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Neoproterozoic oceans in the Ribeira Belt (southeastern Brazil): The Pirapora do Bom Jesus ophiolitic complex

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Within the São Roque Domain of the Neoproterozoic Ribeira Fold Belt (southeastern Brazil) we have identified an ophiolitic complex (Pirapora ophiolite) displaying a characteristic oceanic lithospheric stratigraphy. From bottom to top, it includes: 1) a lower crustal/upper mantle section (dunitic cumulates with chromite-magnetite layers); 2) a lower crustal section (metagabbro and flasergabbro mafic cumulates with gabbroic pegmatoids); and 3) an upper crustal section (deformed fine-grained, greenschist facies metabasalts with remains of a sheeted dike complex, pillow lavas and cherts). The metabasaltic rocks have geochemical characteristics that are transitional between those of MORB and island arc basalts, similar to basaltic rocks from mature back-arc basins where the influence of subduction components should not be dominant. U-Pb ages of 628 ± 9 Ma are interpreted as the crystallization age of mafic magmas, and altogether the geochronological data suggests that the emplacement of Pirapora ophiolite (~ 620 Ma) took place shortly after oceanic crust generation, probably during oceanic ridge collision with the continental margin.

Introduction

The Neoproterozoic Ribeira Fold Belt (Almeida et al., 1973; Cordani and Brito Neves, 1991) extends along the southeastern Brazil and, together with the Damara Belt in Africa, comprises an orogenic system which borders the São Francisco and Congo Cratons, and an inferred cratonic block that actually occurs under the Paleozoic sedimentary rocks of the Paraná Basin. The Ribeira Belt system was active during the later stages of Brasiliano (Pan-African) Wilson Cycle. It is composed of Archean, Paleoproterozoic and Mesoproterozoic rocks, reworked between 700–470 Ma during the amalgamation of the Gondwana Supercontinent (Figure 1).

The central segment of Ribeira Belt, in São Paulo State, displays a long-term continuous orogenic evolution, from 650 to 480 Ma (Dias Neto, 2001), which was previously considered in terms of two orogenic cycles (Brasiliano: 670–600 and Rio Doce: 590–480 Ma, orogenies; Campos Neto and Figueiredo, 1995). The central part of the Ribeira Belt is composed of three different geological domains (Costeiro, Embu and São Roque), separated by prominent shear zones, and differing from each other on the age of their respective

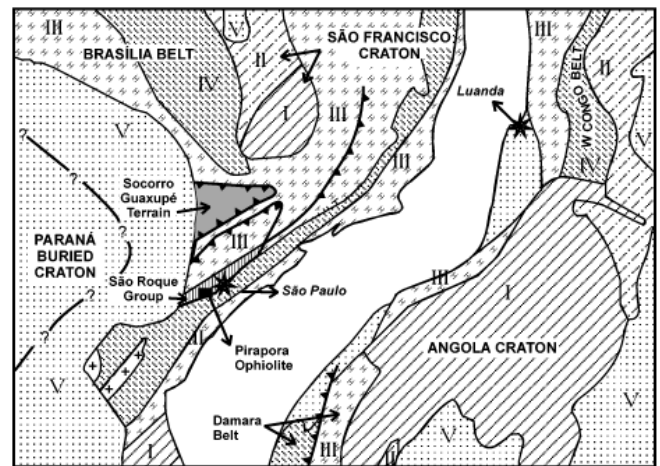


Figure 1 The Pirapora ophiolite in the Brazil-Africa sketch map. I – Cratonic basement; II – Cratonic cover; III – Neoproterozoic fold systems including older fold systems; IV – Neoproterozoic fold belts; V – Phanerozoic cover; ? – Buried cratonic limits. (After Sadowski and Tassinari, 1991, modified).

crustal protholiths, lithological assemblages and geological evolution. The Costeiro and Embu domains consist of Paleoproterozoic and Archean-Paleoproterozoic crust, respectively, both intensely reworked by Brasiliano deformation, high-grade metamorphism and partial melting processes. The São Roque Domain (Serra do Itaberaba and São Roque Groups; Juliani et al., 2000; Hackspacher et al., 2000) is composed of Meso- to Neoproterozoic low/medium grade volcano-sedimentary sequences. The São Roque Group has been interpreted (Figueiredo et al., 1982; Bergmann, 1988; Lazzari, 1987; Tassinari, 1988; Sadowski and Tassinari, 1991; Hackspacher, 2000) as developed in an ensialic back-arc environment.

Neoproterozoic units with ophiolitic affinities (816 Ma; Pedrosa Soares et al., 1998) have been suggested in the northern region of the Ribeira Belt. However, in the central segment of Ribeira Belt the available tectonic models have considered exclusively an ensialic evolution (Tassinari, 1988; Bergmann, 1988; Sadowski and Tassinari, 1991; Trompette 1994; Hackspacher et al. 2000), involving intense Brasiliano extensional reactivation of older (Archean to Paleoproterozoic) continental basement.

Recent research in the central Ribeira Belt meta-volcanics from São Roque Group, Pirapora Formation (SE São Paulo state) has allowed us to identify an ophiolitic complex. The main aim of this paper is to characterize the geological, geochemical/geochronological and tectonic features of the Pirapora ophiolite. These findings have important consequences for Brasiliano geodynamics (particularly in the central segment of the Ribeira Belt) that will be discussed in this paper.

Geological setting

The São Roque Group is a Neoproterozoic metavolcano-sedimentary sequence (Hackspacher, 2000), which overlies the Mesoproterozoic Serra do Itaberaba Group (Juliani et al., 2000), and it is bordered to the north by the Jundiuvira shear zone and to the south by the Taxaquara-Jaguari fault zones. These faults are represented by extensive NE-SW mylonite belts which acted as dextral for Taxaquara fault and oblique-slip for Jundiuvira fault (Sadowski, 1983) (Figure 2).

In the studied area (Pirapora de Bom Jesus county, São Paulo state; see Figure 3) we have established several lithotectonic units separated by major thrust surfaces. The degree of exposure is generally poor, but major thrusts are well delineated by increasingly sheared domains of metric thickness. Those lithotectonic units include, from bottom to top, the following:

Autochthon

Autochthon units in the area comprise the Serra Itaberaba Group (1395 ± 10 Ma; Juliiani et al., 2000) and the São Roque Group (~630 Ma; Hackspacher et al., 2000), whereas the Serra Itaberaba Group underwent polyorogenic (Uruaçuano/Brasiliano; up to amphibolite facies) metamorphism and deformation, the upper São Roque Group displays a simpler tectonothermal evolution. São Roque Group was deposited unconformably on top of the Serra do Itaberaba Group and has been exclusively affected by Brasiliano deformation and low-grademetamorphism.

The autochthon São Roque Group units comprise calc-silicated, phyllites, and psammitic rocks of the Estrada dos Romeiros Formation and clastic to volcanic-clastic rocks of the Boturuna Formation (Bergman, 1988). All these units have been affected by two main phases of Brasiliano deformation. D1 reflects the emplacement of the allocthonous unit, and corresponds to NE verging recumbent folds, with axial plane slaty cleavage contemporaneous with green-schist facies (biotite-grade) metamorphism; D2 is upright folding with NE-SW axes generating the main synform and antiform regional structures, with gentle to moderate axial plunges.

Parautochthon

The São Roque Group parautochthonous unit is separated from the autochthon by a thrust plane, constituting thrust duplexes below

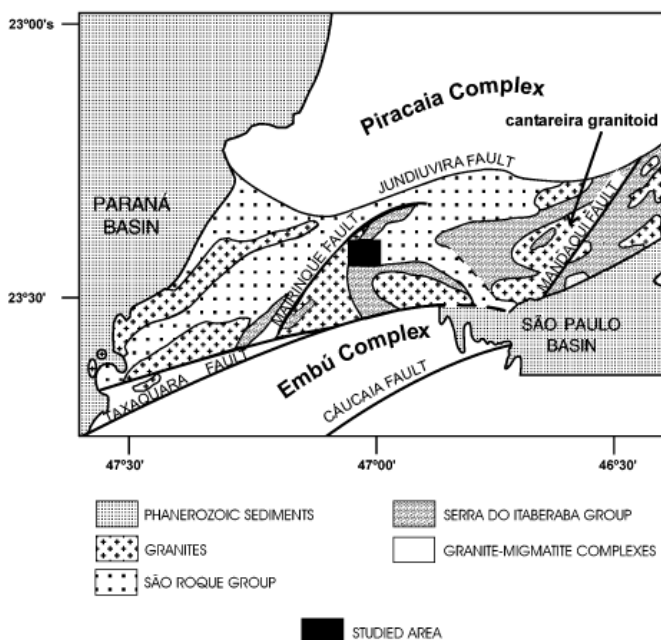


Figure 2 Geological outline of the São Roque Domain, including the studied area.

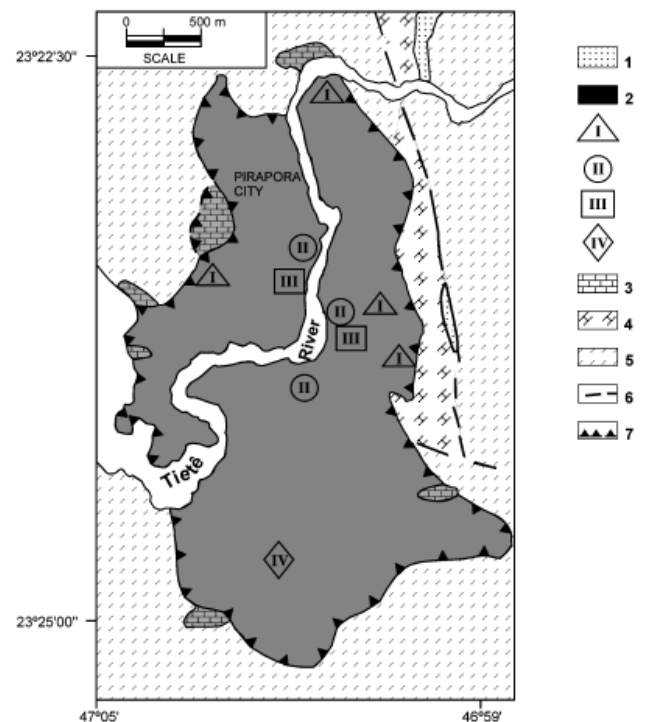


Figure 3 Geological outline of the Pirapora area. 1 – Quaternary sediments; 2 – ophiolite (observed outcrops: I–pillow lava structures; II–fine-grained mafic rocks (sheeted dike complex?); III–gabbros and flaser gabbros, locally cut by fine-grained mafic rocks; IV–banded ultramafic rocks with magnetite pods); 3 – stromatolitic dolomites; 4 – calci-phyllites and marbles; 5 – pelitic phyllites, sandstones, quartzites and meta-arkoses; 6 – faults; 7 – thrust surfaces.

the upper Allocthon unit (Figure 4). It is composed mainly of stromatolitic carbonates displaying normal polarity.

Allocthon

The allocthon is composed of the Pirapora de Bom Jesus ophiolite (Figure 4). The general characteristics of the Pirapora ophiolite complex will be described in the next paragraph.

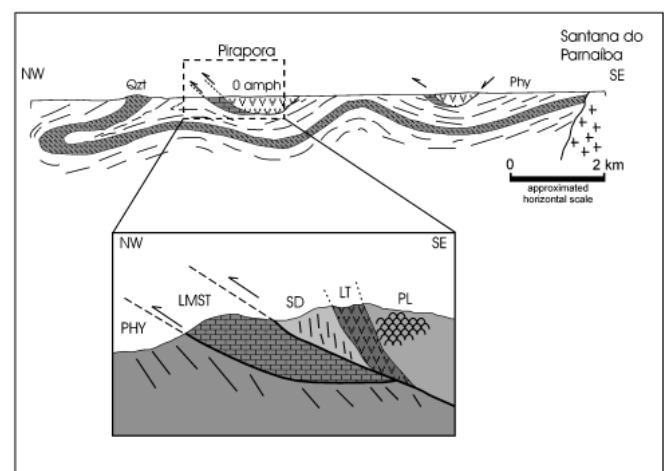


Figure 4 Schematic cross-section of the São Roque Group and Pirapora ophiolite. Allocthonous: PL – pillow lavas, LT – lavas and tuffs, SD – sheeted dikes; Parautochthon: LMST – stromatolitic limestones; Autochthon: Phy – phyllites, Qtz – quartzites.

Pirapora ophiolite

General geology

Despite of the restricted areal outcropping distribution of the ophiolitic complex, detailed mapping (Bistrichi, 1982; Bergman, 1988; this study) has allowed identification of various domains within it, showing internal organization and contrasting lithostratigraphic characteristics. No single domain has shown a complete record of the typical oceanic/ophiolitic stratigraphy; however, by adding up the partial sections that they collectively record, it is possible to recognize a characteristic oceanic lithospheric stratigraphy in the area. These include: 1) a lower crustal/upper mantle section, including the chromitite lenses described by Bergman (1988) and magnetite massive pod-like bodies (5–50 cm thick, 2–3 m long) associated with weathered metabasic rocks on the top and talc schist on the bottom. The magnetite grains display cumulate texture, are euhedral to rounded and submillimetric in size, and appear associated with filossilicate minerals composed mainly of talc and serpentine; 2) a lower crustal section which includes metagabbro and flasergabbro mafic cumulates, displaying plagioclase-rich gabbroic pegmatoids and (discrete) dyke intrusions towards the top; and 3) an upper crustal section mainly composed of highly deformed (fine-grained), greenschist facies mafic schists. Nevertheless, within less-deformed areas it is possible to identify the remains of a sheeted dyke complex, as well as a typical pillow lava member (Figueiredo et al., 1982; Lazzari, 1987) and chemically precipitated chert sediments. Despite the difficulties to precisely define the limits between lithological

units, (Burke et. al., 1981), this is a typical ophiolite sequence with normal polarity at the cartographic scale. It is confirmed by polarity criteria observed in the field and carefully documented by Lazzari (1987) for the pillow lava member. The oceanic interpretation of this stratigraphy is supported by the available geochemical data.

Geochemistry

On the basis of major element geochemistry Lazzari (1987) suggested general oceanic (MORB) affinities for the Pirapora metabasaltic rocks.

Our own new Pirapora geochemical study includes major and trace element data and Sr and Nd isotopic analysis (Tables 1 and 2). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are rather high, mostly ranging from 0.705097 to 0.706505 (with one sample, TC-Pi-01, at 0.712322; Table 2). High $^{87}\text{Sr}/^{86}\text{Sr}$ values obviously result from oceanic hydrothermal alteration processes (reflected by the presence of small stockwork type quartz-sulfide mineralisations, mainly associated with thrust faults in contact zones), which increased the original igneous Sr isotopic compositions; in contrast, Nd isotopic compositions seem unaffected by those processes (e.g., DePaolo, 1988). Thus, in the following discussion we will use exclusively the relatively immobile elements and Nd isotopic compositions.

The petrographic and geochemical data support Lazzari's observations (1987), indicating that the Pirapora mafic rocks were originally tholeiitic basalts/dolerites/gabbros. They are characterized by rather low incompatible element contents, with concentrations of Zr, Hf, Ta, La, Ce, P and Th (Table 1) well within the range of reported values for ocean-floor tholeiites (e.g. Kay and Hubbard,

Table 1 Representative chemical analysis of Pirapora ophiolite rocks

Sample N° Rock Type	TCPI01 basalt	TCPI4C basalt	TCPI04A dyke	TCPI4B dyke	TCPI4D dyke	TCPI4E dyke	TCPI08 dyke	TCPI07 gabbro	TCPI11 gabbro	TCPI12 gabbro
SiO ₂ wt%	52.91	52.55	48.15	48.49	48.82	48.38	49.65	49.13	49.75	48.08
TiO ₂	1.32	1.19	1.05	1.09	1.07	1.08	1.35	1.07	1.16	1.02
Al ₂ O ₃	13.45	13.53	13.83	14.10	14.10	14.09	14.20	14.62	15.77	14.70
Fe ₂ O ₃ (t)	11.65	10.26	11.54	10.43	11.90	11.97	13.69	12.35	12.08	12.25
MnO	0.21	0.13	0.17	0.17	0.18	0.18	0.21	0.17	0.16	0.17
MgO	6.48	5.95	7.04	6.38	7.29	7.60	6.95	7.81	6.93	6.35
CaO	6.87	7.51	10.57	14.21	10.47	9.62	7.74	9.12	7.05	11.81
Na ₂ O	4.35	4.05	3.03	2.17	2.97	2.97	3.86	3.19	4.27	3.01
K ₂ O	0.06	0.14	0.11	0.10	0.14	0.16	0.26	0.39	0.26	0.13
P ₂ O ₅	0.11	0.10	0.09	0.08	0.08	0.12	0.11	0.09	0.10	0.09
LOI	2.04	3.44	2.46	1.97	2.57	2.47	2.27	2.47	2.60	2.54
Total	99.45	98.85	98.04	99.19	99.59	98.64	100.29	100.41	100.13	100.16
Cr ppm	235	103	71	92	98	85	237	352	103	104
Ni	83	94	5	30	35	5	84	129	161	142
Sc	43	40	36	36	38	36	43	39	40	37
V	309	294	154	257	294	233	358	301	318	291
K	498	1162	913	830	1162	1328	2158	3238	2158	1079
Ba	41	27	18	10	18	18	330	95	39	25
Sr	48	69	88	169	98	79	143	168	78	169
Ta	0.3	0.2	0.1	0.2	0.2	0.2	0.3	0.7	0.3	0.7
Nb	4.6	3.7	0.9	2.5	2.9	1.9	5	12	5	12
Hf	2.2	2.0	1.5	1.6	1.7	1.5	2.1	1.6	1.6	1.7
Zr	70	65	50	52	52	48	74	60	66	63
Ti	7901	7158	6307	6535	6427	6499	8105	6409	6930	6145
Y	21	20	19	20	21	20	24	20	21	19
Th	0.39	0.29	0.23	0.23	0.25	0.2	0.1	0.5	0.2	0.4
La	3.88	2.65	2.94	3.18	3.48	3.02	4.8	3.6	3.1	3.6
Ce	10.0	7.4	7.8	8.3	8.5	7.4	12.0	9.0	8.0	9.0
Pr	1.54	1.22	1.20	1.24	1.38	1.18				
Nd	7.95	6.66	6.27	6.67	7.33	6.37	9.0	7.0	6.0	7.0
Sm	2.53	2.32	2.09	2.14	2.30	2.06	2.88	2.22	2.34	2.30
Eu	0.79	0.81	0.93	0.93	1.07	0.95	0.99	0.78	0.72	0.83
Gd	2.92	2.88	2.57	2.72	2.87	2.59				
Tb	0.58	0.57	0.52	0.52	0.57	0.52	0.60	0.50	0.50	0.50
Dy	3.80	3.62	3.12	3.26	3.69	3.20				
Ho	0.81	0.79	0.71	0.71	0.80	0.72				
Er	2.48	2.40	2.11	2.09	2.35	2.16				
Tm	0.37	0.35	0.30	0.32	0.35	0.32				
Yb	2.22	2.21	1.95	1.94	2.12	1.98	2.75	2.09	2.05	1.96
Lu	0.31	0.29	0.26	0.26	0.29	0.27	0.42	0.31	0.30	0.29

Analyses by ICP-MS and XRF-INAA at Activation Laboratories (Canada)

Table 2 Sm, Nd and Sr isotopic compositions of the Pirapora ophiolite

SPS	Field No.	Rock type	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	(2 σ) error	$^{143}\text{Nd}/^{144}\text{Nd}$	(2 σ) error	$\epsilon_{(600)}$	$^{87}\text{Sr}/^{86}\text{Sr}$	(2 σ) error
1661	TC Pi-4B A71	WR/Basalts.	2.451	7.386	0.2006	0.0007	0.512805	0.000010	2.96	0.705097	0.000010
1662	TC Pi-4A A71	WR/Basalts.	2.375	7.120	0.2017	0.0007	0.512823	0.000014	3.23	0.706000	0.000018
1663	TC Pi-01 A71	WR/ Basalts.	2.721	8.306	0.1981	0.0007	0.512738	0.000013	1.84	0.712322	0.000043
1664	TC Pi-4C A71	WR/ Basalts.	2.538	7.218	0.2126	0.0007	0.512878	0.000015	3.47	0.706505	0.000021
1665	TC Pi-4E A71	WR/ Basalts.	2.490	7.468	0.2016	0.0007	0.512804	0.000018	2.86	0.705664	0.000021
1686	TC Pi-4D A71	WR/ Basalts.	2.530	7.669	0.1995	0.0007	0.512797	0.000017	2.89	0.705423	0.000042
1657	TC Pi-4D A71	Plagioc./Basalts.	0.538	1.758	0.1850	0.0006	0.512614	0.000029	0.43	--	--
1659	TC Pi-4D A71	Amphib./Basalts.	8.984	25.221	0.2154	0.0007	0.512934	0.000010	4.34	--	--

ANALYTICAL PROCEDURES OF ISOTOPIC ANALYSES

All Rb-Sr and Sm-Nd isotopic analyses were carried out at the Geochronological Research Center of University of São Paulo (CPGeo). To Rb-Sr isotopic analyses all metabasaltic whole rock were performed on totally digested samples with HF(conc.) plus HNO₃(conc.) in a proportion 2:1. Then the solutes were evaporated to dryness; converted to chloride form with 2.62N HCl and Sr was separated in AG 50 WX8, 200–400 mesh cationic resin. The Sr separated were loaded on Ta filaments together with 2ml H₃PO₄ and analyzed in the 354 VG mass spectrometer. The reproducibility was controlled by the NBS987 standard analyses, averaging a value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.71024 \pm 0.0002$. Total procedure blank for Sr was 5 ng.

Samples for Sm-Nd analyses were spiked with a $^{150}\text{Nd}/^{149}\text{Sm}$ spike and dissolved with HF(conc.) and HNO₃ (conc.) in proportion 2:1. The solutes were evaporated; converted to chloride form with 0.2 ml 2.5N HCl and the rare earth elements (REE) were separated with 6.2N HCl in a AG 50WX8, 200–400 mesh cationic exchange resin. Afterwards, the solutions were dried and eluted with 0.26N HCl and Sm was collected with 0.55N HCl. Both elements were loaded as phosphates on Re filaments. Measurements of $^{143}\text{Nd}/^{144}\text{Nd}$ were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.719$. Repetitive analyses of the La Jolla standard was used to calculate reproducibility. Isochron age was calculated using ISOPLOT program of Ludwig (1999).

1978; Sun et al., 1979), and most samples display relatively depleted to flat LREE patterns ($\text{La}/\text{Sm}_{\text{cn}} = 0.70\text{--}1.02$; $\text{La}/\text{Yb}_{\text{cn}} = 0.79\text{--}1.21$; Figure 5a), similar to those of N/T-MORB (normal to transitional mid-ocean ridge basalts) and basalts from other ophiolites (e.g., Menzies et al., 1977; Pedersen and Hertogen, 1990). In accordance with their REE patterns, Pirapora samples (except for cumulate metagabbros) are characterized by near chondritic Ti/Zr (109–135) and Zr/Y (2.5–3.4), and by slightly Nb, Ta depleted Zr/Nb (15–56) and Zr/Ta (240–500) values, which are also comparable to those commonly reported for N/T-MORB (Sun et al., 1979).

Despite their general oceanic geochemical characteristics, Pirapora metabasites show variable incompatible element ratios (e.g., $\text{La}/\text{Nb} = 0.7\text{--}3.3$; $\text{La}/\text{Th} = 10\text{--}48$; Table 1) and isotopic compositions ($\epsilon_{\text{Nd}}(T = 600 \text{ Ma}) = +1.8$ to $+3.5$; Table 2), implying derivation of the original basaltic magmas from an heterogeneous mantle source. Examination of the geochemical data (Tables 1 and 2) indicates that there is a negative correlation between $\epsilon_{\text{Nd}}(T = 600 \text{ Ma})$ values, La/Yb ratios (Figure 5b) and LREE abundances, suggesting that it might be possible to derive the Pirapora magmas by mixing of an LREE-enriched low- ϵ_{Nd} magma with a N-type MORB, or by mixing of sources (Langmuir et al., 1978). Moreover, some Pirapora

metabasalts/dykes display La and Th enrichment relative to Nb and Ta (see Figure 5a), leading to a decoupling between large ion lithophile (LILE) and high field strength (HFSE) elements, which distinguishes these samples from MORB and within-plate basalts (Wood et al., 1981). Indeed, HFSE are characteristically depleted in island-arc and continental margin basalts (Perfit et al., 1980; Pearce, 1982), suggesting that the Pirapora ophiolite trace element chemical characteristics are transitional between that of oceanic ridge and orogenic basalts; this same chemical pattern has also been reported from many back-arc basins and is accepted as the fundamental characteristic of back-arc basin basalt geochemistry (e.g., Saunders and Tarney, 1991). The tectonic situation of back-arc spreading (Karig, 1974) is one where there is potential for involvement of subduction-related components that would certainly affect back-arc basin basalt source compositions and magma generation processes. As it might be anticipated, there is a geochemical continuum in back-arc basin basalts (Crawford et al., 1981; Saunders and Tarney, 1984; Hawkins and Melchior, 1985; Gill, 1987; Hickey and Vargas, 1989), from those of orogenic character to those with variable LREE

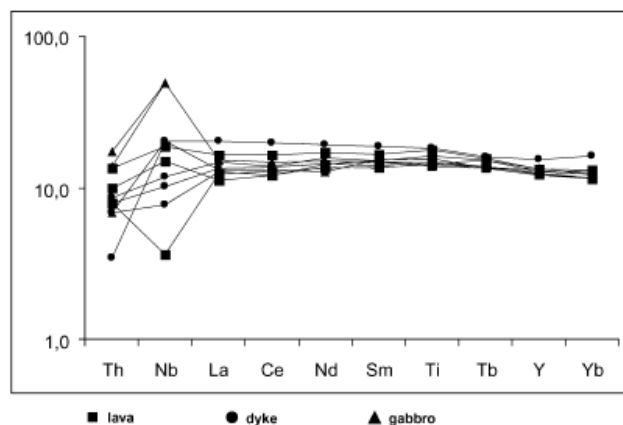


Figure 5a Chondrite normalized (Sun and McDonough, 1989) trace element diagram for the mafic rocks from Pirapora ophiolite.

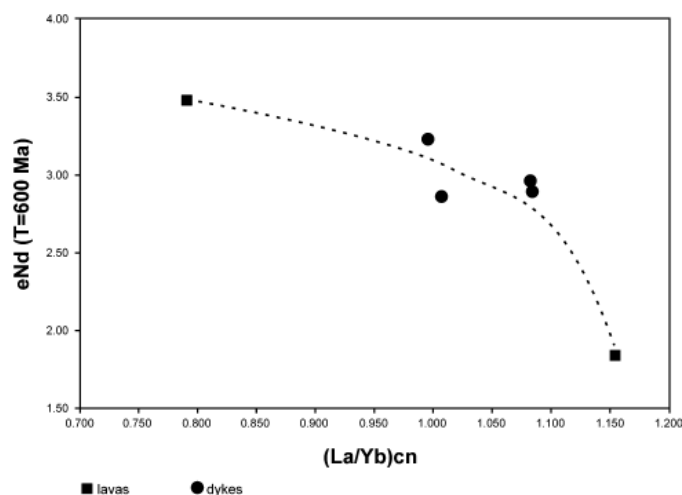


Figure 5b ϵ_{Nd} plotted against La/Yb (chondrite normalized) for lavas and dikes from Pirapora ophiolite.

depleted/enriched MORB characteristics from mature back-arc basins. Like most back-arc basin basalts, Pirapora metabasaltic rocks also have geochemical characteristics that are transitional between those of MORB and island arc basalts, but their consistent LILE-depletion further suggests that the generation of the Pirapora ophiolite took place in a mature back-arc basin where the influence of subduction components should not be dominant. In this situation rising diapirs of partially melted, variously depleted (heterogeneous) MORB-type source (related to back-arc spreading) may still interact with leftovers of the overlying, less refractory, arc-related mantle wedge, inducing further generation of minor LILE-enriched melts. Variable mixing, prior to eruption, between (dominant) MORB and LILE-enriched magma types could well account for the observed isotopic and trace element variations in the Pirapora ophiolite.

Available research suggests that the origin of many ophiolites is best explained by spreading in association with convergent plate margins (Pearce et al., 1984; Nicholas, 1989). These ophiolitic fragments will potentially exhibit a complex geology often juxtaposing various components which are typical of different tectonic settings (e.g., normal oceanic crust, island-arc or active continental margin complexes and crust formed by back-arc spreading). The Pirapora ophiolite is indicative of a major Neoproterozoic geosuture in the Brasiliano orogen. Its geochemical characteristics also imply an origin (at a back-arc setting) in the vicinity of a subduction zone.

Geochronology

Previous geochronological studies of the São Roque Domain (Juliani et al., 2000) have dated (U-Pb, zircon) the basal volcanic unit of the Serra do Itaberaba Group, constraining the maximum age of the autochthonous unit at 1395 ± 10 Ma.

Hackspacher et al. (2000) reported U-Pb ages of 628 ± 9 Ma on a near concordant monazite from the Pirapora Formation metabasalts, which they interpreted as the crystallization age of the respective magmas. Thus, this age corresponds to the generation age of the oceanic crust now represented by the Pirapora ophiolite.

Regional granitoid intrusive activity represented by the late-tectonic Cantareira batholith, which has been dated (zircon U-Pb) at 669 ± 8 Ma (Tassinari, 1988), demonstrates that convergence inside the Brasiliano orogen had already started when the ophiolite was generated by oceanic spreading. It supports our geochemical inferences, indicating that the Pirapora ophiolite was generated in a back-arc basin environment. A rhyolite dike (607 ± 28 Ma; Hackspacher et al., 2000) which crosscut the metasediments of the upper Estrada dos Romeiros Formation, suggests the persistence of felsic magmatism in the back-arc basin continental margin, contemporaneous with oceanic spreading. Sm-Nd mantle-depleted model ages of ca. 2.0 Ga obtained for most of the intrusive granitoid rocks, which occurs in the São Roque Group (Tassinari & Sato, 1996; Dantas et al., 2000), suggests that the Brasiliano, Pirapora back-arc basin, oceanization process took place within a paleoproterozoic continental basement.

We have attempted a direct Sm-Nd dating of syn-D1, green-schist facies albite-actinolite assemblage from a Pirapora Formation dyke, in order to constrain the emplacement age of the ophiolite. The results define a line slope corresponding to 558 ± 68 Ma, and initial $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.51194 ± 0.00011 (Figure 6). Despite the large error, the age brackets overlap the more precise K-Ar cooling age determinations ($610\text{--}620$ Ma; Tassinari et al., 1985) of syn-D1 metamorphic biotites from the Autochthonous unit.

Altogether, geochronological data suggests that the emplacement of Pirapora ophiolite (~ 620 Ma) took place shortly after its generation (628 ± 9 Ma) at the oceanic ridge, probably during oceanic ridge collision with the continental margin. The implied obduction mechanism for the Pirapora ophiolite supports the observation that many ophiolites are tectonically decoupled along the (mechanically weak) lithosphere-asthenosphere boundary and initially displaced as immature oceanic lithosphere in close proximity to the respective spreading center (Spray, 1984).

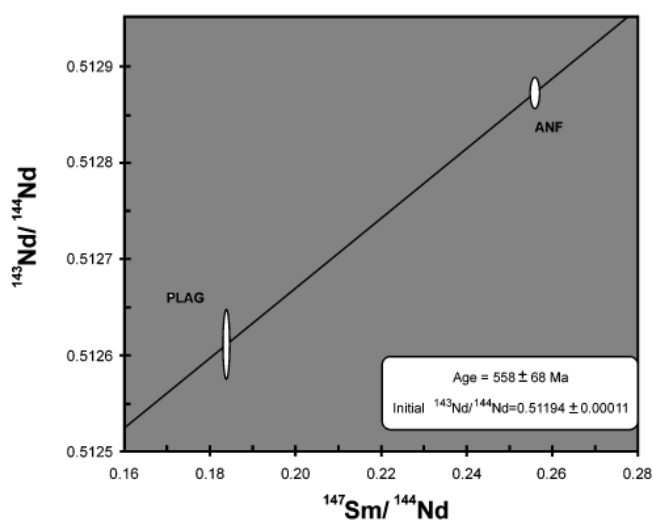


Figure 6 Two mineral Sm-Nd isochron line for a metabasaltic dike from the Pirapora Ophiolite. (Plag. – plagioclase; Anf. – amphibole).

Geodynamic model

As already referred, each tectonic unit occurring in the studied area (Pirapora de Bom Jesus county, Central Ribeira Belt, SE São Paulo state) has normal polarity, with contrasting lithologies and corresponding to very different sedimentary and/or petrotectonic environments.

The Autochthon represents a passive margin of the Brasiliano cycle, as indicated by the maturity of the sedimentary sequence (Bergman, 1988). Previous regional studies favoring an ensialic evolution (Tassinari, 1988; Bergmann, 1988; Sadowski and Tassinari, 1991; Trompette, 1994; Hackspacher et al., 2000) rest on the assumption that the Pirapora Formation was developed "in situ", as a member of the São Roque Group. In contrast, the present study indicates that the Pirapora Formation is part of a distant ophiolite allochthon, unrelated to the São Roque Group.

The Paraautochthon is interpreted as carbonate barrier in the oceanic side of the passive margin (or, alternatively, around an oceanic island).

The Allochthon represents oceanic crust and (eventually) sub-oceanic mantle. Both the geochemical signature and geochronological constraints point to a derivation from a back-arc basin inside the Brasiliano orogen. Indeed, the age of the ophiolite protolith (628 ± 9 Ma; Hackspacher et al., 2000) is younger than other Brasiliano orogenic events and related intrusive activity (Tassinari et al., 1985; Tassinari and Campos Neto, 1988), showing that convergence inside the orogen had already started when the ophiolite was generated by back-arc spreading.

The Pirapora ophiolite was obducted on a carbonate barrier (adjacent to it) and finally emplaced on top of the passive margin. Both the location of the back-arc basin and the direction of obduction remain controversial, because these earlier (obduction related) orogenic events were obliterated by later transpression in the Ribeira Belt, associated with oblique continental collision. Narrow back-arc basins related to closure of the Adamastor ocean at about $550\text{--}530$ Ma (Brito Neves et al., 1999) became cryptic sutures separating the Costeiro, Embú and São Roque Domains, with large components of dextral transpression. Given the orogenic polarity of the Ribeira-Damara Belt (Porada, 1989), derivation of the Pirapora ophiolite from inside the Brasiliano branch is more probable than from the Damaran branch of the orogen. The geometry and kinematics of the ophiolite slice are thus conjectural, but the absence of a clear meta-

morphic sole suggests ophiolite emplacement as a thin obducted nappe, with very large displacement on its base.

We must conclude that the Ribeira-Damara Belt was produced by plate tectonic processes; indeed, the Pirapora back-arc basin must have been induced by the closure of a possibly large ocean (Adamastor) involved in the respective Wilson cycle. The scarcity of ophiolites, high-pressure suture rocks and the large volume of synorogenic granitoids, as well as the large width of the belt, show that the Ribeira-Damara system is of Variscan type rather than of Alpine type affinities (Rey et al., 1997; Ribeiro, 1999).

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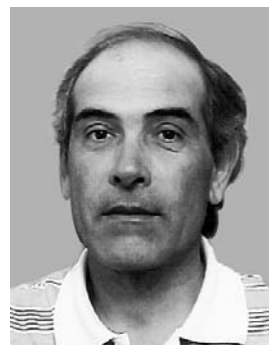
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