Tectonic boundaries, crustal weakness zones and plume-subcontinental lithospheric mantle interactions in the Serra do Mar dyke swarm, SE Brazil

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Abstract Tholeiitic basalts of Early Cretaceous age (ca. 132 Ma) integrate the Serra do Mar Dyke Swarm in Southeastern Brazil. The dolerites are included in a transitional tholeiitic series that can be divided in a low-TiO₂ and high-TiO₂ suites on a geochemical basis. Parental compositions have La/Yb_N and La/Nb_N > 1 pointing to a predominantly contribution from the subcontinental lithospheric mantle in the generation of the two suites. However, the occurrence of a high-TiO₂ dolerite in the swarm with La/Nb_N=0.3 and La/Yb_N=9.9 ratios can indicate a contribution of a fertile sublithospheric mantle in the generation of the Serra do Mar Dyke Swarm likely to be represented by the Tristan da Cunha plume. This paper proposes that the Tristan da Cunha plume may have melted locally in places where the Gondwanaland lithosphere had undergone greater thinning due to the reactivation of crustal weakness zones nearby major terrane boundaries amalgamated in Proterozoic times resulting in the generation of restricted volumes of plume-derived tholeiitic basalts.

Keywords: Tholeiitic basalts, subcontinental lithospheric mantle, Tristan da Cunha plume and dykes.

Resumo Limites tectônicos, zonas de fraqueza crustal e interações entre pluma e manto litosférico subcontinental no Enxame de Diques da Serra do Mar, SE do Brasil. Basaltos toleíticos do Cretáceo Inferior (ca. 132 Ma) integram o Enxame de Diques da Serra do Mar no Sudeste do Brasil. Estes basaltos incluem-se numa série transicional de afinidade toleítica com duas suítes: baixo-TiO₂ e alto-TiO₂. Líquidos parentais da suíte de baixo-TiO₂ e alto-TiO₂ apresentam razões La/Yb_(N) e La/Nb_(N) > 1. Estes dados sugerem pelo menos uma contribuição do manto litosférico subcontinental na geração dos basaltos de ambas as suítes. A ocorrência de um dique de basalto no enxame com La/Nb_N=0.3 and La/Yb_N=9.9 pode sugerir a contribuição de um componente mantélico sublitosférico fértil na geração do Enxame de Diques da Serra do Mar, possivelmente representado pela pluma de Tristão da Cunha. Este trabalho propõe um modelo geodinâmico em que a pluma pode ter fundido em locais onde a litosfera do Gondwana foi submetida a maior afinamento devido à reativação de zonas de fraqueza crustais, e consequente transferência de *stress* ao manto subjacente, próximo aos principais limites tectônicos associados à amalgamação daquele supercontinente no Neoproterozóico, resultando na geração de pequenos volumes de basaltos toleíticos com assinatura sublitosférica fértil.

Palavras-Chave: Basaltos toleíticos, manto litosférico subcontinental, pluma de Tristão da Cunha e diques.

INTRODUCTION The geochemical provinciality is one of the most relevant aspects concerning the continental basalt provinces. Such provinciality has been attributed by many authors to either distinctive partial melting degrees of a single mantle source or derivation from different mantle sources (e.g., Fodor *et al.*, 1985; Gibson *et al.*, 1995; Marques *et al.*, 1999, 2003).

Dykes of Early Cretaceous age (148-132 Ma; whole-rock and plagioclase Ar-Ar and K-Ar data; Turner *et al.*, 1994; Guedes *et al.*, 2005) intrude gneisses and granitoids of the Upper Proterozoic-Silurian, Ribeira Orogen (Heilbron *et al.*, 2000; Schmitt *et al.*, 2004) comprising the so-called Serra do Mar Dyke Swarm

(Valente *et al.*, 1998a) along Southeastern Brazil.

In this paper we present simple geodynamic scenarios for the Gondwanaland breakup based on geochemical data (Valente, 1997; Corval, 2005) obtained for the high-TiO₂ tholeiitic suites within the central portion of the Serra do Mar Dyke Swarm.

GEOLOGICAL AND GEODYNAMIC SETTINGS

The main events related to the South American Platform reactivation (Almeida *et al.*, 1976) include widespread tholeiitic basalt magmatism and the formation of rift basins along the Brazilian continental margin (Chang *et al.*, 1992; Milani and Thomaz Filho,

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2000; Misuzaki and Thomaz Filho, 2004). These events are related to the rifting of the West Gondwanaland which started in Early Cretaceous times (*ca.* 137 Ma; Ar-Ar, whole-rock and plagioclase, Turner *et al.*, 1994) or even earlier (*ca.* 193 Ma; K-Ar, whole-rock, Guedes *et al.*, 2005). Such magmatism is mostly represented by extrusion of basaltic flows in both Palaeozoic (Paraná; e.g., Piccirillo and Melfi, 1988; Peate, 1997) and Mesozoic basins (Pelotas, Santos, Campos and Espírito Santo; e.g., Fodor *et al.*, 1983/84; Fodor and Vetter, 1984; Misuzaki *et al.*, 1992; Caineli and Mohriak, 1999; Thomaz Filho *et al.*, 2000; Mohriak *et al.*, 2002). Coeval dyke swarms, namely the Serra do Mar Dyke Swarm (e.g. Comin-Chiaramonti *et al.*, 1983; Regelous, 1993; Garda, 1995; Valente *et al.*, 1998a,b; 1999a,b; Guedes *et al.*, 1999; Lobo *et al.*, 1999), the Ponta Grossa (and East Paraguay) Dyke Swarm (e.g., Piccirillo *et al.*, 1990) and the Florianópolis Dyke Swarm (Raposo *et al.*, 1998) occur associated with those basaltic flows (Fig. 1).

In general, the Mesozoic rift basins and the tholeiitic magmatism have been taken as resulting from the rotation of the south portion of the South America plate with the development of internal deformation which is indicated by the extension in the NE-SW direction observed in the Ponta Grossa and the East of Paraguay dyke swarms (Turner *et al.*, 1994). Regardless the cause-effect relationships between plume impact and rifting, the basaltic magmatism seems to be related to lithospheric extension (Chang *et al.*, 1992; Cainelli and Mohriak, 1999) and the presence of a regional thermal anomaly usually associated with the Tristan da Cunha plume (Gibson *et al.*, 1995; Valente, 1997; Mohriak *et al.*, 2002).

THE SERRA DO MAR DYKE SWARM The Serra do Mar Dyke Swarm was emplaced in the central segment of the Upper Proterozoic/Silurian, Brasiliano/Pan-African-related Ribeira orogen in SE Brazil (Fig. 2). The dyke swarm comprises an Early Cretaceous tholeiitic basalt series with hundreds of regular, long, tens of metres-thick, vertical, predominantly ENE-trending dolerites with remarkably uniform textures and structures (Valente, 1997), although NNW-trending dolerites occur locally in the northwest portion of the dyke swarm (Guedes *et al.*, 2005).

The Serra do Mar dykes are relatively evolved (MgO ~4-11 wt.%; Mg# ~38-71), transitional, mostly quartz- and hypersthene-normative basalts that can be grouped in a predominantly high-TiO₂ suite and a subordinately low-TiO₂ suite unrelated by any evolutionary process (Valente, 1997; Tetzner *et al.*, 2001; Corval, 2005). The occurrence of high- and low-TiO₂ suites imprints a geochemical provinciality in the dyke swarm similar to that observed in the Paraná-Etendeka province (e.g., Piccirillo and Melfi, 1988; Peate, 1997).

Two main low-TiO₂ suites have been discriminated in the Serra do Mar Dyke Swarm on a geochemical basis (Monteiro and Valente, 2003),

namely the Búzios (e.g. La/Yb_(N) > 5) and the Serrana (e.g. La/Yb_(N) < 5) suites. Proposed petrogenetic models for the Búzios basalts pointed out that they evolved by AFC (Assimilation and Fractional Crystallisation) without changing of the fractionating assemblage whilst the Serrana basalts seem to have evolved solely by fractional crystallisation with changing of the fractionating assemblage (Monteiro and Valente, 2003). Both low-TiO₂ suites have La/Yb_(N) and La/Nb_(N) ratios higher than unity indicating at least a contribution from the subcontinental lithospheric mantle in the generation of these basalts (Corval, 2005).

Three high-TiO₂ suites have been discriminated in the Serra do Mar Dyke Swarm on the basis of their distinctive La/Yb ratios as well as partial melting modelling, although one of them largely predominates in the swarm (Corval, 2005). This predominately high-TiO₂ suite in the Serra do Mar Dyke Swarm closely resembles the Urubici basalts of the Paraná-Etendeka province (Peate *et al.*, 1992) and evolved by AFC without changing of the fractionating assemblage. Parental compositions in this suite have La/Yb (14.2) and La/Nb (1.8) ratios that indicate at least a contribution from enriched mantle sources (Corval, 2005). Table 1 presents average Ti/Y, La/Yb and La/Nb ratios of the main low and high-TiO₂ suites of the Serra do Mar Dyke Swarm.

PETROGENETIC MODELS FOR THE HIGH-TiO₂ BASALTS: EVIDENCE FOR THE INVOLVEMENT OF LITHOSPHERIC AND SUBLITHOSPHERIC, PLUME-LIKE MANTLE COMPONENTS Lithogeochemical data obtained by the authors of this paper in previous works (Valente, 1997; Corval, 2005; Dutra, 2006) have been used to constrain preliminary petrogenetic and geodynamic models (e.g. Valente *et al.*, 1999a). These data show that the parental composition (sample RJ-19) of the predominantly high-TiO₂ basaltic suite in the Serra do Mar Dyke Swarm can be associated with an enriched source (e.g. Valente *et al.*, 1998a). Such source is likely to be represented by the subcontinental lithospheric mantle taken as a major enriched reservoir (e.g., Hawkesworth *et al.*, 1992). This is in general agreement with models showing the non-involvement of a plume-like component and an exclusive role of the subcontinental lithospheric mantle in the genesis of continental basalts elsewhere (e.g. Paraná-Etendeka) as pointed out by some authors in recent papers (e.g., Marques and Ernesto, 2004).

We used selected isotope data obtained for the predominantly high-TiO₂ basalts of the Serra do Mar Dyke Swarm (Valente, 1997) with discernable lithospheric signatures (e.g. La/Nb > 1) to constrain Sr-Nd binary mixing models to test for the possible involvement of plume-like and lithospheric components in their petrogenesis (Fig. 3). Selected end-members used in the modelling were average compositions for the Tristan da Cunha ankaramitic basanites and basanites (LeRoex *et al.*, 1990) as well as an average lamproite composition (Rock, 1991) likely to represent the plume-like and the subcontinental lithospheric mantle

Figure 1 - Sketch map showing the main lithological units of the Paraná Continental Flood Basalt Province, the Paraná basin-related sedimentary sequence as well as the major dyke swarms in southeastern Brazil (modified from Marques & Ernesto, 2004). The dashed line rectangle represents approximately the area shown in Figure 2. Inset: Location (square) of the area of the sketch map in South America. Inset: Location (square) of the area of the sketch map in South America. Modified from Marques & Ernesto, 2004.

components, respectively. The results indicate that the Sr and Nd isotope compositions of sample RJ-19 taken to represent the parental liquid of this high-TiO₂ suite plot on the mixing curve between plume-like and lithospheric components. The trend towards higher ⁸⁷Sr/⁸⁶Sr₍₁₃₂₎ values are likely to result from crustal contamination processes (Valente, 1997).

As aforementioned, the high-TiO₂ basalts of the Serra do Mar Dyke Swarm display La/Nb > 1 ratios typically associated with lithospheric sources. As such, these samples display a Nb negative anomaly when plotted in chondrite-normalized multielement diagrams (Fig. 4). For instance, sample RJ-19 represents the parental liquid of the predominantly high-TiO₂ suite within the swarm (Valente, 1997) whereas sample DB-I-34 represents an evolved composition of the same suite (Corval, 2005) and both display a Nb negative anomaly. As a noticeable exception, sample FR-2001B displays a pronounced Nb positive anomaly and a La/Yb_N ratio greater than unity (Fig. 4) typical of plume-like components (Corval, 2005). It should be noted that samples DB-I-34 and FR-2001B have

similar MgO contents (Fig. 4) and as such differences in the Nb anomalies shown in the diagram cannot be attributed to evolutionary processes. In addition, such differences cannot be attributed to either within-dyke differentiation processes (e.g. simple contamination) or to the presence of unusual fractionating phases on the basis of field or petrographic evidence (Tavares *et al.*, 2003). Finally, analytical errors are unlikely since sample FR-2001B also bears high Ta concentration as expected considering the Nb-Ta geochemical affinities. In conclusion, the Nb positive anomaly shown in the diagram of figure 4 can be considered as an evidence of the involvement of a fertile, plume-like component in the petrogenesis of the high-TiO₂ basalts of the Serra do Mar Dyke Swarm.

Many authors have pointed to Tristan da Cunha as the plume involved with the geodynamic processes during the Gondwanaland breakup although the role of the plume in the rifting remains under debate (e.g. Gibson *et al.*, 1995; Valente *et al.*, 1999a; Mohriak *et al.*, 2002; Marques and Ernesto, 2004).

The diagram in figure 4 presents the pattern of

Figure 2 - Geological map of the Serra do Mar Dyke Swarm. The Além Paraíba Shear Zone (APSZ), the Central Tectonic Boundary (CTB) and location of samples FR2001b, DB-I-34 and RJ-19 are indicated. Regional structures of the Proterozoic basement are not shown as a matter of simplification. Modified from Valente et al., 2005a.

a Tristan da Cunha basanite (TDC91; Le Roex *et al.*, 1990) likely to represent a plume-related liquid. The MgO contents (MgO=4.77 wt.%) of sample TDC91 is similar to that of the high-TiO₂ basalt FR-2001B (4.75 wt.%). Samples TDC91 and FR-2001B show similar patterns in the multielemental diagram with high LILE/HFSE ratios (TDC91: Ba/Y_(N)=14.2; FR-2001B: Ba/Y_(N)=7.9). The greater enrichment factors of sample TDC91 are attributed to its alkaline composition likely to be related to lesser partial melting degrees of mantle sources when compared to the tholeiitic composition of sample FR-2001B. Both samples TDC91 and FR-2001B display the Nb positive anomaly typically associated with fertile mantle sources. In conclusion, the aforementioned features shown in the chondrite-normalized multielemental diagram (Fig. 4) in addition to the results of the Sr-Nd binary mixing modelling (Fig. 3) are indicative of a contribution of a Tristan da Cunha

component in the petrogenesis of the high-TiO₂ basalts of the Serra do Mar Dyke Swarm.

GEODYNAMIC IMPLICATIONS OF THE PETROGENETIC MODEL

The geochemical data presented in the previous sections showed that the petrogenesis of the high-TiO₂ basalts in the Serra do Mar Dyke Swarm is likely to have involved both the subcontinental lithospheric mantle and the Tristan da Cunha plume. Such petrogenetic model indicates that lithospheric and plume-like mantle components may have interacted during the Gondwanaland breakup.

Plume-like geochemical signatures (sample FR-2001B; La/Yb_N=9.9 and La/Nb_N=0.3) were found in a dyke intruded in the Proterozoic granulites of a major crustal structure, the so-called Além-Paraíba Shear Zone (APSZ; Campanha *et al.*, 1985) along the northern portion of the Serra do Mar Dyke Swarm (Fig. 2).

Table 1 - Average Ti/Y, La/Yb and La/Nb ratios of the main low- and high-TiO₂ suites of the Serra do Mar Dyke Swarm. Sources: Valente (1997); Corval (2005); Dutra (2006).

Suite	Ti/Y	La/Yb	La/Nb
Low-TiO ₂ (Serrana)	290	6.3	1.7
Low-TiO ₂ (Costa Azul)	284	4.5	1.3
High-TiO ₂ (Suite 1; Urubici-like)	603	14.2	1.6
High-TiO ₂ (suite 2)	392	8.0	1.5
High-TiO ₂ (suite 3)	883	29.2	2.8

Figure 3 - Sr-Nd binary mixing modelling superimposed on the Sr-Nd isotopic trend of the high-TiO₂ basalts of the Serra do Mar Dyke Swarm with discernible lithospheric signatures. The mixing curve (tick marks) is shown with increments at 10% intervals; parameters being indicated. Tristan da Cunha data: ankaramitic basanites and basanites averages (Le Roex *et al.*, 1990). Average lamproite is from Rock (1991). The Tristan da Cunha lavas were age-corrected (132 Ma) using the published Nd data assuming Sm/Nd=0.2597 (typical OIB, Sun & McDonough, 1989). The high-TiO₂ basalts trend (parental, less contaminated sample RJ-19, filled circle; contaminated dolerites, open circle) is shaded.

In this context, the following geodynamic scenarios may be envisaged for the Serra do Mar Dyke Swarm during the Gondwanaland breakup (Fig. 5).

One scenario implies the whole area of the Serra do Mar Dyke Swarm being submitted to the same amount of lithospheric thinning (ie., same β factor) in

a time a cold continental lithosphere with original differential thickness was placed over a thermal anomaly (plume) (Fig. 5a). The complex accretionary process of Gondwana in Proterozoic times (Heilbron *et al.*, 2004; Valente *et al.*, 2005b) may potentially have led to the amalgamation of terranes with variable lithospheric thickness. As much as the anomalously thinned continental lithosphere allowed sublithospheric-related basalts (i.e., La/Nb<1) would spread over the entire dyke swarm (Fig. 5b). In this case, the occurrence of basalts showing the contribution of sublithospheric components would not have to be coincident with major crustal weakness zones such as the APSZ. Another scenario implies the presence of a cold continental lithosphere over a thermal anomaly with an overall original uniform thickness (Fig. 5c) but submitted to distinctive β factors that would be greater when coincident with major crustal structures such as the APSZ (Fig. 5d). Such crustal structure could have acted as weakness zones reactivated as a result of the Gondwanaland breakup and might have released stress onto the adjoining subcontinental lithospheric mantle leading to greater lithospheric thinning on a local scale. Structural studies on the rift basins along the Eastern Rift System of Brazil have stressed the role of reactivation processes during basin formation related to the Gondwanaland breakup (e.g., Chang *et al.*, 1992; Mohriak *et al.*, 2002). The widespread occurrence of subcontinental lithospheric mantle-derived melts within the Serra do Mar Dyke Swarm indicates that such crustal reactivation and its possible related stress release onto the subcontinental lithospheric mantle was not great enough to result in amounts of lithospheric thinning capable of promoting adiabatic decompression and melting of the subjacent mantle plume on a large scale. It should be noted that the APSZ is located about 20Km north to the Central Tectonic Boundary, a main suture bounding the so-called Eastern and Western terranes (Fig. 6) within the Ribeira Orogen (Heilbron *et al.*, 2004).

Figure 4 - Chondrite-normalized multielemental diagram (Thompson, 1982) for selected samples of the high-TiO₂ suite of the Serra do Mar Dyke Swarm. Sample TDC91 (Tristan da Cunha basanite; Le Roex *et al.*, 1990) is also shown in the diagram as an example for a plume-related liquid. The Nb anomalies are shown in light-grey areas. MgO contents in wt.%.

Figure 5 - Envisaged scenarios for the geodynamics of the Gondwanaland breakup and its related magmatism within the Serra do Mar Dyke Swarm. (a) and (b) respectively represent the unstretched and stretched continental lithosphere of variable thickness and impinging plume in the Serra do Mar Dyke Swarm latitudes under uniform lithospheric thinning (ie., β factors); (c) and (d) represent the unstretched and stretched continental lithosphere of same thickness and impinging plume in the Serra do Mar Dyke Swarm latitudes under different β factors. Expected partial melting zones and La/Nb ratios are indicated. APSZ is the Além Paraíba Shear Zone. Not in scale.

Figure 6 - Diagram representing the preferred geodynamic scenario for plume-lithosphere interactions during Gondwanaland breakup and the Serra do Mar related magmatism. Tectonic terranes, boundaries and domains after Heilbron et al. (2004). Not in scale. **CTB**: Central Tectonic Boundary limiting the Oriental and Occidental Terranes. **APSZ**: Além Paraíba Shear Zone.

In this case, on the basis of those evidences we prefer a model that places crustal reactivation zones nearby major tectonic terrane boundaries, the latter being potential *loci* of originally anomalously thinned lithosphere so that an ascending plume would be able to melt by adiabatic decompression. In conclusion, the Tristan da Cunha plume may have melted locally in places where the Gondwanaland lithosphere had undergone greater thinning due to the reactivation of crustal weakness zones nearby major terrane boundaries amalgamated in Proterozoic times resulting in the generation of restricted volumes of plume-derived tholeiitic basalts. In contrast, on a regional scale the thick Gondwanaland lithosphere may have largely prevented plume melting even in places where crustal reactivation occurred and in these cases heat may have been conducted to and largely melted the heterogeneous, overlying subcontinental lithospheric mantle.

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