

The Santa Luz chromite-peridotite and associated mafic dykes, Bahia-Brazil: remnants of a transitional-type ophiolite related to the paleoproterozoic (>2.1 Ga) Rio Itapicuru greenstone belt?

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Abstract The Santa Luz chromite-rich peridotite complex crops out in the Serrinha Block (NE São Francisco craton), approximately between grey gneisses of the Archaean basement and supracrustal rocks of the Palaeoproterozoic Rio Itapicuru greenstone belt. It comprises serpentinite, serpentinised harzburgite, massive chromitites, gabbroic pockets and amphibolite dykes/veins with epidote-rich margins, all intruded by pegmatitic and aplite dykes. The mafic-ultramafic rock association is interpreted as basaltic melt percolation through mantle peridotites. Massive chromitites show major element chemistry and platinum group elements signature similar to ophiolite chromitites. The complex is older than 2085 ± 12 Ma and younger than 2983 ± 8 Ma based on U-Pb ages obtained respectively on aplite dyke and host banded gneiss. The Santa Luz peridotite complex and associated mafic dykes may be related to rifting of a magma-poor continental margin that later evolved into an ocean, the closing of which eventually formed the Palaeoproterozoic Rio Itapicuru greenstone belt.

Keywords: transitional ophiolite, melt impregnation, magma-poor rifted continental margin, palaeoproterozoic greenstone belt, São Francisco craton.

Resumo *O peridotito cromitífero de Santa Luz e diques máficos associados, Bahia-Brasil: remanescentes de um ofiolito transicional relacionado ao greenstone belt paleoproterozóico (>2.1Ga) do rio Itapicuru?* O complexo peridotítico de Santa Luz ocorre no Bloco Serrinha (NE do Cráton do São Francisco), aproximadamente entre gnaisses do embasamento arqueano e rochas supracrustais do greenstone belt do Rio Itapicuru. Ele contém serpentinitos, harzburgitos serpentinizados, cromititos maciços, faixas gabbroicas e diques/veios de anfíbolitos. Todo o conjunto é cortado por pegmatitos e aplitos. A associação máfica e ultramáfica é interpretada como percolação de magma basáltico em peridotitos do manto. Os cromititos maciços apresentam química mineral e padrões de elementos do grupo da platina semelhantes aos de cromititos de ofiolitos. O complexo é mais antigo que 2085 ± 12 Ma e mais novo que 2983 ± 8 Ma, idades obtidas respectivamente em dique aplitico e gnaissado encaixante. O complexo peridotítico de Santa Luz e os diques máficos associados podem ser relacionados à fase *rifte* de uma margem continental pobre em magma, a qual evoluiu para a abertura de um oceano e posteriormente se fechou para finalmente formar o *greenstone belt* do Rio Itapicuru durante colisão continental no Paleoproterozóico.

Palavras-chave: ofiolito transicional, *rifte* de margem continental pobre em magma, *greenstone belt* paleoproterozóico, Cráton do São Francisco.

INTRODUCTION The discovery of ophiolitic remnants in the geological record is a subject of major interest, not only for tectonic reconstruction of ancient orogenic belts but also to constrain how far back in time modern style plate tectonics has been in operation.

Ophiolites are thought to have formed at mature mid-ocean ridges or back-arc basins, and their lithological succession generally comprises a layer of pillowed basalts, often with interlayered chemical sediments, followed downwards by sheeted dykes, noncumulate gabbro, cumulate gabbro and ultramafic rocks, and tec-

tonized mantle peridotite (Anonymous 1972, Condie 2005). Although relatively well-ordered ophiolite complexes are sometimes preserved in the continents (e.g. Oman, Troodos), most commonly they are considerably disrupted and occur in apparently chaotic terrains.

In contrast with the idealized section of the oceanic lithosphere suggested for several ophiolite complexes, the Alpine-Apennine ophiolites have anomalous lithological successions. Among other features (Rampone & Piccardo 2000, Piccardo 2003, Muntener & Piccardo 2003), (i) MORB-type gabbroic rocks are

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intruded into mantle peridotites and (ii) serpentinized mantle peridotites are directly covered by MORB lava and oceanic sediments, which characterize the steps of rifting during transition from passive lithosphere extension to active oceanic drifting.

Here, we present field relationships and geochemical signatures of chromite-rich peridotites and associated mafic rocks of the Santa Luz ultramafic com-

plex, and discuss the implication for the early evolution of the Rio Itapicuru greenstone belt.

GEOLOGICAL SETTING The Santa Luz peridotite complex, also known in the literature as the Pedra Preta basic-ultramafic complex (Carvalho Filho *et al.* 1986, Oliveira & Knauer 1993), crops out 2 km east of the Santa Luz city, Bahia, and is one of several minor peridotite occurrences bordering the Palaeoproterozoic

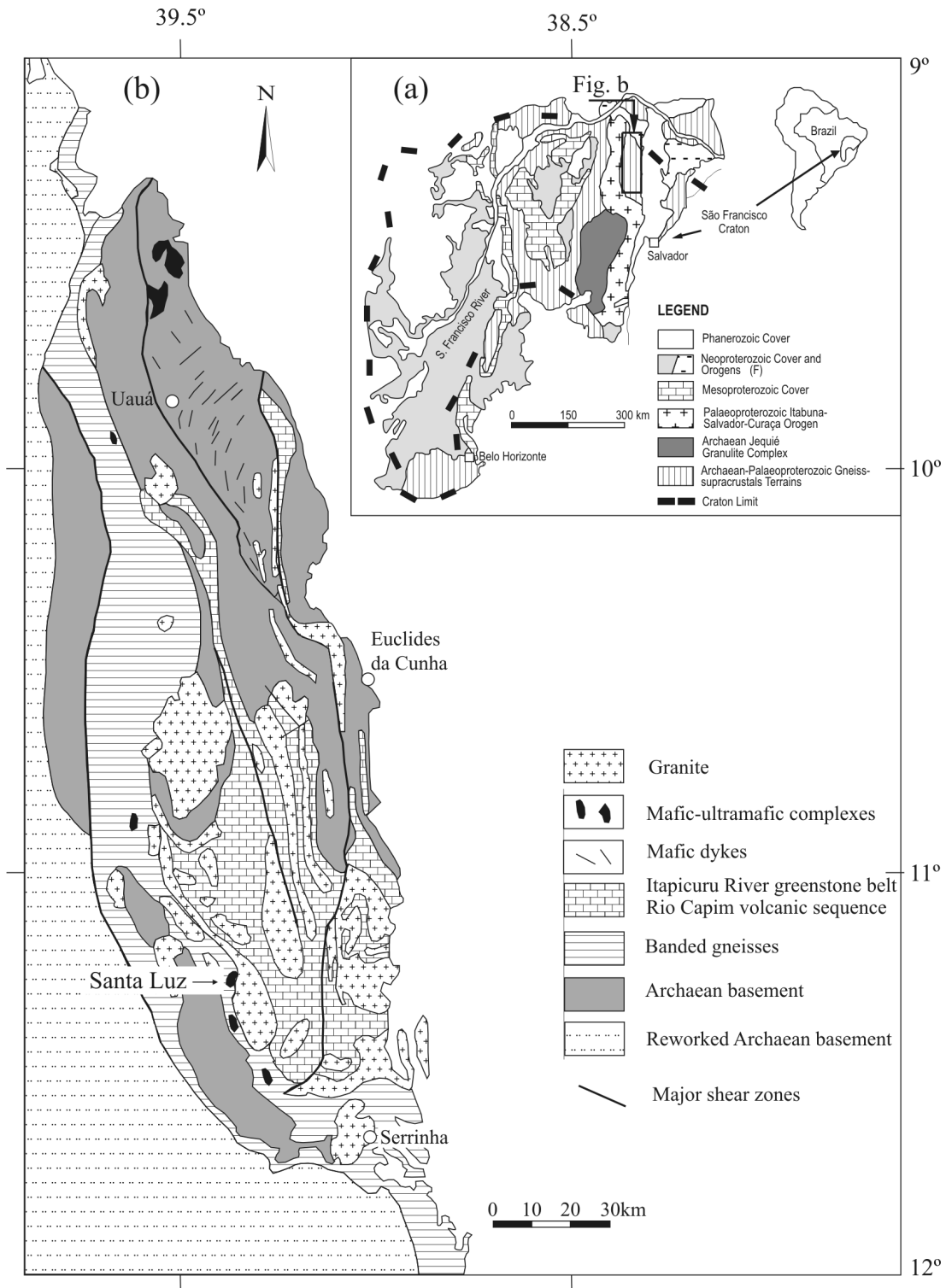


Figure 1 - Northern segment of the Itabuna-Salvador-Curaçá orogen and location of peridotite complexes. Modified after Souza *et al.* (2003) and Oliveira *et al.* (2004).

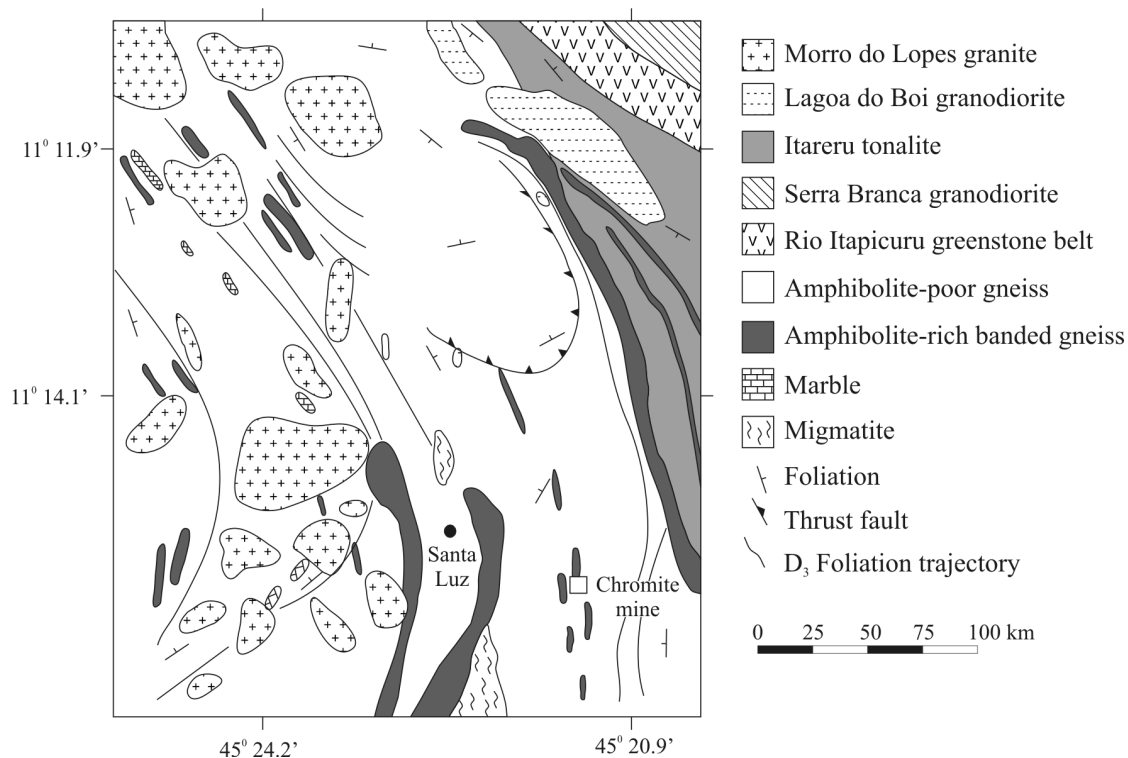


Figure 2 - Geological map of the Santa Luz area. Modified after Oliveira et al. (2002).

Rio Itapicuru greenstone belt (Figs. 1 e 2). It is economically important because of the high-quality refractory chromite exploited since the Second World War. Currently, Magnesita S.A. holds the right of mineral exploitation.

The complex is a small body (about 400 m long and 100 m wide) conformably interleaved with NW-trending, tightly folded, nearly upright banded gneisses composed of decimetre- to a few metre-thick bands of amphibolite and felsic gneisses. Regional geological mapping at the 1: 25000 scale revealed that these banded gneisses are the products of deformation of Archaean grey gneisses intruded by much younger mafic dykes. The contact between the regional gneisses and the ultramafic body is tectonic and marked by narrow shear zones, at places enriched in biotite-phlogopite; the ultramafic rocks may have been folded along with the host gneisses to account for minor occurrences of serpentinite within the latter. Although the rocks are highly weathered in the open-pit mine, drill-core samples reveal that the complex is chiefly composed of serpentinite and serpentinitized harzburgite with disseminated and massive chromite. Quartz veins, aplites, pegmatites and mafic dykes crosscut these rocks. Fractures and shear zones are common in the peridotites and are usually associated with alteration of the ultramafic rocks into dark mica and tremolite-rich bands.

The Archaean basement rocks of the Santa Luz region are poly-deformed and represented by grey gneisses and migmatites of the Retirolândia block (3085-2998 Ma; Oliveira et al. 2004). A swarm of mafic dykes intruded these gneisses, especially along the eastern part of the block. In the more preserved por-

tions, the migmatites present a steeply dipping, NE-trending foliation parallel to mafic dykes and Archaean gneiss. In some outcrops, the dykes are tightly folded and conformably interleaved with the host Archaean gneisses, but elsewhere the original discordant relationship is preserved.

Coarse-grained gneisses (deformed porphyritic granites), garnet-bearing paragneisses, white marbles, calc-silicate gneisses and quartzites also occur in the Santa Luz region, although their relationships with the Archaean gneisses is not clear.

The entire rock sequence underwent at least four ductile deformation phases. Intrafolial recumbent folds (axis oriented E-W or NW-SE) affecting decimetre-size pegmatite neossomes within banded gneisses register the first event (D_1), which is possibly younger than the one encountered in the Archaean gneisses. The second deformation (D_2) formed the most penetrative foliation in the region. Strongly stretched granite- to trondhjemitic neossomes, recrystallization of brown hornblende and garnet (with plagioclase corona) in amphibolites and paragneisses characterize this event. The respective stretching lineation (L_2) is of low angle and oriented in the WNW-ESE (270 to 330° Az) direction. The third event (D_3) controls the regional structure through inverted antiforms and synforms with axial plane (S_3) directed N-S to NNW-SSE and fold axis and stretching lineation (L_3) with moderate rake (up to 30°) dipping to NNW. The superposition between the D_2 and D_3 events produced interference patterns intermediated between coaxial (ex. in the chromite mine) and boomerang. In the proximity of N-S to NNW-ESE trending dextral ductile shear zones the S_2 and S_3 fabrics show

progressive verticalization. The dextral kinematics continued under brittle conditions opening space for the intrusion of 30-70° Az directed granite dykes, aplite and pegmatite dykes. The last event (D₄) is marked by open to gentle folds with vertical axial plane trending E-W, indicating a late N-S shortening.

THE SANTA LUZ PERIDOTITE COMPLEX In order to set constraints on the tectonic significance of the Santa Luz peridotite we combined field relationships between the rock types in the open-pit mine with geochronology, mineral chemistry and whole rock geochemistry. We carried out electron microprobe chemical analyses on the massive-type chromitites, SHRIMP U-Pb geochronology on zircons from an aplite dyke that cuts a peridotite, whole rock Sm-Nd isotope data of mafic dykes intrusive into the peridotites, and whole rock geochemistry of the mafic dykes and host peridotites.

Field relationships and petrography The most outstanding feature of the Santa Luz peridotite complex is the occurrence of decimetre- to metre-thick dykes, lenses and irregular bodies of coarse- to medium-grained amphibolites intrusive into the serpentized peridotites or in structural conformity with them (Fig. 3a). The serpentinites are apparently not much deformed but the mafic dykes are clearly foliated (Fig. 3b). The dykes are composed mostly of pale green amphibole, fresh to totally altered plagioclase, diopside and minor epidote and titanite. The mafic dykes and lenses associated with the Santa Luz peridotites differ from metamorphosed dykes of the country rock banded gneisses in the amphibole type. Amphiboles from the former are pale green, whereas from the latter are dark green to brown. At the contact with the host serpentinite, most mafic dykes and gabbroic lenses show a few decimetre-wide band enriched in epidote and zoisite, with minor pale green amphibole, diopside and titanite. This aspect is similar to the metasomatic process of rodingitization described in ocean-floor rocks and in ophiolite complexes worldwide (Bideau *et al.* 1991, Rösli *et al.* 1991, Puga *et al.* 1999). Accordingly, the mantle-derived basic magmas percolate the mantle section of the oceanic lithosphere, as dykes or irregular bodies, and subsequently all rocks undergo ocean-floor metasomatism, converting partially the mantle peridotites into serpentinite and the basic dykes into low grade metamorphic rocks with hydrogarnet-bearing assemblages (rodingite). During such a process, there is a significant amount of element losses and gains, and these features were observed in mafic dykes of the Santa Luz peridotite complex, as briefly commented in the geochemistry section.

Analytical techniques We collected major element data on chromium-rich spinels on a JEOL JXA-8600 microprobe of the Institute of Geosciences of University of São Paulo. Whole rock major and trace element analyses were performed respectively on fusion beads and pressed powder pellets at the X-ray fluorescence laboratory of the Geosciences Institute of UNICAMP.

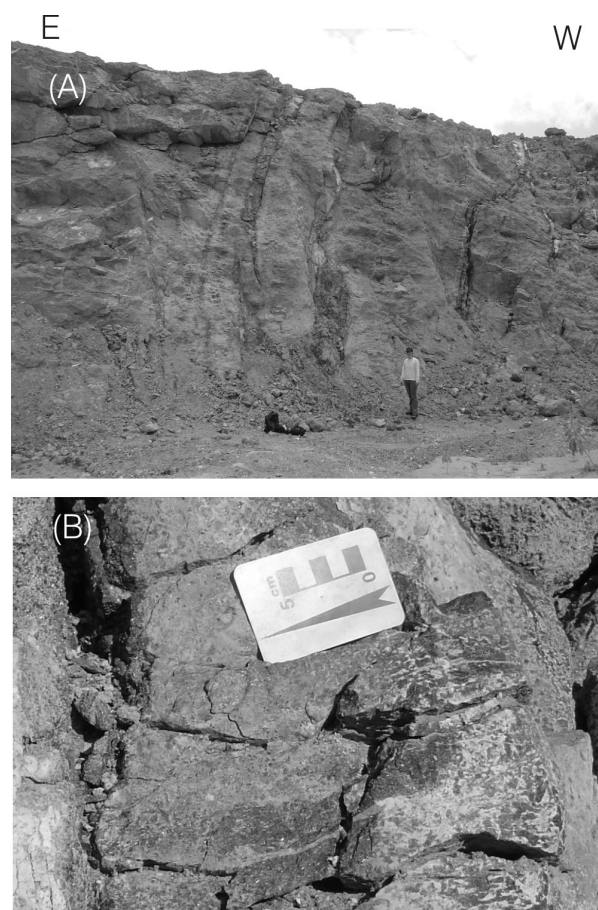


Figure 3 - Mafic dykes intrusive into serpentinites, Santa Luz peridotite complex (A), as evidence for melt impregnation; Detail of a foliated and amphibolitized mafic dyke (B).

The analytical precision is checked against the international reference samples WSE (dolerite) and RGM-1 (rhyolite); for the major and minor elements the instrumental errors are less than 1.2 %, whereas for most trace elements except Th (7%), Pb (5%), and Nb and Ga (3%) the errors are below 1.5%. Zircon U-Pb SHRIMP data were acquired on the SHRIMP-II laboratory at Perth, Australia, following the operation conditions described by Smith *et al.* (1998); 7 analyses of the CZ3 standard zircons indicated a Pb/U calibration reproducibility (1 σ) of 1.42 %. Common-Pb corrections were made assuming Broken Hill common-Pb compositions for all sample analyses. Pooled ages are quoted at 1 σ error and dates from analyses that are <95% concordant were regarded as minimum ages. Geoanalysis, Perth-Australia, analysed four massive-type chromitites for platinum group element (PGE). Finally, the Sm-Nd isotope data were collected at the Geochronology laboratory of University of Brasilia, according to the protocols of Gioia & Pimentel (2000).

Geochronology Five representative samples of amphibolite dykes, gabbro lenses, peridotite and an epidote-rich rock were analysed for Sm-Nd isotopes in order to constrain the timing of melt impregnation (data

in Table 4). Unfortunately, the data fit in no reasonable isochron.

Nevertheless, a minimum age for the complex is estimated from U-Pb SHRIMP analyses of zircon grains extracted from an aplite dyke intrusive into the peridotite. The results are presented in figure 4 and in table 1.

The amount of zircon grains recovered in the sampled aplite is small; ten grains were analysed but only six are suitable for age calculation. Most of the zircon grains are inherited from the basement (individual ages vary from 3020 Ma to 3145 Ma) with only two nearly-concordant grains giving a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2085 ± 12 Ma. Although the data is limited, we suggest that the peridotite complex is older than 2085 Ma. A felsic portion of the host banded gneiss yields an Archaean U-Pb SHRIMP age (2983 ± 8 Ma, Oliveira *et al.* 2004); this date sets an upper age limit for the ultramafic rocks.

Chemistry of massive-type chromitites

Massive and disseminated chromites are ubiquitous in the Santa Luz peridotite complex. The former occurs as disrupted and faulted pods (Carvalho Filho *et al.* 1986). In this study, we emphasized only the massive chromitites because the disseminated chromites are prone to chemical exchange with associated silicates. In order to assess the extent to which post-magmatic element mobility affected the chromite composition, we carried out a detailed analytical traverse across a euhedral massive-type chromite grain (Fig 5). With the exception of Cr, Al and Ti at the very end of a grain rim, no significant element variation is observed in the central portion of the grains. As such, the homogeneous core of chromite grains in the massive chromitites is interpreted as the best estimate of the primary cumulus chromite composition (cf. Eales & Reynolds 1986, Suita & Strieder 1996, Spier & Ferreira Filho 2001, Marques & Ferreira Filho 2003). Therefore, in the following discussion we consider only spot analyses from the core of individual chromite grains.

Representative microprobe data of chromite grains are in Table 2 and the chemical variation of the full data set is shown in figure 6.

In several diagrammes like those of figure 6, the Santa Luz chromites plot in the ophiolite or Alpine peridotite field, although an unequivocal distinction from layered complexes is not always possible. As an additional evidence in support of our interpretation that the core of chromite grains closely approach the original igneous composition, the studied chromite grains do not show a trend towards iron enrichment, a characteristic of metamorphosed chromite (e.g. Suita & Strieder 1996). The high Cr* (Cr/Cr+Al) values of the Santa Luz chromites (Cr* = 0.60-0.70) imply a high percentage of melt extraction from a mantle harzburgite, according to the algorithm of Hellebrand *et al.* (2001).

Platinum group element (PGE) analyses of massive chromitites are in table 3 and figure 7. The chondrite normalized PGE patterns (Fig. 7) are similar to chromitites with very low sulphide contents such as

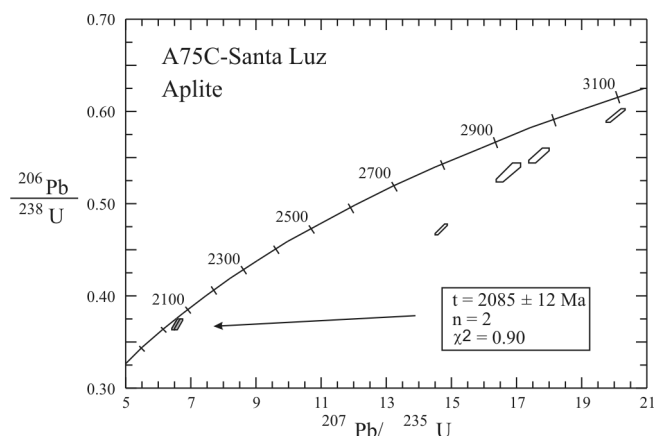


Figure 4 - Zircon SHRIMP U-Pb ages of an aplite intrusive in serpentinite of the Santa Luz peridotite complex.

Table 1 - SHRIMP U-Pb data on zircons from a pegmatite intrusive into serpentine of the Santa Luz Peridotite Complex.

grain-spot	U (ppm)	Th (ppm)	Th/U	4f206 (%)	204-corrected-->				206* 238*	+/-	207* 235*	+/-	208* 232*	+/-	207* 206*		
					207* 206*	+/-	208* 206*	+/-							207* 206*	Age (Ma)	+/-
1-1	117	42	0.361	0.26	0.232	0.0018	0.1049	0.0022	0.5546	0.0079	17.7383	0.3015	0.1611	0.0043	93	3066	12
1-2	141	56	0.395	0.10	0.244	0.0009	0.1059	0.0011	0.5978	0.0076	20.1003	0.2744	0.1602	0.0028	96	3145	6
2-1	197	86	0.437	0.42	0.2254	0.0010	0.1529	0.0016	0.4736	0.0057	14.7171	0.1955	0.1656	0.0028	83	3020	7
3-1	25	1	0.026	0	0.2274	0.0022	0.0087	0.0006	0.5352	0.0103	16.7835	0.3824	0.1793	0.0137	91	3034	16
4-1	187	1	0.003	0.06	0.1284	0.0009	0.0018	0.0012	0.3697	0.0059	6.54440	0.1203	0.2018	0.1277	98	2076	13
7-1	243	21	0.086	0.19	0.1301	0.0012	0.0218	0.0010	0.3693	0.0062	6.62490	0.1318	0.0929	0.0046	97	2099	16

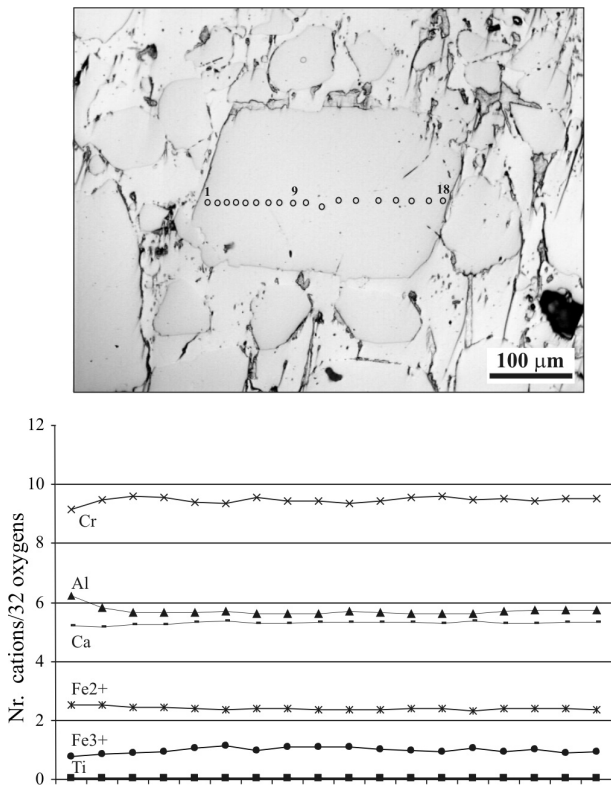


Figure 5 - Electron microprobe analyses across a chromite grain showing weak zoning of Al, Cr and Fe³⁺ at the rim. Analytical data are listed in Table 2.

those from ophiolite complexes and from the lower layers of the Critical Zone (LG-1) of the Bushveld layered complex (Von Gruenewaldt & Merkle 1995). The studied chromitites bear no similarity with chromitites with sulphide inclusions, as the UG-2 chromitites from the Bushveld complex.

Geochemistry of the mafic rocks The samples that underwent a large extent of metasomatism, such as the epidote-rich dyke margins are depleted in Na₂O and enriched in CaO, and follow the rodingite trend in figure 8. In general, the least metasomatized, fine- to coarse-grained amphibolite dykes have geochemical characteristics comparable to continental tholeiites and transitional-type MORB, and are slightly more primitive than similar dykes associated to the regional gneisses (Table 4). The silica contents of the former (41.98-47.09 wt%) fall in the range of picritic basalts to basalts with low TiO₂ abundances (0.2-0.8 wt%). The incompatible element ratios Zr/Y (1.4-2.9), Y/Nb (4-14.2), Zr/Nb (14-18), Ti/Y (110-178), Ti/Zr (62-80) and Ti/V (13-20) are similar to either T-MORB (Floyd 1989), low-Ti continental flood basalts (Hergt et al. 1991, Peate 1997) and continental mafic dykes (Oliveira et al. 1990, Bellieni et al. 1995).

The negative Nb anomaly on mantle-normalized, multi-element diagramme (Fig. 9) indicates a significant crustal signature. The CaO-rich samples show high-field

strength element (HFSE) abundances similar to the other amphibolite dykes but significantly lower values of low-field strength elements (LFSE). On the other hand, sample K from this dyke group has undergone both LFSE and HFSE depletion, especially Zr and Ti.

DISCUSSION Field relationships, rock association and the geochemical characteristics of massive chromitites and amphibolite dykes/lenses are the evidences we present to support the interpretation that the Santa Luz peridotite complex is similar to ophiolitic complexes found in the Alpine-Apennine orogenic belts. The ophiolites in these belts are anomalous with respect to the idealized ophiolite pseudo-stratigraphy which comprises ultramafic rocks at the base, with variable amounts of harzburgite, lherzolite and dunite (commonly serpentinized), overlain by layered/non-layered gabbros, then by a sheeted dyke complex and basic volcanic rocks with a cover of deep-sea sediments (Anonymous 1972, Coleman 1977). The Alpine-type peridotites comprise mantle peridotites intruded by MORB-type gabbroic rocks; MORB lava flows and oceanic sediments may directly cover serpentinized mantle peridotites (Rampone & Piccardo 2000). This type of ophiolite is named “transitional ophiolites” (Windley 2005), and its formation may have taken place at ocean-continent transitions of a magma-poor rifted margin (Wilson et al. 2001, Manatschal 2004). This type of rifted continental margin is one of the three classes recognised: volcanic, magma-poor and strike-slip. The former is characterized by voluminous emplacements of predominantly mafic rocks which do not originate at normal seafloor spreading centers, such as those off East Greenland, Norway, and the South Atlantic rifted margins at the Rio Grande and Walvis ridges (Gladczenko et al. 1997). Strike-slip margins are typified by the Cote D’Ivoire-Ghana margin and are marked by a sharp transition between thinned continental crust and an adjacent oceanic crust; the transition is underlined by a marginal ridge with a steep continental slope (Mascle et al. 1995). Magma-poor continental margins, on the other hand, are characterized by thinned continental crust dissected by low-angle detachment faults, with oceanward increasing of mafic melt volumes, that merges into oceanic crust (e.g. Whitmarsh et al. 2001, Wilson et al. 2001). According to Whitmarsh et al. (2001), during the rifting stage of a magma-poor continental margin the lithosphere extends and thins, the lithospheric mantle exhumed to the seafloor and the upwelling asthenosphere undergoes partial melting by adiabatic decompression; the zone of exhumed continental mantle evolves oceanward into seafloor spreading with increasing magmatic activity.

The present-day analogues of the transitional-type ophiolites lie offshore the Iberia continental margin (Whitmarsh et al. 2001, Wilson et al. 2001, Piccardo 2003), at the Southwest Australian passive margin (Beslier et al. 1999, 2004) and probably in the island of Zabargad, Northern Red Sea (Bonatti et al. 1983, Nicolas et al. 1987). In the intensively studied Iberia continental margin a zone of exhumed sub-con-

Table 2 - Representative chemical analyses of cores of chromite grains from massive chromitites of the Santa Luz Peridotite Complex. Analytical data for the chemical traverse of Fig. 5 are listed as SL-01.

Sample #	SL 02	SL 02	SL 02	SL 02	SL 02	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	SL 01	
grain spot	3	8	10	13	21	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO ₂	0.00	0.00	0.00	0.01	0.00	0.06	0.05	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.05	0.02	0.03	0.02	0.02	0.00	0.01	0.04	0.01
TiO ₂	0.24	0.25	0.18	0.28	0.29	0.17	0.16	0.15	0.18	0.20	0.16	0.24	0.21	0.22	0.21	0.17	0.22	0.11	0.21	0.13	0.16	0.19	0.18
Al ₂ O ₃	15.27	16.76	18.75	18.76	19.11	21.10	19.83	19.52	19.47	19.49	19.46	19.28	19.38	19.21	19.39	19.38	19.31	19.47	19.35	19.49	19.58	19.48	19.62
Cr ₂ O ₃	52.79	50.67	48.65	49.95	49.26	46.44	47.99	49.28	49.20	48.22	47.49	49.00	48.39	47.88	47.60	48.18	49.17	49.45	48.72	48.65	48.18	48.29	48.58
FeOT	17.79	17.20	16.84	16.87	16.62	15.46	16.01	16.01	16.25	16.47	16.38	16.16	16.65	16.31	16.38	16.12	16.14	16.11	16.15	15.87	16.10	15.57	15.72
MnO	0.74	0.68	0.71	0.74	0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	12.20	12.85	13.38	12.21	12.92	13.98	13.89	14.27	14.35	14.45	14.43	14.41	14.42	14.41	14.37	14.43	14.50	14.50	14.65	14.36	14.35	14.32	14.43
CaO	0.00	0.02	0.02	0.02	0.00	0.03	0.00	0.02	0.02	0.00	0.00	0.00	0.03	0.00	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.05
ZnO	0.14	0.11	0.05	0.04	0.04	0.00	0.03	0.05	0.01	0.02	0.07	0.11	0.07	0.09	0.09	0.04	0.08	0.01	0.06	0.04	0.12	0.02	0.05
NiO	0.14	0.18	0.17	0.22	0.16	0.21	0.16	0.17	0.21	0.18	0.16	0.21	0.17	0.17	0.19	0.18	0.21	0.13	0.19	0.23	0.17	0.18	0.19
Total	99.31	98.72	98.76	99.09	99.13	97.45	98.12	99.47	99.70	99.03	98.15	99.41	99.33	98.29	98.31	98.53	99.66	99.81	99.35	98.77	98.69	98.11	98.84
O	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00
Si	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00
Ti	0.05	0.05	0.03	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.04	0.03	0.04	0.02	0.04	0.02	0.03	0.04	0.03
Al	4.61	5.03	5.55	5.59	5.65	6.20	5.83	5.67	5.64	5.67	5.71	5.60	5.63	5.63	5.68	5.67	5.59	5.63	5.61	5.69	5.72	5.72	5.72
Cr	10.68	10.20	9.67	9.99	9.78	9.16	9.47	9.60	9.56	9.41	9.34	9.55	9.43	9.42	9.36	9.45	9.56	9.59	9.48	9.53	9.44	9.51	9.50
Fe ²⁺	3.22	3.01	2.86	3.28	3.05	2.51	2.54	2.45	2.44	2.39	2.35	2.40	2.40	2.36	2.38	2.37	2.39	2.41	2.33	2.38	2.39	2.40	2.37
Fe ³⁺	0.59	0.65	0.68	0.29	0.44	0.76	0.84	0.90	0.95	1.07	1.12	0.98	1.09	1.10	1.09	1.03	0.98	0.95	1.04	0.95	1.00	0.90	0.93
Mn	0.16	0.15	0.15	0.16	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	4.65	4.88	5.01	4.60	4.84	5.20	5.17	5.24	5.26	5.32	5.35	5.30	5.30	5.35	5.33	5.34	5.31	5.30	5.37	5.30	5.30	5.32	5.32
Ca	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Zn	0.03	0.02	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.00	0.01	0.01	0.02	0.00	0.01
Ni	0.03	0.04	0.03	0.04	0.03	0.04	0.03	0.03	0.04	0.04	0.03	0.04	0.03	0.03	0.04	0.04	0.04	0.02	0.04	0.05	0.03	0.04	0.04
Total	24.01	24.02	24.01	24.01	24.01	23.93	23.93	23.94	23.94	23.94	23.95	23.94	23.94	23.94	23.94	23.94	23.94	23.94	23.94	23.94	23.94	23.94	23.94
Cr/(Cr+Al)	0.70	0.67	0.64	0.64	0.63	0.60	0.62	0.63	0.63	0.62	0.62	0.63	0.63	0.63	0.62	0.63	0.63	0.63	0.63	0.63	0.62	0.62	0.62
Mg/(Mg+Fe)	0.59	0.62	0.64	0.58	0.61	0.67	0.67	0.68	0.68	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.70	0.69	0.69	0.69	0.69

tinental lithospheric mantle contains diffuse and thin sheets of amphibole-diorites, weakly deformed gabbros and pyroxenites, and late-stage T-MORB to continental dolerite dykes (Chazot *et al.* 2005). In the Zabargad island, although there is a considerable debate about the peridotites ages, i.e. whether Neoproterozoic or Miocene, or both (Snow & Schmidt 1999), basaltic dykes

cut mantle peridotites and continental gneisses. The geochemistry of the basaltic dykes is similar to basalts from the transition between distensive continental margins and ocean floor (Petrini *et al.* 1988).

A similar scenario is envisaged for the Santa Luz peridotite and associated mafic dykes, as well as for the regional gneisses intruded by mafic dykes and

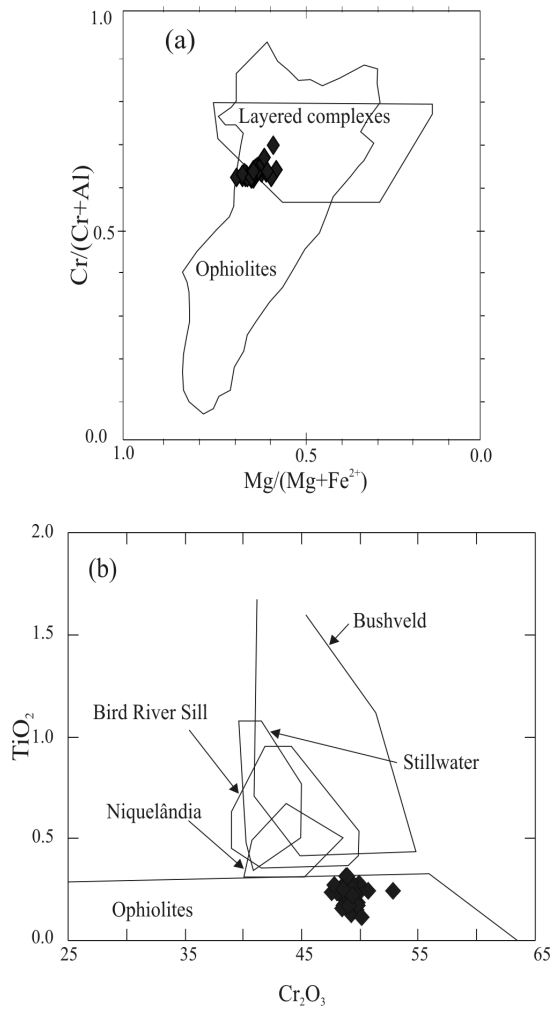


Figure 6 - Major element diagrammes for massive-type chromites of the Santa Luz peridotite complex. Data from this work and from Araújo (1998). Fields in (a) and (b) are respectively from Dick & Bullen (1984) and Suita & Strieder (1996).

Table 3 - Platinum group element data for massive chromites from the Santa Luz Peridotite Complex.

	Os (ppb)	Ir (ppb)	Ru (ppb)	Rh (ppb)	Pt (ppb)	Pd (ppb)
AM2-A	90	118	265	17	20	8
AM2-B	94	120	270	17	18	10
SLM04-2W	56	54	210	20	32	64
SLM04-4W	62	74	200	17	6	4

later deformed and metamorphosed. In a previous publication (Oliveira et al. 2005), we suggested that the mafic dykes associated to the banded gneisses and to

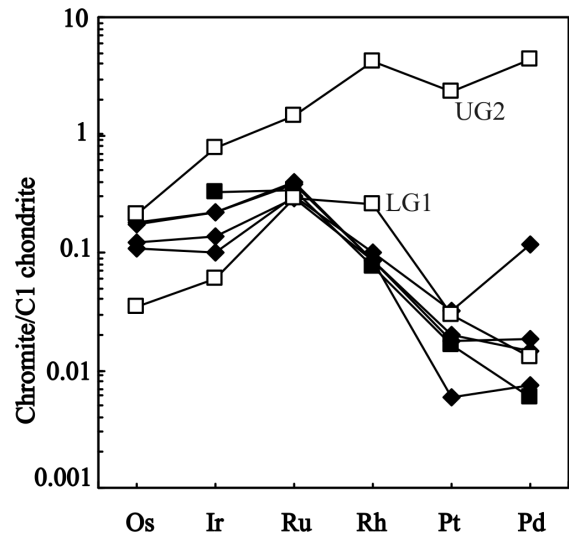


Figure 7 - Chondrite-normalized platinum group elements for massive-type chromites from the Santa Luz peridotite complex (diamonds) compared with chromites from ophiolite complex (filled square) and layered intrusion (Bushveld UG2 and LG1, open square). Data after Mathez & Peach (1989) and Von Gruenewaldt & Merkle (1995). Chondrite abundances after Naldrett & Duke (1980).

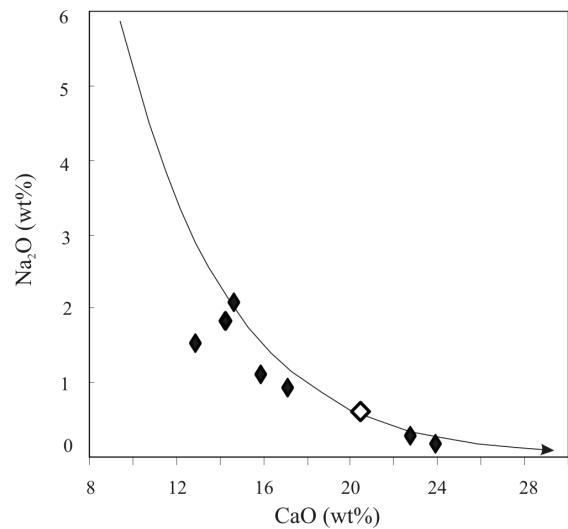


Figure 8 - CaO vs Na₂O plot for mafic rocks intrusive into the Santa Luz peridotites, illustrating the chemical changes during epidotization at dyke margin. Rodingite trend and average (open diamond) after Puga et al. (1999).

the peridotite complex could be much younger and unrelated to the peridotites. However, given the different amphibole type (brown) of the gneiss-associated amphibolite dykes and the high average abundances of SiO₂, TiO₂, P₂O₅ and low abundances of MgO, CaO and Cr of these dykes compared to similar dykes related to

Table 4 - Whole rock major and trace element data, and Sm-Nd isotope data of representative rocks from the Santa Luz Peridotite Complex. * rodingites after Puga et al. (1999); na - not analysed.

Sample	M1	M2	N	J	K	O	SLB101EB drill-core	average regional dykes	average rodingites*
Rock type	amphibolite dyke	amphibolite dyke	rodingite? (margin M2)	gabbro (margin J)	rodingite? (margin J)	serpentinite (close to M2)	rodingitic amphibolite	amphibolite n=16	n = 27
SiO ₂	46.42	41.98	45.88	47.09	45.42	43.42	45.21	49.53	39.62
TiO ₂	0.82	0.859	0.563	0.283	0.207	0.067	0.75	1.24	1.96
Al ₂ O ₃	13.9	15.36	13.22	16.16	12.78	1.63	14.10	14.78	14.56
Fe ₂ O ₃	10.57	11.9	7.57	7.94	6.89	7.35	9.94	13.68	10.75
MnO	0.246	0.209	0.313	0.14	0.227	0.069	0.22	0.2	0.21
MgO	9.69	9.87	7.9	10.09	8.23	21.41	8.98	6.7	8.88
CaO	14.27	15.85	22.73	14.62	23.92	6.96	17.13	10.91	20.85
Na ₂ O	1.84	1.13	0.27	2.09	0.17	0.05	0.91	2.46	0.81
K ₂ O	1.06	0.47	0.08	0.75	0.01	0.02	0.29	0.63	0.2
P ₂ O ₅	0.101	0.058	0.087	0.032	0.061	0.015	0.09	0.12	0.39
LOI	1.28	2.37	1.92	0.92	2.32	17.43	2.30	0.64	1.47
Total	100.2	100.1	100.5	100.1	100.2	98.4	99.98	100.89	99.7
Trace elements (in ppm)									
Ba	220	47	39	56	7.9	36	90	260	44
Ce	30	24.5	27.7	18.6	18	-	na	na	na
Cr	478	494	302	501	655	6050	425	158	228
Ga	16.6	19.6	16.8	15.1	13	4	na	na	na
La	<4	<4	<4	<4	<4	44	na	na	na
Nb	4.5	5.3	3.9	1.5	1.2	-	5	5	na
Nd	14	24	10	<8	10.9	-	na	na	na
Ni	131	186	79	87	61	1750	153	79	183
Pb	20.1	45	31	29.4	39	-	na	na	na
Rb	35	5.1	4.2	13.8	0.7	-	5	18	na
Sc	46	53	34	38	33	-	na	na	na
Sr	287	396	196	216	211	61	77	138	334
V	246	289	200	129	124	55	216	274	276
Y	27.6	28.9	21	15.4	18	-	20	24	32
Zn	66	70	30	51	64	32	78	99	na
Zr	79	78	61	21.1	19.4	-	76	75	161
Sm	2.912	2.161		12.448	1.026	0.024			
Nd	11.491	8.671		4.675	3.862	0.104			
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.1532	0.1506		0.161	0.1606	0.1409			
¹⁴³ Nd/ ¹⁴⁴ Nd	0.511772	0.511771		0.511592	0.511699	0.51167			
±	6	6		13	22	15			
E(0)	-16.89	-16.91		-20.4	-18.31	-18.88			
T _{DM} (Ga)	3.25	3.11		4.43	4.02	2.89			
Zr/Y	2.9	2.7	2.9	1.4	1.1		3.8	3.12	5.0
Zr/Nb	17.6	14.7	15.6	14.1	16.2		15.2	15	
Y/Nb	6.25	5.55	5.26	10.00	14.28		4.0	4.8	
Ti/V	20.0	17.8	16.9	13.2	10.0	7.3	21.0	10.8	42.6
Ti/Zr	62.2	66.0	55.3	80.4	64.0		59.8	99.1	73.0
Ti/Y	178.1	178.2	160.7	110.2	68.9		227.3	309.7	367.2

the Santa Luz peridotites (Table 4) we conclude that the two dyke sets may have distinct petrogenesis, although not necessarily too much different in age.

Melt impregnation and ocean-floor metasoma-

tism We interpret the occurrence in the Santa Luz peridotite complex of irregular amphibolite dykes and gabbroic lenses within fully serpentinized peridotites as basic melt percolation in mantle-like peridotites. A num-

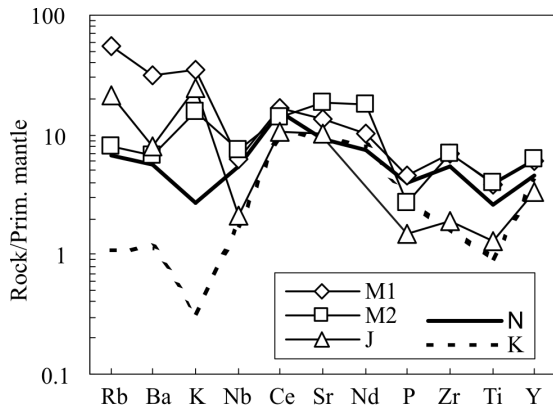


Figure 9 - Mantle-normalized multi-element patterns of mafic dykes intrusive into peridotites of the Santa Luz Peridotite Complex. Individual rock numbers as in Table 4. Normalizing values after Sun & McDonough (1989).

ber of ophiolite complexes worldwide presents these features (Spray 1982, Paixão & Nilson 2002, Schaltegger et al. 2002, Muntener & Piccardo 2003, Rampone et al. 2005). The epidote-rich margins in the intrusive mafic rocks apparently formed during serpentinization of the host peridotite by ocean-floor metasomatism, in a manner similar to rodingitization. The latter process is characterized by the occurrence of various hydrous Ca-Al silicates in veins, such as hydrogrossular, or as replacement products after plagioclase (Honorez & Kirst 1975).

Implications for the Rio Itapicuru greenstone belt The implications of our discovery for the regional evolution depend on the precise age dating of the Santa Luz peridotite complex and of basalts of the Rio Itapicuru greenstone belt. The timing of peridotite formation and mafic dyke intrusion is bracketed by the ages of an intrusive aplite (2084 ± 12 Ma) and the regional gneisses (2983 ± 8 Ma). Yet, the minimum age can be set at ca. 2110 Ma, i.e. the age of the Itareru Tonalite (Carvalho & Oliveira 2003), which is not cut by mafic dykes. On the other hand, basalts of the Rio Itapicuru greenstone belt yielded a Pb-Pb isochron at 2209 ± 60 Ma (Silva et al. 2001). Basalts from this greenstone belt are tholeiites of two types: one has geochemical affinities with T- to N-MORB (tholeiite I) and the other (tholeiite II) with continental tholeiites with a marked negative Nb anomaly (Fig. 10).

The latter type could be representative of basalts erupted during the early opening stage of an ocean basin, whereas the other group would be less evolved and has erupted as transitional to normal ocean-floor basalts. Interestingly, the Rio Itapicuru basalts crop out to the east of the Santa Luz peridotite complex (present day geographic coordinates), i.e. exactly where they should be found in the model of ocean-continent transition of a magma-poor rifted margin, oceanward of the rifted continental margin represented in part by the

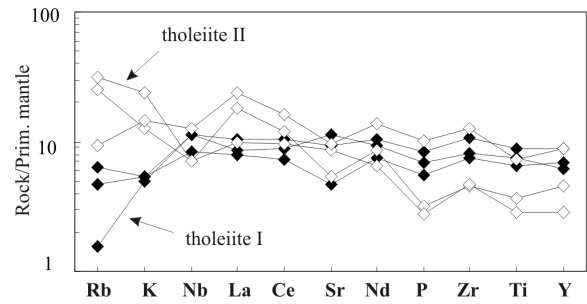


Figure 10 - Mantle-normalized multi-element patterns of basalts of the Rio Itapicuru greenstone belt. Data from Silva (1987). Normalizing values after Sun & McDonough (1989).

Santa Luz peridotites and associated mafic dykes. In this scenario, the regional banded gneisses (amphibolite dykes and Archaean gneisses) and the interleaved marble lenses, quartzite and metapelitic rocks (garnet-bearing paragneisses) would be part also of the rifted continental margin that later underwent deformation during the closure of the ancient Itapicuru ocean by continent-continent collision.

The model put forward here requires further improvements, especially on the precise age dating of mafic dykes of the Santa Luz peridotite complex and of those related to the regional Archaean gneisses, as well as metabasalts of the Rio Itapicuru greenstone belt, a study that is in progress. Nonetheless, this part of the São Francisco craton has an enormous potential to contain one of the world's oldest transitional-type ophiolite formed at a magma-poor rifted continental margin, the study of which and of the regional rocks may help understand the mode of formation of ancient passive margins, their evolution after tectonic inversion, the style of plate tectonics that was in operation in the Palaeoproterozoic time, and contribute to the debate of Palaeoproterozoic supercontinent assembly and breakup.

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