APÊNDICE A - Seismic volcano-stratigraphy in the basaltic complexes on the rifted margin of Pelotas basin, southeast Brazil (Artigo Científico)

Seismic Volcano-Stratigraphy in the Basaltic Complexes on the Rifted Margin of Pelotas Basin, Southeast Brazil

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Abstract

The synrift and breakup stages of the Pelotas basin in southeast Brazil are characterized by scarce siliciclastic deposits and widespread volcanism in the form of seaward-dipping reflectors (SDRs). Using high-quality seismic reflection and refraction profiles integrated with gravity, magnetics, and exploratory boreholes, a volcanostratigraphic analysis has been undertaken to understand the geological processes observed during the rifting and breakup stages of this segment of the South Atlantic continental margin. Ten volcanic units have been identified and mapped within the extended continental crust and into the transitional and oceanic crusts. The magmatic cycle began during the early synrift stage, with alkaline, high TiO_2 basalts produced at 125 Ma. This was followed by the formation of a series of voluminous tholeiitic, high TiO_2 SDR wedges during the late synrift and breakup stages. The end of the breakup process was marked by flat-lying, late synrift/early postrift, tholeiitic, low TiO_2 basalts at 118 Ma. During the Late Cretaceous and Early Paleogene, the magmatic activity continued only in the oceanic crust, forming igneous intrusions (volcanic cones or seamounts).

A comparison between the Pelotas basin and the Lüderitz and Walvis basins offshore Namibia is discussed by integrating regional geological maps, potential field methods, seismic data, and results of exploratory drilling. The SDR province in the Pelotas basin coincides geographically with the Paraná basin continental flood basalts onshore Brazil, which crop out near the coastline. This makes the Pelotas basin an ideal place to understand the relationships between the tectonic-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.

Introduction

This contribution is a regional analysis of the volcanic rifted margin of the Pelotas basin in the southeast Brazilian Atlantic margin, focusing on the seismic stratigraphy of its voluminous volcanic flows. This analysis includes a comparison with neighboring volcanic provinces, such as the Paraná basin continental flood basalts in Brazil, and analysis of the volcanism in the Walvis and Lüderitz basins along the conjugate margin of West Africa. We also discuss the relationship between lithospheric extension and volcanism observed in the Pelotas, Paraná, Walvis, and Lüderitz basins in order to understand the possible tectonic mechanisms and magmatic episodes that operated during the formation of a passive margin regime throughout the Gondwana breakup (Fig. 1).

The Brazilian seismic reflection data set comprises approximately 15,000 km of 2D seismic lines, courtesy of the "Agência Nacional de Petróleo (ANP)," the Brazilian Navy (LEPLAC Project), and the ION-GXT website showing public data. The potential field data integrates ANP data sets with publically available worldwide gravity and magnetic data sets (Sandwell and Smith, 2009; Maus *et al.*, 2009). The well data set provided by ANP includes 28 exploratory wells drilled in the Pelotas and Paraná basins. The work has been completed by integrating refraction seismic profiles (Fig. 2) after Ewing *et al.* (1963) and Leyden *et al.* (1971). For the West African segment counterpart, the data set used includes 2D seismic lines and exploratory wells from published data.

Geological Framework

The South American/West African and the South Atlantic large igneous provinces

Two of the world's most extensive large igneous provinces are found in the South Atlantic, across the conjugate continental margins of South America and West Africa (Menzies *et al.*, 2002). These are the Paraná-Etendeka continental flood basalt province (CFB in figures) and the South Atlantic seaward-dipping reflector wedges (SDR) province (Fig. 1), which are both related to Gondwana breakup and the opening of the South Atlantic Ocean (Gladczenko *et al.*, 1997; Courtillot *et al.*, 1999). The volcanic units of interest here are related to the northwest arm of the South Atlantic SDR province, here referred to as the Pelotas volcanic province (abbreviated VP in figures). There is an extensive array of geological literature that focuses on the Paraná-Etendeka continental flood basalt province and the South Atlantic SDR provinces. In order to discuss the linkage between these large provinces and the Pelotas volcanic province, a regional overview of the magmatic episodes geochronology is discussed below.

The Paraná and Etendeka continental flood basalt provinces

The large igneous province of Paraná, also known as the Serra Geral Formation in Brazil (White, 1908), consists of lava flows, dykes, and sills. The Paraná continental flood basalt province crops out from southeast Brazil to northern Argentina, eastern Paraguay, and northwest of Uruguay in South America, and correlates with the magmatic province of Etendeka in Namibia (Fig. 1; Erlank *et al.*, 1984; Bellieni *et al.*, 1984). Regional estimates suggest depositional areas in the order of 1,2000,00 km^2, and 1.7 km of thickness have been drilled in the deepest parts of the Paraná basin (Bellieni *et al.*, 1986a, b; Zalán *et al.*, 1987; Peate, 1997; Nardy *et al.*, 2002; Frank *et al.*, 2009). Compositionally, the Paraná continental flood basalt province consists of basic rocks (97%) and minor acid rocks, named (*sensu lato*) as "basalts" and "rhyolites" respectively (Hawkesworth *et al.*, 2000), although petrologically, the province comprises a broader range of compositions.

There is lack of consensus among researchers about the age, duration, magma type distribution, magmatic sources, and magmatic differentiation processes that generated the voluminous magmatism. There is a large number of radiometric ages published in the geological literature (*e.g.*, Almeida *et al.*, 2013) and in order to display the variability exhibited, a compilation of several $^{39}K/^{40}Ar$, $^{40}Ar/^{39}Ar$, $^{87}Rb/^{86}Sr$, $^{238}U/^{206}Pb$ ages have been included in the probability density plot of Figure 3. The large age dispersion explains the different opinions in reference to the temporal-geographical evolution of this province and reflects the analytical difficulties of dating basalts, resulting from using different radiometric techniques and laboratories (Gibson *et al.*, 2006).

In a radiometric ages reinterpretation, Gibson *et al.*, (*op cit*), indicated that the initiation and finalization of the Paraná magmatic cycle, as a whole, could be marked by the alkaline complexes of Paraguay, followed by the main tholeiitic lava flows and the dyke swarms. The ages for the alkaline complexes range from 146.7 to 124.6 Ma; the main tholeiitic lava flows between 139 to 127 Ma (with a magmatic pick activity at 134/132 Ma); and the dyke swarms at 134 to 127 Ma (Gibson *et al.*, 2006; Renne *et al.*, 1996a; Rocha Campos *et al.*, 1988; Turner *et al.*, 1994; Ulbrich and Gomes, 1981; Peate, 1997).

Thiede and Vasconcelos, 2010, summarized the disputes about the age of the main tholeiitic lava flows of the Paraná continental flood basalt province generated by conflicting $^{40}Ar/^{39}Ar$ geochronology data sets (Renne *et al.*, 1992, 1996a, 1996b, 1997; Turner *et al.*, 1994; Stewart *et al.*, 1996). To resolve this disagreement, Thiede and Vasconcelos (*op cit*), applied the laser incremental methods and re-dated three of the oldest and youngest samples of Turner *et al.*, (1994) and Stewart *et al.*, (1996). Their analyses resulted in statistically indistinguishable new ages that confirmed the previous 134.7 ± 1 Ma result, supporting a short time-span hypothesis for the Paraná continental flood basalt province volcanism (Thiede and Vasconcelos, 2010).

The volcano-stratigraphy of the Paraná CFB has been approached mainly by geochemical analysis of minor, trace and isotopes elements. The Paraná magma types distinguished by Peate *et al.*, (1992) are defined solely on compositional characteristics and are not stratigraphically defined units. Peate *et al.* (*op cit*) identified several different magmatic types grouped in high and low TiO_2 suites, but there is a strong agreement among the researchers that the Paraná magma types cannot be considered chronostratigraphic units (Turner *et al.*, 1994, 1999; Garland *et al.*, 1995; Stewart *et al.*, 1996).

The large spread of magmatic compositions suggests variations in mantle sources, as well as differentiation mechanisms such as fractional crystallization and crustal contamination. Contrasting hypotheses have been proposed to explain the source of the large volcanic volumes, such as: (1) a lithospheric continental mantle, (2) a fertile asthenospheric mantle, (3) variable melting of a single mantle source, and (4) heterogeneous mantle sources in conjunction with magmatic differentiation mechanisms (Fodor, 1987). There is a general agreement that the origin of the Paraná continental flood basalt province is related to the passage of the Tristão da Cunha mantle plume through the South American plate during the Early Cretaceous. But in most of the petrological-based published contributions, there is a lack of a direct geochemical correlation between the Paraná rocks and the actual Tristão da Cunha and Gough islands rocks, along with the N-MORB basalts, according to Peate, 1997. The role of the Tristão mantle plume appears to have been largely passive, by conductive heating facilitating mobilization of old lithospheric material (Peate, 1997).

There are also questions about the amount of partial fusion and the rate of extension needed in the process of generation of this volcanism during the rifting of the western Gondwana (Ernesto *et al.*, 1999; Ewart *et al.*, 1998, 2004; Kirstein *et al.*, 2001; Hawkesworth *et al.*, 2000). Alternative models for the origin of Paraná continental flood basalts province, as well as for the addition of heat to the crust by lithospheric stretching, can be found in Mohriak *et al.*, 2002.

The Etendeka igneous province forms the easternmost extents of the much larger Paraná-Etendeka large igneous province that originally spanned the incipient continental margins of southern Brazil and Southwest Africa. Magmatic rocks crop out mainly in the Namib desert of northwest Namibia (Fig. 1), but remnants of the Etendeka province are scattered north and south in Nigeria, Angola, and in the Orange basin (Jerram *et al.*, 1999; Marzoli *et al.*, 1999; Reid *et al.*, 1994; Gladczenko *et al.*, 1998). This province erupted in the Early Cretaceous interval of about 122 to 139 Ma, a more narrow time span when compared with the Paraná large igneous province (Fig. 3). The areal extension is in the order of about 80,000 km^2 and has a maximum preserved thickness of about 900 m (Erlank *et al.*, 1984; Milner *et al.*, 1995). The good exposures in three-dimensional outcrops have allowed detailing the volcanic stratigraphy of the magmatic rocks mainly in the Huab Basin (Milner *et al.*, 1995; Jerram *et al.*, 1999). The Etendeka lavas are divided stratigraphically into two volcanic sequences separated by a disconformity (Jerram *et al.*, 1999). Similarly to the Paraná province, the Etendeka province igneous rocks vary in composition from basic tholeiitic basalts to alkaline rocks and dyke swarms; however, the latter are less expressively developed than in the Paraná's dyke swarm province.

The oldest and youngest radiometric ages in Etendeka are associated with alkaline intrusive rocks (Allsop and Hargraves, 1985; Issa *et al.*, 1991; Milner *et al.*, 1995), the same behavior has been reported by Gibson *et al.* (2006) for the Paraná continental flood basalts. The magmatic origin of the Etendeka lava flows province is also in debate. Most basalts of the Etendeka province do not show Tristão da Cunha hot spot signatures, except for the Damaraland igneous complexes. Plume signatures have been found in gabbros of the Okenyenya complex, gabbros and syenites from the Messum complex, and in the Brandberg anorogenic granite intrusion, which is the highest mountain in Namibia (Milner *et al.*, 1995; Trumbull *et al.* 2007; Schmitt *et al.*, 2000; Fig. 1). In the Paraná-Etendeka province, the debate on the absolute dating of the igneous rocks and the magma origin is still ongoing in the geological literature.

The South American SDRs province

The South Atlantic SDRs province extends along the southern South Atlantic Ocean in both the South American and the West African continental margins (Gladczenko *et al.*, 1997). The South American SDRs branch prolong from the Golfo San Jorge basin, south Argentina, to the southern part of Santos basin, Brazil (Fig. 1), covers an estimated area in the order of 1,186,000 km^2, and has an extruded volume of 2,400,000 km^3 (Gladczenko *et al.*, 1997; Hinz *et al.*, 1999; Eldholm *et al.*, 2000; Schumann, 2002; Franke *et al.*, 2002, 2007). The West African branch extends along the coast of South Africa and Namibia. A volume of approximately 420,000 km^3 is estimated for this segment of the South Atlantic (Gladczenko *et al.*, 1998), indicating an asymmetric distribution both in prerift magmatism (Serra Geral Formation in the Paraná basin,