MANTLE SOURCES OF THE PARANÁ MAGMATIC PROVINCE

MARQUES, L.S. Instituto Astronômico e Geofísico - University of São Paulo, São Paulo, Brazil.

Summary

The Paraná Magmatic Province (PMP) is represented by flood tholeiites (133-132 Ma) and associated dyke swarms of Ponta Grossa (131-129 Ma), Florianópolis (129-119 Ma) and Santos-Rio de Janeiro (132-119 Ma). The PMP basalts are divided into high- (HTi) and low-TiO_2 (LTi) tholeiites. HTi dominate in the northern PMP, whereas LTi are predominant in the southern PMP. Minor HTi and LTi are found in southern and northern PMP, respectively. Most dykes are HTi-type. The geochemical and isotopic signatures of the northern and southern PMP tholeiites do not show evidence of a significant participation of N-MORB and/or modern Tristan da Cunha mantle components in their genesis, suggesting that such tholeiites generated from heterogeneous (lithospheric) mantle. The HTi and LTi basalts from northern Paraná, as well as Early and Late Cretaceous alkaline and carbonatitic magmatism that surrounds the central-northern PMP, were significantly dominated by the EMI mantle component. In contrast, depleted DMM-type and EMII components are required to explain the genesis of the LTi tholeiites from southern PMP.

Introduction

The origin of large igneous provinces is a subject widely investigated in the recent years and is still debated in terms of the asthenospheric and lithospheric mantle source contributions in the basalt genesis. Such voluminous magmatism may have been triggered by the arrival of a starting plume head beneath a continental plate (e. g. Richards *et al*. 1989), or by rifting across an area of anomalously hot mantle (White and MacKenzie 1989). According to these models the basalts have not undergone significant interaction with the lithospheric mantle, which predicted participation is about 2% (Campbell and Griffiths 1990; Arndt and Christensen 1992). Therefore, the basalt compositions would mainly reflect a deep asthenospheric mantle signature. Actually, some igneous provinces exhibit geochemical and isotopic signatures that indicate the incorporation of plume material (e.g. Holm *et al*. 1993; Peng and Mahoney, 1995). In contrast, some continental flood basalts (e.g. Paraná, Karoo and Ferrar) would have evidence that their genesis are related to heterogeneous (lithospheric?) mantle source (Piccirillo and Melfi 1988; Hergt *et al*. 1991; Cox 1992; Hawkesworth *et al*. 1992; Molzahn *et al*. 1996).

For the Paraná Magmatic Province, although very detailed studies have been conducted, there is not a consensus about its tholeiite genesis. The geochemical and isotopic characteristics of low- and high-TiO_2 tholeiites, associated with their spatial distribution in the province, indicate origin in the lithospheric mantle (e.g. Piccrillo and Melfi 1988; Peate and Hawkesworth 1996; Comin-Chiaramonti *et al*. 1997). On the other hand, according to some interpretations (Gibson *et al*. 1995; Milner and Le Roex 1996; Gibson *et al*. 1999) the flood basalt compositions substantially reflect an asthenospheric mantle plume (Tristan da Cunha) source.

Geological Setting and Volcanism Age

The opening of the South Atlantic Ocean was preceded by voluminous magmatism in Southeastern Brazil, giving rise to the Paraná Magmatic Province, which is one of the largest igneous province of the world.

The volcanic rocks are of Early Cretaceous age (Renne *et al*. 1992; Turner *et al*. 1994) and were erupted into a Paleozoic intracratonic sedimentary basin (Paraná Basin). The total area flooded by the tholeiitic magmatism largely exceeded that of the present occurrence of the volcanics (1,200,000 km^2). Numerous basalt dykes, related to the tholeiitic magmatism, intruded Paleozoic sediments and the Proterozoic - Archean crystalline basement.

The Paraná Magmatic Province is represented by continental flood basalts and dyke swarms that are concentrated towards the eastern continental margin. The Ponta Grossa is the most important swarm of the province and it is characterized by hundreds of basalt dykes (mainly NW-SE trending). The Florianópolis dyke swarm, that occurs on the Santa Catarina Island, as well as those exposed from Santos to Rio de Janeiro are coast-parallel (c.a. NE-SW).

A considerable number of $^{40}Ar/^{39}Ar$ dating allowed to well constrain the age of PMP rocks, indicating that the main magmatic activity occurred in few million years. These data show that flood volcanism (mainly 133-132 Ma; Renne *et al*. 1992; Turner *et al*. 1994) was followed by the emplacement of the dyke swarms. The Ponta Grossa dykes intruded in a narrow interval (131-129 Ma; Renne *et al*. 1996), although some dykes as young as 120 Ma can be found towards the continental margin. The radiometric ages of Florianópolis dykes vary between 129-119 Ma (Raposo *et al*. 1998; Deckart *et al*. 1998), whereas for the Santos - Rio de Janeiro swarm they span from 132 to 119 Ma (Renne *et al*. 1993; Turner *et al*. 1994; Deckart *et al*. 1998).

The Paraná Magmatic Province Tholeiites

The volcanics and intrusives of the Paraná Magmatic Province (PMP) are represented by dominant tholeiitic basalts and minor tholeiitic andesites and rhyodacites-rhyolites. The tholeiites are differentiated (mg-# < 0.56) and are represented by: (1) LTi basalts, low in TiO_2 (< 2 wt%) and incompatible elements (e.g. P, Sr, Ba, Zr, Ta, Y and

LREE) and (2) HTi basalts, high in TiO_2 (> 2 wt%) and incompatible elements. HTi tholeiites dominate the northern Paraná Basin (north of latitude ~26°S), whereas LTi tholeiites prevail in the southern PMP (south of latitude ~26°S). Minor HTi and LTi are found in the southern and northern PMP, respectively.

Detailed geochemical studies revealed important differences between LTi tholeiites from southern and northern Paraná Magmatic Province. HTi tholeiites from southern PMP usually have $TiO_2 > 3$ wt%, and are also distinct from the analogues of northern PMP (Bellieni et al., 1984; Piccirillo and Melfi, 1988). The incompatible trace element distribution patterns normalized to primordial mantle for HTi and LTi tholeiites from northern PMP are very similar. In contrast, the distribution patterns for LTi tholeiites from northern PMP are characterized by a strong U negative anomaly, which is not observed in the LTi from southern PMP with initial $^{87}Sr/^{86}Sr < 0.7060$ (Marques *et al*. 1989). The latter tholeiites are also distinct due to their relatively low La/Ce ratios, specially those with initial Sr isotope ratios lower than 0.7052. Finally, all southern and northern tholeiites have Ta negative anomaly, which may be considered a mantle source feature.

The variation in incompatible trace element abundances and ratios are accompanied by systematic different Sr-Nd-Pb isotopes, indicating the participation of distinct mantle sources in PMP basalt genesis (Mantovani *et al*. 1985; Petrini *et al*. 1987; Piccirillo *et al*. 1989; Peate and Hawkesworth 1996; Marques *et al*. 1999; Peate *et al*. 1999).

The tholeiites from the dyke swarms present close geochemical and isotopic characteristics of the flood plateau Paraná basalts, in spite that most tholeiitic dyke swarms of Ponta Grossa (PG), Florianópolis (FL) and Santos-Rio de Janeiro (SRJ) are of HTi-type (Comin-Chiaramonti et al. 1983; Piccirillo et al. 1990; Hawkesworth *et al*. 1992, Marques et al., 1993; unpublished data).

Mantle Source Characteristics

If PMP tholeiites were generated by the arrival of the Tristan da Cunha plume head beneath the Western Gondwanaland, the mantle components potentially involved in the basalt genesis could be represented by: (1) depleted upper mantle (N-MORB type); (2) plume material (OIB type); (3) lithospheric mantle.

The remarkable differences in incompatible trace element ratios among Paraná tholeiites, N-MORB and Tristan da Cunha least evolved alkaline volcanics (e.g. La/Th, Nb/La, Zr/Ta, Ce/Pb) are indicative that these mantle components did not play a substantial role in the Paraná basalt generation (Marques *et al*. 1999). This is strenghtened by radiogenic isotopic ratios, specially Pb isotopes that do not give evidence of a significant involvement of a N-MORB type source. The sharp distinction between Pb signatures of Tristan da Cunha volcanics and Paraná rocks does also apparent a minor role, if any, of Tristan da Cunha OIB plume component (Peate and Hawkesworth 1996; Marques *et al*. 1999; Peate *et al*. 1999) in the PMP basalt genesis.

In addition, $^{207}Pb/^{204}Pb$ x $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ x $^{206}Pb/^{204}Pb$ arrays of Paraná rocks are also different from those of Walvis Ridge basalts, which are commonly believed as the trace left by the continuous magmatic activity of the Tristan da Cunha plume. However, the most unradiogenic compositions of Walvis Ridge basalts (DSDP 525A; formerly EMI mantle component) are similar to the HTi from southern ($^{206}Pb/^{204}Pb$: 17.5 - 17.8). The EMI signature also applies to Sr-Nd isotopes, suggesting the involvement of a common depleted end member source for both Walvis Ridge basalts and HTi from southern PMP. The mantle heterogeneity involved in the Paraná magmatism is not simply confined to tholeiites, but also to the associated alkaline and alkaline-carbonatitic magmatism. Note that the Early and Late Cretaceous alkaline and carbonatitic magmatism, that surround the central-northern PMP, also have Pb isotope ratios very similar to those of the HTi basalts (Marques *et al*. 1999; Peate *et al*. 1999), indicating the participation of the same mantle component in their genesis.

In contrast, the LTi tholeiites from southern PMP exhibit the highest Pb isotopic ratios ($^{206}Pb/^{204}Pb$: 18.3 - 18.4). According to mixing systematics, a highly depleted component similar to DMM and an enriched one of EMII-type are required as end members.

Concluding Remarks

The geochemical and isotopic characteristics of the Paraná Large Igneous Province indicate that the tholeiites were generated by melting of heterogeneous (lithospheric) mantle reservoirs.

As shown modern Tristan da Cunha mantle source signature is not appreciable in the Paraná tholeiites. However, it has been suggested that the present-day plume compositions underwent substantial variations, over the last 130 Ma, due to the interaction of plume material with surrounding lithospheric mantle (Gibson et al. 1995; Ewart et al. 1998). In this case, the LTi and HTi tholeiites from the Paraná Basin would require plume-derived basalts almost completely contaminated by lithospheric components, and appropriate subcontinental mantle plume materials to explain the generation of low- and high-TiO_2, in southern and northern Paraná regions, respectively.

References

Arndt, N.T. and Christensen, U., 1992. The role of lithospheric mantle in continental flood volcanism: thermal and geochemical constraints. J. Geophys. Res., 97 (B7): 10967-10981.

Bellieni, G., Comin-Chiaramonti, P., Marques, L.S., Melfi, A. J., Nardy, A. J. R., Piccirillo, E. M. and Stolfa, D., 1984. High-

and low-TiO_2 flood basalts from the Paraná plateau (Brazil): petrology and geochemical aspects bearing on their mantle origin. Neues Jahrb. Mineral. Abh., 150: 273-306.

Campbell, I.H. and Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth Planet. Sci. Lett., 99: 79-93.

Comin-Chiaramonti, P., Gomes, C.B., Piccirillo, E.M. and Rivalenti, G., 1983. High TiO2 dikes in the coastline of São Paulo and Rio de Janeiro States. Neues Jahrb. Mineral. Abh., 146: 133-150.

Comin-Chiaramonti, P., Cundari, A., Piccirillo, E.M., Gomes, C.B., Castorina, F., Censi, P., De Min, A., Marzoli, A., Speziale, S. and Velázquez, V.F., 1997. Potassic and sodic igneous rocks from Eastern Paraguay: their origin from the lithospheric mantle and genetic relationships with associated Paraná flood tholeiites. J. Petrol., 38(4): 495-528.

Deckart, K., Féraud, G., Marques, L.S. and Bertrand, H., 1998. New time constraints on dyke swarms related to the Paraná-Etendeka magmatic province, and subsequent South Atlantic opening, southeastern Brazil. J. Volcanol. Geoth. Res., 80: 67-83.

Ewart, A., Milner, S.C., Armstrong, R.A. and Duncan, A.R., 1998. Etendeka volcanism of the Goboboseb Mountains and Messum Igneous Complex, Namibia. Part I: geochemical evidence of Early Cretaceous Tristan plume melts and the role of crustal contamination in the Paraná-Etendeka CFB. J. Petrol., 39(2): 191-225.

Gibson, S.A., Thompson, R.N., Dickin, A. P. and Leonardos, O. H., 1995. High-Ti and low-Ti mafic potassic magmas: key to plume-lithosphere interactions and continental flood-basalt genesis. Earth Planet. Sci. Lett., 136: 149-165.

Gibson, S.A, Thompson, R.N., Leonardos, O.H., Dickin, A.P. and Mitchell, J.G., 1999. The limited extent of plume-lithosphere interactions during continental flood-basalt genesis: geochemical evidence from Cretaceous magmatism in southern Brazil. Contrib. Mineral. Petrol., 137: 147-169.

Hawkesworth, C.J., Gallager, K., Kelley, S., Mantovani, M.S. M., Peate, D., Regelous, M. and Rogers, N., 1992. Paraná magmatism and the opening of the South Atlantic. In: Storey, B., Alabaster, A., Pankhurst, R. (Eds.), Magmatism and the Causes of Continental Break-up. Geological Society Special Publication 68: 221-240, London.

Hergt, J., Peate, D. W. and Hawkesworth, C. J., 1991. The petrogenesis of Mesozoic Gondwana low Ti flood basalts. Earth Planet. Sci. Lett., 105: 134-148.

Holm, P.M., Gill, R.C.O., Pedersen, A.K., Larsen, J.G., Hald, N., Nielsen, T.F.D. and Thirwall, M.F., 1993. The Tertiary pricrites of West Greenland: contributions from 'Icelandic' and other sources. Earth Planet. Sci. Lett., 115: 227-244.

Mantovani, M.S.M., Marques, L.S., Sousa, M.A., Atalla, L.T., Civetta, L. and Innocenti, F., 1985. Trace element and strontium isotope constraints on the origin and evolution of Paraná continental flood basalts of Santa Catarina State (southern Brazil). J. Petrol., 26: 187-209.

Marques, L.S., Piccirillo, E.M., Melfi, A.J., Comin-Chiaramonti, P. and Bellieni, G., 1989. Distribuição de terras raras e outros elementos traços em basaltos da Bacia do Paraná (Brasil Meridional). Geochim. Brasil., 3: 33-50.

Marques, L.S., Bellieni, G., de Min, A. and Piccirillo, E.M., 1993. O enxame de diques da Ilha de Santa Catarina: resultados geoquímicos preliminares. IV Cong. Bras. Geoquim., Resumos: 3-4.

Marques, L.S., Dupré, B. and Piccirillo, E.M., 1999. Mantle source compositions of the Paraná Magmatic Province: evidence from trace element and Sr-Nd-Pb isotope geochemistry. J. Geodynamics, 28: 439-459.

Milner, S.C. and Le Roex, A.P., 1996. Isotope characteristics of the Okenyenya igneous complex, northern Namibia: constraints on the composition of the early Tristan Plume and the origin of the EM1 mantle component. Earth Planet. Sci. Lett., 141: 277-291.

Molzahn, M., Reisberg, L. and Wörner, G., 1996. Os, Sr, Nd, Pb, O isotope and trace element data from the Ferrar flood basalts, Antarctica: evidence for an enriched subcontinental lithosphere source. Earth Planet. Sci. Lett., 144: 529-546.

Peate, D. and Hawkesworth, C.J., 1996. Lithospheric to asthenospheric transition in low-Ti flood basalts from Southern Paraná, Brazil. Chem. Geol., 127: 1-24.

Peate, D.W., Hawkesworth, C.J., Mantovani, M.S.M., Rogers, N.W. and Turner, S.P., 1999. Petrogenesis and stratigraphy of the high-Ti/Y Urubici magma type in the Paraná flood basalt province and implications for the nature of 'Dupal'-type mantle in the South Atlantic Region. J. Petrol., 40(3): 451-473.

Peng, Z.X. and Mahoney, J.J., 1995. Drillhole lavas from the north-western Deccan Traps, and the evolution of Réunion hotspot mantle. Earth. Planet. Sci. Lett., 134, 169-185.

Petrini, R., Civetta, L., Piccirillo, E.M., Bellieni, G., Comin-Chiaramonti, P., Marques, L.S. and Melfi, A.J., 1987. Mantle heterogeneity and crustal contamination in the genesis of low-Ti continental flood basalts from the Paraná plateau (Brazil): Sr-Nd isotope and geochemical evidence. J. Petrol., 28: 701-726.

Piccirillo, E.M. and Melfi, A.J., 1988. The Mesozoic Flood Volcanism of the Paraná Basin: Petrogenetic and Geophysical Aspects. Instituto Astronômico e Geofísico - University of São Paulo, 600p., São Paulo.

Piccirillo, E.M., Civetta, L., Petrini, R., Longinelli, A., Bellieni, G., Comin-Chiaramonti, P., Marques, L.S. and Melfi, A.J., 1989. Regional variations within the Paraná flood basalts (southern Brazil): evidence for subcontinental mantle heterogeneity and crustal contamination. Chem. Geol., 75: 103-122.

Piccirillo, E.M., Bellieni, G., Cavazzini, G., Comin-Chiaramonti, P., Petrini, R., Melfi, A.J., Pinese, J.P.P., Zantadeschi, P. and De Min, A., 1990. Lower cretaceous tholeiitic dyke swarms from the Ponta Grossa Arch (southeast Brazil): Petrology, Sr-Nd isotopes and genetic

relatioships with the Paraná flood volcanics. Chem. Geol., 89: 19-48.
Raposo, M.I.B., Ernesto, M., Renne, P.R., 1998. Paleomagnetism and $^{40}Ar/^{39}Ar$ dating of the early Cretaceous Florianópolis dike swarm (Santa Catarina Island), Southern Brazil. Phys. Earth Planet. Int., 108: 275-290.
Renne, P.R., Ernesto, M., Pacca, I.G., Coe, R.S., Glen, J.M., Prévot, M. and Perrin, M., 1992. The age of Paraná flood volcanism, rifting of Gondwanaland, and the Jurassic-Cretaceous boundary. Science, 258: 975-979.
Renne, P.R., Mertz, D.F., Ernesto, M., Marques, L.S., Teixeira, W., Ens, H.H. and Richards, M.A., 1993. Geochronologic constrains on magmatic and tectonic evolution of the Paraná Province. EOS, Am. Geophys. Union, 26: 553.
Renne, P.R., Deckart, K., Ernesto, M., Féraud, G. and Piccirillo, E.M., 1996. Age of the Ponta Grossa Dike Swarm (Brazil), and implications to Paraná Flood Volcanism. Earth Planet. Sci. Lett., 144: 199-211.
Richards, M.A., Duncan, R. A. and Courtillot, V. E., 1989. Flood basalts and hot spot tracks: plume heads and tails. Science, 246: 103-107.
Turner, S., Regelous, M., Kelley, S., Hawkesworth, C. and Mantovani, M., 1994. Magmatism and continental break-up in the South Atlantic: high precision ^{40}Ar-^{39}Ar geochronology. Earth Planet. Sci. Lett., 121: 333-348.
White, R. and MacKenzie, D.J., 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. J. Geophys. Res., 94 (B6): 7685-7729.

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