deep mantle beneath the island. Therefore, the involvement of the Tristan da Cunha mantle plume cannot be ruled out as a heat supplier to trigger the melting of the lithospheric mantle.

The Tristan da Cunha plume hypothesis has also been contested by Rocha-Júnior et al. (2012) based on osmium isotopic data that showed no evidence of plume participation. These authors were the first to present osmium isotope and highly siderophile element abundance data for alkaline rocks from Tristan da Cunha Island. The initial $^{187}Os/^{188}Os$ ratios of the three basalts, calculated for 1 Ma, vary from 0.146 to 0.228 (initial $\gamma^{187}Os$ values range from +15 to +80). All three samples are considerably more radiogenic than the PMP source (Rocha-Júnior et al., 2012, 2020). Thus, PMP magmatism may be attributed to local hotter mantle conditions due, for example, to the combined effects of edge-driven convection (King and Anderson, 1998) and huge-scale mantle warming under the Pangea supercontinent (Coltice et al., 2007). The proximity of the PMP magmatism to the craton margins (e.g. São Francisco, Congo, Rio de la Plata, Amazon) is consistent with the “edge-effect” mantle flow model, where a discontinuity drives the small-scale flow in the thickness of the lithosphere.

Fragmented and Metasomatized Lithosphere Under the Paraná Basin

A model involving multiple metasomatic episodes can also be applied to the study region since the physical properties of the underlying lithospheric and asthenospheric mantle concealed by the Paraná Basin have been investigated using electromagnetic induction methods, seismic tomography and a combined geoid inversion and P-wave velocity tomography. These studies indicate significant lateral and vertical heterogeneity in the present-day electrical, seismic, and density lithospheric structure under the Paraná Basin.

Because water (hydrogen) in nominally anhydrous minerals behaves as an incompatible element (Selway, 2014), metasomatism by fluids or melts enriched in incompatible elements may introduce water into SCLM. Hydrogen affects the properties of mantle minerals. It can reduce seismic velocities by reducing the bond strength, but this effect will be only important for very large water contents (0.1-1 wt.%) (Karato, 2006). In contrast, even small amounts of water will significantly reduce the electrical resistivity under lithospheric conditions (Selway, 2014). Hence, metasomatism might reconcile the apparent discrepancies between seismic and electromagnetic studies in some parts of the PMP. High seismic wave velocities and moderate electrical resistivities in the upper mantle probably reflect a depleted and cold cratonic lithosphere metasomatized in later tectonic events.

A possible source of metasomatism is the fluids and melts released from subducting slabs, as suggested by the existence of the WPS and electrical anomalies at the edges of the Paraná Basin. In fact, MT studies (Padilha et al., 2015; Maurya et al., 2018) along a profile across the linear gravity gradient (WPS zone) indicate that on the eastern side of WPS, within Paraná Basin, the lithospheric mantle is electrically more conductive than a depleted, dehydrated cratonic lithosphere. In this context, the WPS zone has induced metasomatic processes within a mantle wedge of a subducting oceanic plate (Clymene Ocean closure?) at the western margin of the Paraná Basin continental lithosphere.

The existence of small cratonic blocks, instead of one a single craton in the north-central segment of Paraná Basin, is also recognized in the gravity anomaly map (Dragone et al., 2017) and individual receiver function analysis (Julià et al., 2008). Indeed, high-density MT profiles (Maurya et al., 2018) revealed a deep local-scale resistivity structure under the north-central part of the Paraná Basin, indicating the presence of a fragmented cratonic basement. Similar fragmentation is also noted in the MT study of Bologna et al. (2013) in the Aporé region, northernmost Paraná Basin. Given these results, Rocha-Júnior et al. (2020) suggested the use of the term "Paranapanema fragmented lithosphere (PFL)" to refer to the ensemble of such lithospheric blocks separated by discontinuities. Note that suture/discontinuity zones are mechanically weak, which under extension, may have facilitated the rise of tholeiitic and alkaline magmas derived from deeper parts of the heterogeneous lithosphere.

APPENDIX A

Table A1: Paleomagnetic results for the TS section (Taquara-São Francisco de Paula, along road RS-020). Elev = elevation, Dec = declination, Inc = inclination, n/N = number of analyzed specimens/number of specimens included in the mean, α_{95} and k = Fisher's statistical parameters, Lat and Long = VGP coordinates.

Site	Elev. (m)	Dec. (°)	Inc. (°)	n/N	α_{95} (°)	k	Lat. (°)	Long. (°E)
TS-1	78	352.1	-46.0	5/5	5.5	195	82.7	235.3
TS-3	183	153.1	-71.6	11/9	22.7	6	-1.0	114.7
TS-4	185	166.5	6.5	18/14	4.9	66	-60.7	100.8
TS-5	202	166.4	-17.3	16/8	7.8	51	-49.4	108.3
TS-6	207	167.3	-15.4	20/17	3.3	116	-50.6	109.2
TS-7	218	160.9	-4.0	6/5	7.1	117	-53.5	95.9
TS-8	235	167.2	-8.3	13/13	10.0	18	-54.1	107.1
TS-8A	251	71.9	-12.0	7/7	17.5	13	18.7	35.6
TS-8B	257	146.6	-45.7	5/5	9.7	64	-24.9	96.6
TS-8C	261	170.4	-30.4	8/8	10.3	30	-43.1	116.6
TS-9	263	169.9	-11.9	6/6	7.1	91	-53.1	112.4
TS-9A	322	359.4	-41.7	9/9	4.8	116	84.4	-56.4
TS-10	390	363.4	-48.0	5/5	5.8	177	87.0	30.3
TS-11	392	364.7	-53.6	10/10	7.5	43	83.9	89.5
TS-12	396	370.9	-39.9	7/7	7.8	60	78.1	6.8
TS-13	398	320.7	-13.4	5/5	39.3	5	46.6	243.0
TS-14	414	357.6	-51.1	8/8	7.3	59	86.9	171.2
TS-15	466	357.0	-45.3	8/8	2.2	647	86.2	264.4
TS-16	483	378.4	-61.3	13/13	1.9	462	70.4	85.3
TS-17	488	323.9	-55.7	6/5	20.6	15	59.1	197.0
TS-18	497	335.3	-29.4	6/5	21.6	14	63.5	245.1
TS-19	503	186.9	42.4	5/4	20.3	21	-82.1	182.1
TS-20	543	170.4	44.1	7/6	6.1	120	-80.8	60.2
TS-21	586	181.0	54.9	5/5	5.1	229	-84.0	301.5
TS-22	630	150.8	19.7	5/5	7.0	120	-56.6	68.6
TS-23	643	342.9	-47.6	4/2	7.5	1120	75.1	218.2
TS-25	660	365.1	-40.2	4/4	12.4	56	82.0	345.5
TS-27	851	345.8	-35.4	4/4	3.7	616	73.8	253.7
TS-28	897	342.6	-47.5	9/9	9.3	32	74.8	218.3
TS-29	923	357.8	-27.6	11/11	6.0	59	75.1	301.1

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