PETROLOGY OF THE BARRO VERMELHO Fe-Ti ORE BODY AND ITS METAMAFIC HOSTROCKS, CUSTÓDIA-PE, NORTHEAST BRAZIL.

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Resumo *PETROLOGIA DA OCORRÊNCIA DE Fe-Ti DE BARRO VERMELHO E SUAS METAMÁFICAS ENCAIXANTES, CUSTÓDIA-PE, NORDESTE DO BRASIL* A ocorrência de minério de Fe-Ti de Barro Vermelho está localizada a 12 a este da cidade de Custódia-PE e a 390 a oeste de Recife-PE, Nordeste do Brasil. A ocorrência é parte de um megaenclave inserido em ortognaisses de composição granítica a tonalítica, os quais constituem o embasamento do cinturão de dobramento proterozóico Pajeú-Paraíba na Província Borborema. Relações de campo, feições petrográficas, dados geoquímicos e datações U/Pb em zircões sugerem que os ortognaisses de composição granítica formaram-se a 2,1 Ga pela migmatização de tonalitos com idade de cristalização 2,44 Ga. Muitos enclaves (decimétricos a métricos, alguns hectométricos) metamorfisados e de composição petrográfica variada, destacando-se os de anortositos, gabros, gabronoritos, dioritos bandados a anfibolitos gabróicos, cálcio-silicáticas e trondhjemitos, estão aleatoriamente distribuídos nos ortognaisses. O minério de Fe-Ti ocorre na forma de um corpo tabular maciço com 0,8 m de espessura e um comprimento que varia entre 60 e 80 m, envolvido por gabro-anortositos, anfibolitos bandados e metatrondhjemitos que juntos formam um megaenclave hectométrico nos ortognaisses. Algumas apófises do minério, formado essencialmente por magnetita martitizada e ilmenita, intersectam as rochas máficas encaixantes. O anfibolito bandado em torno do minério é idêntico aos que ocorrem como diques e enclaves sin-plutônicos nos ortognaisses tonalíticos, enquanto que os gabro-anortositos são similares àqueles encontrados como xenólitos nos ortognaisses. Feições petrográficas, diagramas de variação e padrões de distribuição de elementos traços e de terras raras sugerem fortemente que os gabro-anortositos, gabronoritos e trondhjemitos são produtos da diferenciação de um magma toleiítico de afinidade oceânica ou originado pela fusão de uma fatia crustal composta de toleiítos de arco vulcânico. Os metagabronoritos parecem representar os magmas mais primitivos a partir dos quais os anortositos teriam se formado por cristalização fracionada do plagioclásio enquanto que os protólitos dos anfibolitos teriam cristalizado a partir da fusão residual. O minério representaria a fração residual mais evoluída da suíte.

Palavras-chave: Minério de Fe-Ti, anortositos, enclaves, ortognaisses, Barro Vermelho, Nordeste do Brasil.

Abstract The Barro Vermelho Fe-Ti ore body is located 12 km east of the town of Custódia and 320 km west of the city of Recife in the State of Pernambuco (PE), Northeast Brazil. It is part of many enclave entrained within granitic to tonalitic orthogneisses that constitute the basement of the Proterozoic Pajeú-Paraíba foldbelt in the Borborema Province. The field relationships, petrographic features, geochemistry and U/Pb data on zircons suggest that the gneisses of granitic composition formed at 2.01 Ga by migmatization of the 2.44 Ga old tonalites. Many decimetric to metric and a few hectometric metamorphosed enclaves of anorthosite, gabbro to gabbronorite, banded diorite to gabbroic amphibolites, calc-silicate rocks and trondhjemites are randomly distributed within the orthogneisses. The Fe-Ti ore body occurs as an almost concordant tabular massive unit, 0.8 m thick and 60 m to 80 m long, enclosed in gabbro-anorthosite, banded amphibolite and trondhjemite that together form a hectometric mega-enclave within the orthogneisses. Some apophysis of the ore body, formed by martitized magnetite and illmenite, crosscut the mafic wallrock. The banded amphibolite enclosing the ore body are identical to those found as synplutonic dykes and enclaves in the tonalitic orthogneisses, while the gabbro-anorthosite are similar to those found as xenoliths in the orthogneisses. Petrographic features, variation diagrams, and trace element and REE distribution patterns strongly suggest that the gabbro-anorthosites, gabbronorites, trondhjemites, and banded amphibolites as enclaves are differentiation products of a tholeiitic magma of oceanic affinity or originated by the melting of a crustal slab composed of volcanic arc tholeiites. The metagabbronorites appear to represent the most primitive magma from which the anorthosites are interpreted to have formed by fractional crystallization of plagioclase while the protholiths of amphibolites may have crystallized from the residual melt. The ore body may represent the most evolved melt of this suite.

Keywords: Fe-Ti ore, anorthosites, gabbros, enclaves, orthogneisses, Barro Vermelho, NE- Brazil

INTRODUCTION The Barro Vermelho Fe-Ti ore body is located 320 km west of Recife and 12 km east of the town of Custódia, in the State of Pernambuco (PE), Northeast Brazil. It occurs within the Pajeú Paraíba foldbelt of the Borborema Tectonic Province as defined by Brito Neves (1983), and, according to Santos (1995, 1996), it is hosted in the Paleoproterozoic basement of the Alto Moxotó Terrain of the Transversal Domain of the Borborema Province. The Barro Vermelho ore body together with the Riacho da Posse Fe-Ti ore deposit (near Floresta, 120 km southwest of Barro Vermelho) and the Itatuba Fe-Ti deposits (200 km to the northeast) are aligned along the same regional structural trend following a positive gravimetric anomaly (Rand & Manso 1990, Fig. 1). This trend extends for more than 400 km from the town of Floresta (PE) to the town of Lucena at the coast of the State of Paraíba (PB) and possibly corresponds to a continental suture (Beurlen *et al.* 1992).

Santos (1977, 1995) described the Barro Vermelho ore deposit as part of a stratiform gabbro-anorthositic complex, interpreted as belonging to an intraplate tholeiitic suite identified by this author in the area of Floresta-PE as the Malhada Vermelha Suite. Santos (1995) referred this suite as a series of small tabular intrusions or tectonic slices of mafic-ultramafic rocks in the orthogneisses from

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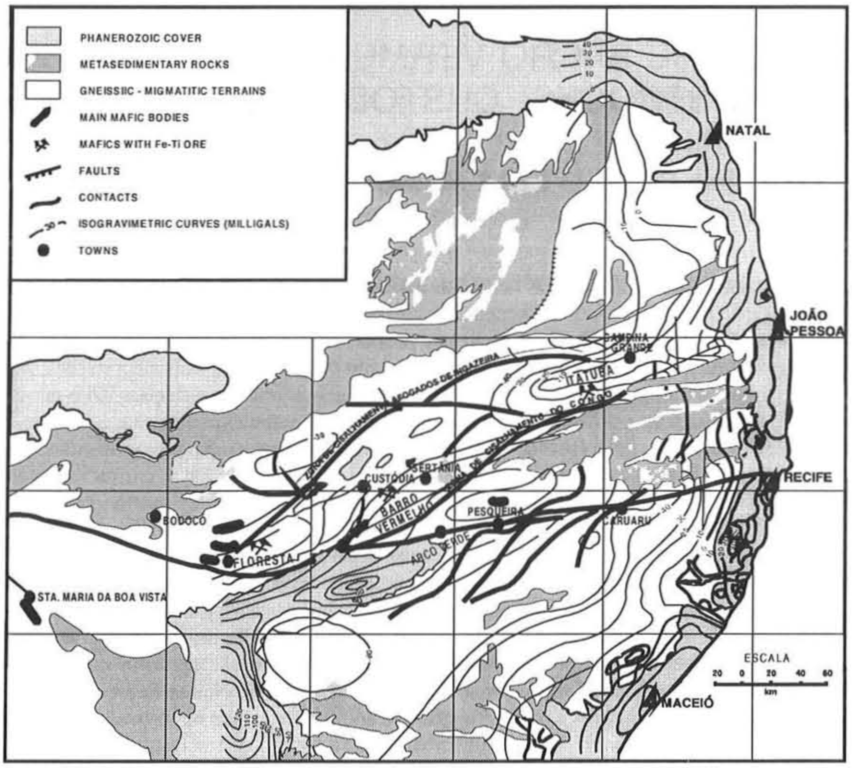

Figure 1 – Regional geologic-gravimetric map that shows the location of Barro Vermelho, Floresta and Itatuba ore occurrences. Modified after Brito Neves (1983) and Rand & Manso (1990).

the Paleoproterozoic Floresta Complex, which he interpreted to represent early tectonic magmatism associated with a Mesoproterozoic "accretionary/contractional event". According to Santos (1995), the Malhada Vermelha Suite includes quartz diorites, diorites, anorthosites, gabbros, amphibolites, hornblendites, calc-silicate rocks and actinolitites. The same rock types are found at Barro Vermelho, but usually as small enclaves within the basement orthogneisses rather than forming well-defined mafic bodies. Also, ultramafic rocks associated with the Fe-Ti ore body at Floresta are not observed near Barro Vermelho.

GEOLOGY OF THE BARRO VERMELHO AREA Detailed geologic mapping of an area of approximately 50 km^2 surrounding the Barro Vermelho Fe-Ti ore deposit allowed to distinguish two lithological domains: 1) a domain of orthogneisses containing mafic enclaves and the Fe-Ti ore in the south and 2) a domain of supracrustal rocks including garnet-cordierite-sillimanite-biotite schists and gneisses, migmatites and anatectic granites, amphibolites and calc-silicate rocks in the north (Fig. 2). The supracrustal rocks belong to the Cabrobó Complex, of assumed Mesoproterozoic age (Santos 1995). The E-W striking contact with the northern orthogneissic domain is parallel to the main foliation of both domains and is mostly covered by regolith. Because the main focus of this work is related to the Fe-Ti ore body and surrounding mafic rocks, a description of supracrustal domain will not be presented in detail.

The enclave-bearing orthogneisses The domain of orthogneisses is composed mainly of leucocratic gneisses of granitic, monzogranitic, granodioritic, quartzdioritic to tonalitic composition, with variable amounts of mafic enclaves. The variations in the bulk compositions of banded leucocratic gneisses are due to the variable ratio between bands of granitic and tonalitic composition, respectively, in the same outcrop, and to the commonly gradational or diffuse contacts between these bands. Where transitional contacts between the bands occur, K-feldspar replaces the plagioclase in the tonalitic gneisses. In the less common cases, however, where the contacts are sharp, the granitic bands clearly crosscut a previous compositional banding of the tonalitic gneisses formed by alternating bands of leucotonalitic to trondhjemitic composition with mafic laminae rich in amphibole and biotite (Fig. 3). All these features suggest migmatization, with the tonalites representing the melanosome and the granites the leucosome. The pure granitic bands have augen texture with microcline megacrysts (1 to 4 cm) in a medium-grained groundmass of quartz, microcline, plagioclase and biotite.

U/Pb data on zircons indicate crystallization ages of 2.44 Ga for the tonalitic melanosome and 2.01 Ga for the granitic leucosome (Melo 1998, Melo *et al.* 2002). These results are consistent with the relative age differences indicated by field relationships and a correlation with the Floresta Complex, as suggested by Santos (1995).

Enclaves of metamafic rocks in the orthogneisses vary in size from a few decimeters (most common) to several meters, but in two cases reach up to a few hundred meters in extension. Based on their shapes, fabrics, composition and field relationships with the tonalitic orthogneisses, the enclaves were classified into five types: 1) rounded to angular gabbro-anorthositic xenoliths; 2) tabular, lenticular to elipsoidal amphibolitic synplutonic enclaves mostly formed by fragmentation of dioritic to gabbroic dykes; 3)

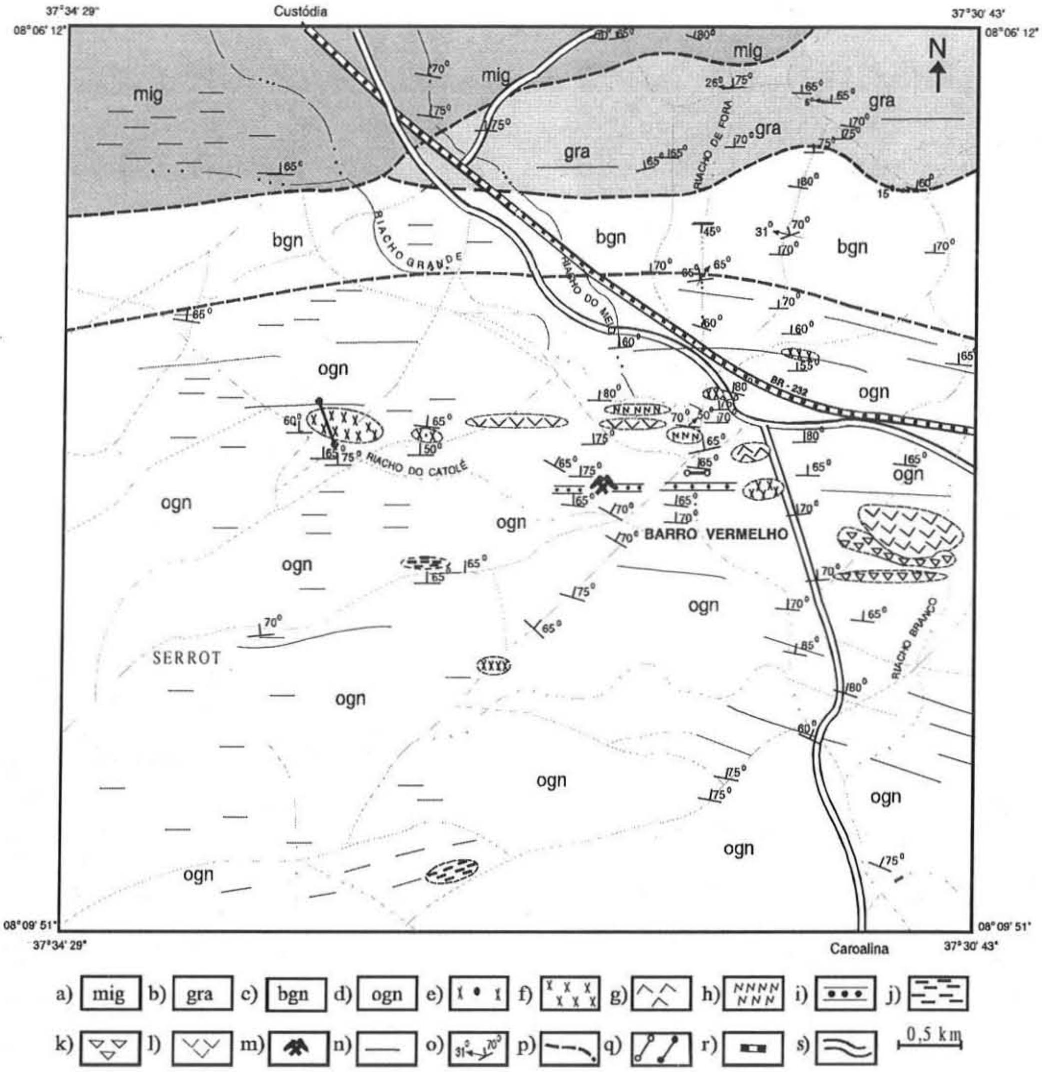

Figure 2 – Simplified geological map around Fe-Ti occurrence of Barro Vermelho, modified from Melo (1998). Supracrustal domain: a) migmatites; b) anatetic granites; c) biotite gneisses. Orthogneisse domain: d) orthogneisses; e) anorthosites; f) leucogabbros; g) gabbros; h) gabbronorites; i) trondhjemites; j) banded amphibolites; k) calc-silicate rocks; l) olivine diabase to troctolite; m) Fe-Ti ore. Other simbols: n) foliation; o) strike and dip of banding with stretch lineation; p) infered geological contact; q) dykes of deformed anorthosite and gabroic rock; r) and s) roads. Obs.: The size of the mafic bodies is out of scale and about 1.5 larger than that showed by the grafic scale.

metagabbronorite enclaves; 4) calc-silicatic rocks and other xenoliths of mafic composition; and) syn- late- and post-migmatitization enclaves and dykes of dioritic to monzogranitic and aplitic compositions, apart from pegmatitic veins. In addition to the mentioned mafic rocks, post-tectonic dykes of olivine gabbro to troctolite are also locally present.

The enclaves are commonly composed of one homogeneous lithologic type, with only slight variations in texture or composition. Usually no direct field relationships between the rock types of the different mafic enclaves can be observed. As detailed in the next section, direct field relationships between the enclaves of type 1, 2 and 3 were observed only in one mega-enclave that also includes the Fe-Ti mineralization.

Gabbro-anorthosite xenoliths exhibit a medium- to coarse-grained flaser texture. Plagioclase (An~50) occurs as lenticular aggregates 1 to 5 cm across, alternating with elongated fine layers of amphibole and clinopyroxene. Slightly variable proportions between fine mafic layers and plagioclase aggregates are interpreted to be the result of the recrystallization of former megacrysts and are responsible for compositional variations observed in different enclaves, from anorthositic to gabbroic/dioritic phases. As this banding is parallel to the main foliation, it is interpreted as a metamorphic rather than igneous banding. Small amounts of garnet may occur at the contact of the plagioclase aggregates and the fine mafic layers. In some cases, where a primary isotropic texture is preserved, the cumulate texture of the plagioclase megacrysts and the *intercumulus* nature of the mafic minerals are evident. Some of these enclaves display an internal foliation that is usually oblique to the external foliation of the gneisses (Fig. 4), indicating that the already solid and deformed anorthosite was disrupted and rotated during the deformation of the tonalitic gneisses.

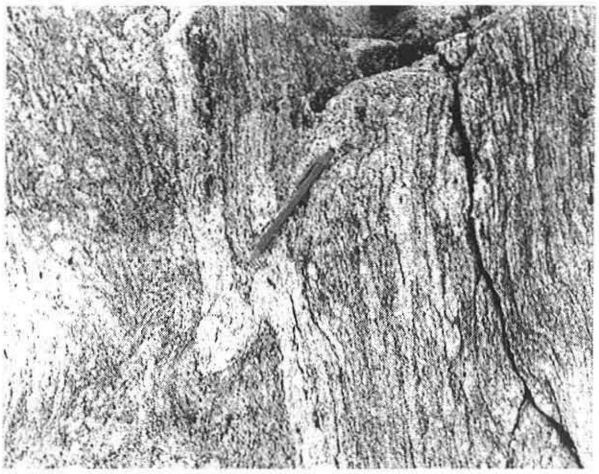

Figure 3 – Bands of granitic (white) and tonalitic (grey) composition in gradational diffuse contacts.

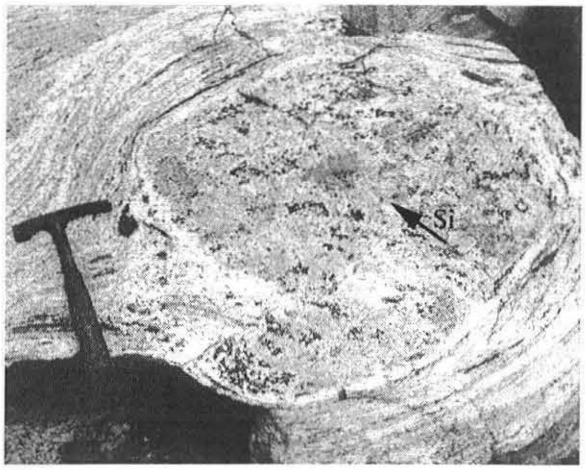

Figure 4 – A decimetric xenolith of leucodiorite showing internal foliation (Si) truncated by the external foliation of the host tonalitic orthogneisse.

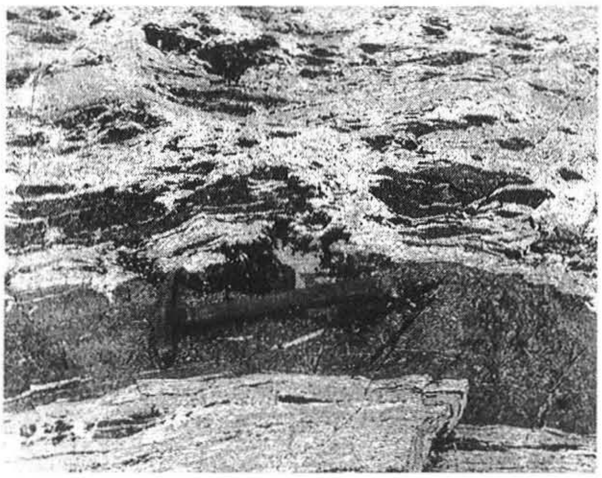

Figure 5 – Amphibolitic synplutonic enclaves mostly formed by fragmentation of dykes.

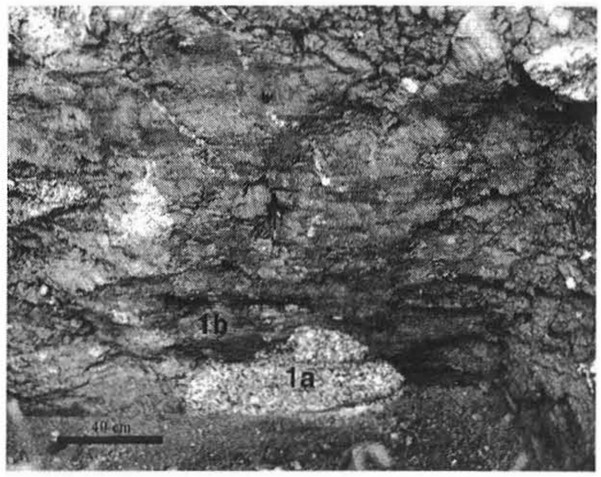

Figure 6 – Trench 4. Rounded leucogabbroic autholith (1a) in contact with comagmatic diorite (1b).

Synplutonic enclaves are fine- to medium-grained amphibolites of dioritic to gabbroic bulk composition (Fig.5). A compositional banding is commonly observed, sometimes including thin bands of trondhjemitic composition. Lobate contacts with the enclosing tonalitic gneisses are also common. The trondhjemitic bands in the synplutonic enclaves are distinguished from similar bands in the tonalitic orthogneisses due to small amounts of orthopyroxene in the latter.

Metagabbronorite enclaves always display a homogeneous composition and texture. Two elongated and slightly foliated decimetric enclaves of these rocks occur extending parallel to the foliation of the enclosing tonalitic gneisses. Their texture indicates a simultaneous crystallization of plagioclase, orthopyroxene and clinopyroxene, with both pyroxenes being often replaced by amphibole at their rims.

The Fe-Ti ore body The Fe-Ti ore body occurs as eluvial blocks of massive ore along the southern slope of an oval-shaped E-W subtle topographic high extending approximately 600 x 800 meters. Fragments of trondhjemite, leucogabbro, orthogneisse and aplite are also locally present with orthogneisses outcrops found all around the base of this topographic high. Direct field observations of the contact between the ore and its wall rocks could only be seen in four trenches cut through the Fe-Ti ore body. A detailed magnetometric survey was also carried out to check the size and structural relationships between the ore body, the mafic wall-rocks and the surrounding orthogneisses. Based on this survey it became clear that the ore constitutes a part of a single enclave extending over 100 m parallel to the banding and foliation of the orthogneisses. The four trenches allowed to establish the field (and age) relationships between the ore, the mafic wall-rocks and orthogneisses as follows: a) the coarse-grained gabbro-anorthosites usually found as xenoliths are now observed as rounded autholiths in the banded amphibolites of dioritic to trondhjemitic composition (Fig. 6); b) trondhjemitic bands form pinch and swell fabrics with the banded amphibolites, sometimes

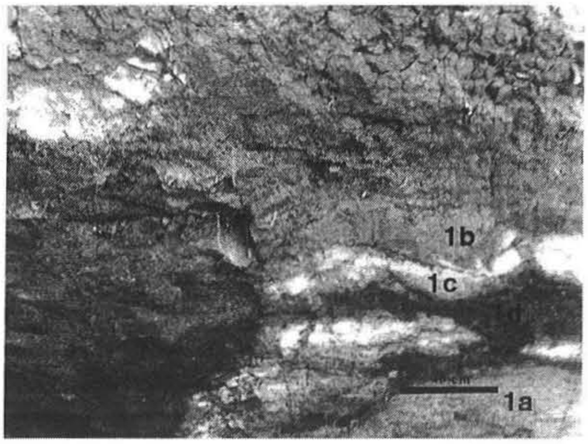

Figure 7 – Trench 2. Vained apophysis of banded Fe-Ti ore (1d) cutting comagmatic leucogabbro (1a), diorite (1b) and trondhjemite (1c) suggesting that the ore represents the most evolved melt of the suite.

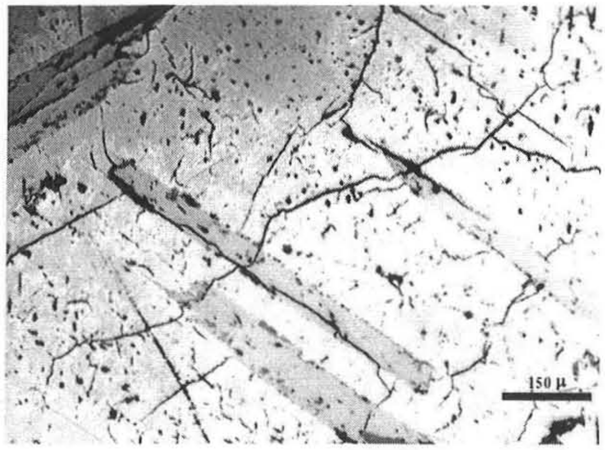

Figure 8 – Polished section of the Fe-Ti ore showing martitized magnetite with ilmenite exsolution lamellae with tiny blebs of spinel at the edge.

with lobate contacts (Fig.7); c) the trondhjemitic and amphibolitic bands are truncated by apophysis of the banded magnetite-illmenite ore (Fig.7, also); d) the granitic augen gneisses form apophysis crosscutting all mafic rocks, and e) all these rocks are cut by subvertical aplite dykes.

Ore petrography The Barro Vermelho Fe-Ti ore body consists of an aggregate of "spongy" textured magnetite (72-76%) and illmenite (14-17%), having less than 10% pore space due to leached silicates and clays. Magnetite occurs as subhedral to polygonal, 1 to 3 mm size grains. The grains usually are almost completely martitized, but large illmenite "oxidation-exsolution" (Buddington & Lindsley 1964) lamellae with 70x400 micron oriented along the octahedron are still recognizable (Fig.8). In the non-martitized parts, tiny blebs of spinel border these illmenite "exsolution" lamellae. A second phase of martitized magnetite also occurs, as lamellae included along the illmenite pinacoid (reduction exsolutions; Haggerty 1981). The illmenite grains are always interstitial to the magnetite grains. At the contact with the polygonal magnetite grains a 20-micron coat with 1 to 5 micron blebs of spinel exsolutions ocurrs. Illmenite also shows a "pseudo" cleavage after 0001 filled by discoidal exsolutions of spinel or corrundum. Oblique and parallel to this direction, narrow (~2.5 micron) exsolution lamellae of hematite are observed. The partially preserved silicates include amphibole, garnet, plagioclase, biotite and apatite.

The calculated reserves of Ti within the Barro Vermelho ore body is about 30,000 tons. The relatively small size of this deposit and the presence of fine hematite exsolution lamellae in the interstitial illmenite prevent this ore body from being economically attractive.

GEOCHEMISTRY Analytical methods Major, trace and rare element chemical analyses were performed in the ACT/ACME labs in Canada, on 24 samples of mafic enclaves and 10 samples of the granitic-tonalitic host gneisses. The INAA technique was applied to REE, Cr, Hf, Rb, Th, U determinations and ICP to major and other trace elements. The mafic enclaves analyzed included 7 samples of gabbro-anorthositic xenoliths, 6 samples of synplutonic enclaves, 4 samples of metagabbronorite enclaves, and 3 ore samples. The accuracy of the results was monitored by including two samples of USGS standards (AGV-1 andesite and RGM-1 rhyolite) in the sample set. In addition, two of the Barro Vermelho samples were included in duplicate. For most elements the analytical errors are below ± 5% in comparision with the standard values (Govindaraju 1984) and with repeated samples. For Th, Cr, Zr, Nb, Nd, Lu larger deviations were obtained, always between 15 to 25% below the standard values. This error is acceptable if the displacement of the elements in geochemical diagrams is not significant.

The mobility of major elements in the mafic rocks during metamorphism, migmatization or some eventual hydrothermal alteration was tested by using molecular proportion diagrams as suggested by Pearce (1968, 1970), but normalized to TiO_2, P_2O_5, and V. The Zr usually used for this purpose was avoided because of the accuracy errors near ± 5%, as mentioned. According to this approach, Al, Ca and Na are the most reliable major elements (less mobilized) for petrological interpretation of the Barro Vermelho sample set. Fe and Mg were moderately mobilized while K and Si were intensively remobilized. This result is consistent with the observed migmatization of the rocks in this area.

Lithogeochemical Data Variation diagrams and the molecular proportion diagrams allowed to distinguish two groups of mafic rocks. The first, composed of gabbro-anorthositic xenoliths samples and the second of synplutonic and metagabbronorite enclaves samples. Distinct linear trends resulted for these two groups in those variation diagrams in which the less mobilized elements (Al, Ca, Ti, Fe, Mg) are used, as shown in figure 9. Calc-silicate and other mafic rocks have been omitted because they never conform to the trends. In the diagrams the gabbro-anorthosites xenoliths display a positive correlation for Ti/Fe, Ti/Mg and Mg/Fe (Figs. 9B, D and F) and a negative correlation for Ti/Al, Ti/Ca and Mg/Al (Figs. 9A, C and E). These correlations are explained as the result of mixing in different proportions of the plagioclase *cumulus* and mafic minerals *intercumulus* rather than by igneous differentiation trends. The group of synplutonic enclaves together with metagabbronorites presents positive Mg/Al (Fig. 9E) and negative Ti/Ca and Mg/Fe correlations (Figs. 9C

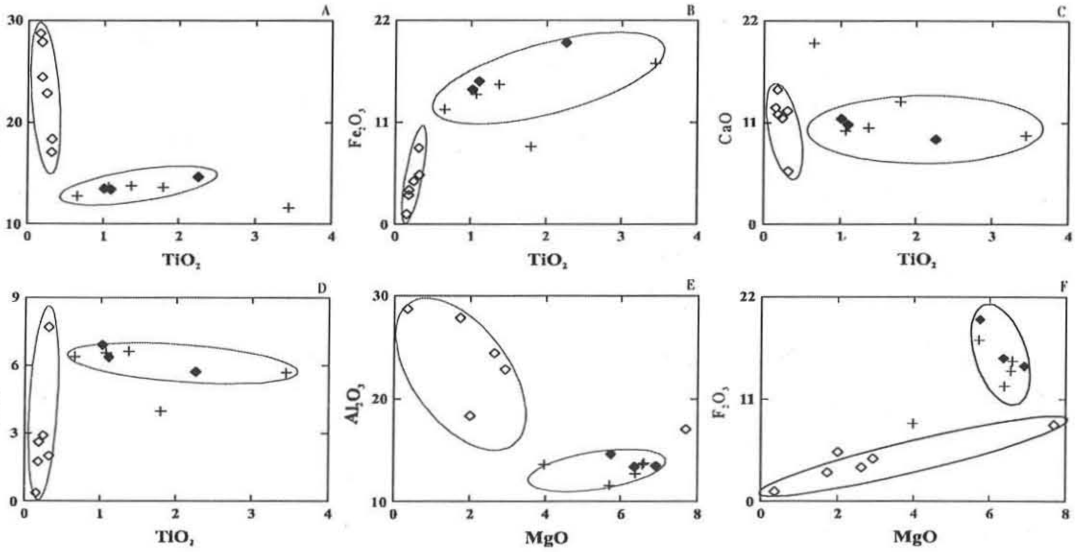

Figure 9 – Variation diagrams for TiO2 and MgO versus major element oxides (weigh percent) . Note the presence of two distinct clusters of samples, one built up by xenoliths and the other by synplutonic enclaves plus metagabbronorites. The xenolith richer in MgO (7.68%) is a metaggabro (strito sensu) and thus it plots close to the samples of synplutonic enclaves in all diagrams. Simbols as in figure 10 for Barro Vermelho, except for ore.

and F), trends that are in opposition to those observed in the gabbro-anorthositic xenoliths. Simultaneous plagioclase and clinopyroxene fractionation from a single parental magma source could explain these trends. The fractionation of plagioclase would imply in loss of Ca and Al in the residual melt, from which the plagioclase could separate by flotation forming the anorthosites in the upper part of the magma chamber; the fractionation of clinopyroxene would reduce the Ca and Mg contents in the melt, with the pyroxene crystals settling in the basal part of the magma chamber to form ultramafic layers.

The chondrite normalized rare earth element (REE) diagram for the Barro Vermelho rocks (Fig. 10) shows that samples of gabbro-anorthositic xenoliths and synplutonic enclaves have patterns approximately parallel to each other, but with opposite Eu anomalies. Synplutonic enclaves are enriched in REE by a factor approximately 5 times than gabbro-anorthositic xenoliths, and the synplutonic enclaves display negative Eu anomalies while the gabbro-anortositic xenoliths show positive anomalies. The total amount of REE increases and the intensity of the positive Eu anomaly decreases with the percentage of interstitial mafic minerals in different samples of gabbro-anorthositic xenoliths. These patterns are very similar to those of massive anorthosite complexes such as the Laramie Range (Goldberg 1984) shown in figure 10. In addition to the geochemical data, the cogenetic nature of the synplutonic enclaves and gabbro-anorthositic xenoliths is also clearly indicated by their field relationships. The REE contents of ore samples from Barro Vermelho also show a distribution parallel to gabbro-anothositic xenoliths and synplutonic enclaves. Contrasting with the strong enrichment observed in Laramie Range ores, at Barro Vermelho the REE contents are depleted as compared to gabbro-anothositic xenoliths. This depletion could be the result of weathering of the Barro Vermelho ore samples, in which the greatest part of silicates and apatite were leached out. The metagabbronorite enclaves have a nearly horizontal REE distribution, absence of Eu anomaly and an intermediate position between the two previous mentioned groups, suggesting that metagabronorites may represent the original (or more primitive) magma of the suite, from which anorthositic rocks fractionated by flotation. The remaining magma may have later produced the synplutonic enclaves while the Fe-Ti ore would represent the most evolved, residual melt of the same suite, similar to the nelsonites of the massive anorthosite

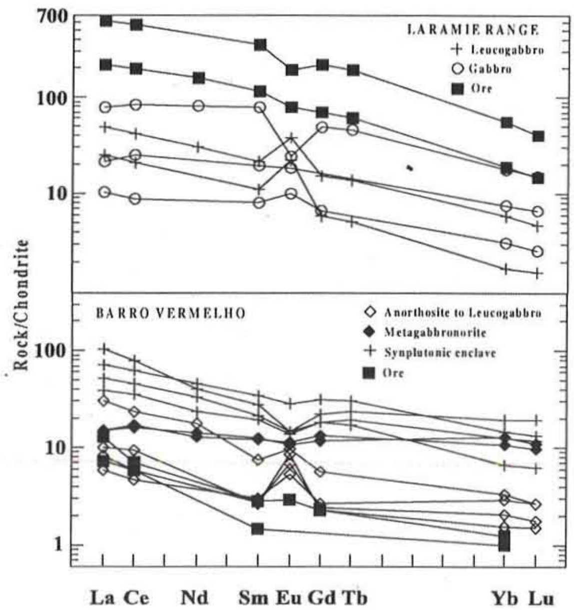

Figura 10 – Chondrite-normalized REE patterns of comagmatic ore, leucogabbros and gabbros of Laramie Range massive complex (Goldenberg, 1984) and of comagmatic similar lithotypes of Barro Vermelho. Normalization factors from Nakamura (1977).

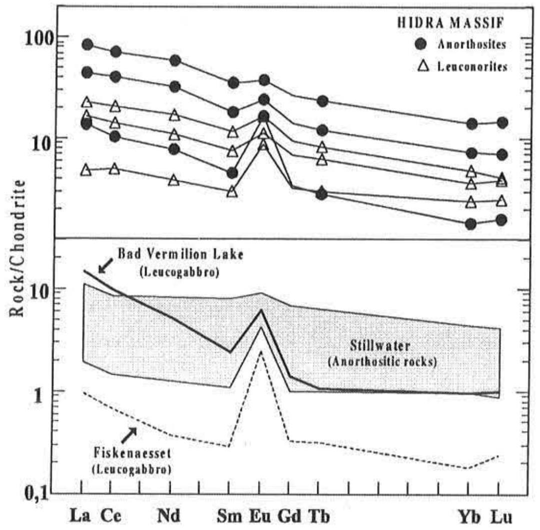

Figure 11 – Chondrite-normalized REE patterns for rocks of Hidra Massif (Demaiffe & Hertogen., 1981), Stillwater (Salpas et al., 1983), Bad Vermilion Lake and Fiskenaesset (Ashwal, 1993). Normalization factors from Nakamura (1977).

complexes or like jotunite and ferronorite ore dykes of Rogaland in Norway (Duchesne 1999).

An opposing patterns observed between gabbro-anorthositic xenoliths and synplutonic enclaves samples is also seen in the chondrite normalized spidergram of figure 12, for Ba, Th, Ta, Sr, P, Zr and Ti (in addition to the REE): depletion of Ta, La, Ce, Nd, P, Zr, Ti and Y and enrichment in K and Sr in gabbro-anorthositic xenoliths and strong enrichment of Ba, Rb, Th, Ta, La, Ce, Nd, P, Sm, Zr, Hf, Y and depletion in K, Sr, and Ti in synplutonic enclaves. Again the metagabbronorite samples lie between the other two groups. The metagabbronorite pattern in a MORB normalized spidergram (Pearce 1982), fits well the pattern of Volcanic Arc Tholeiitic Basalts distinguished from other basalts by lower Cr, Zr, Nb, Sr, Ba and K values (Fig.13). The same oceanic and tholeiitic affinity of the metagabbronorite enclaves is observed in the diagrams $Ti/KO_2/P_2O_5$ (Fig. 14) and $FeOt/MgO/Na_2O+K_2O$ (Fig. 15). The metagabbronorite samples were selected for the interpretation of these diagrams because they are interpreted to be the best representatives of the most primitive magma of the Barro Vermelho mafic suite.

Sm/Nd isotopic analyses were performed on both the mafic enclaves and the surrounding host gneisses. $T_{(DM)}$ model ages for the mafic enclaves show a range between 2.3 and 3.1 Ga (Table 1, Fig. 16). Such a large variation in model ages does not have any bearing on the postulated cogenetic formation of the gabbro-anorthositic xenoliths, synplutonic enclaves and metagabbronorite enclaves. Rather, the range can be attributed to the variations in the Sm/Nd ratios (which influence calculated $T_{(DM)}$ model ages) in the different rocks. These variations are commonly due to different abundances of mafic mineral phases (and garnet) that are preferentially enriched in Sm relative to felsic mineral phases. Although metamorphism can disturb Sm/Nd ratios, it is not common on a whole rock scale. Because the equation for $T_{(DM)}$ model ages was developed to help understand the evolution of *felsic crust*, data from mafic rocks must be interpreted carefully. Rocks with

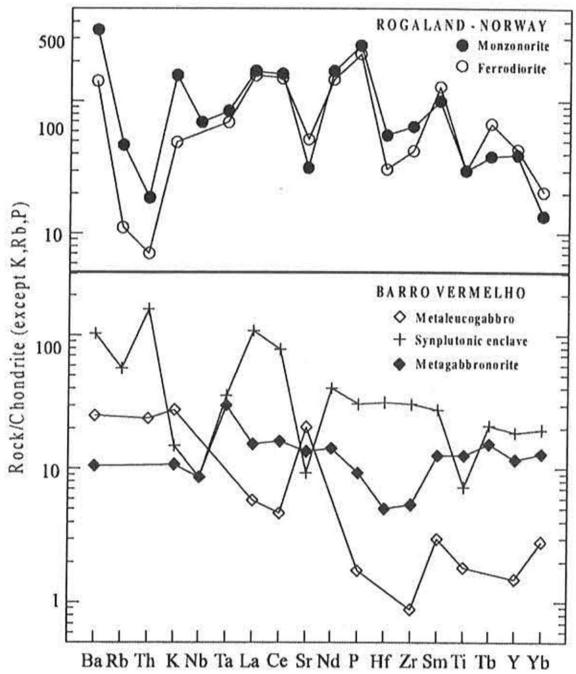

Figure 12 – Chondrite-normalized trace element variation diagram for rocks of Rogaland-Norway (Duchesne et al., 1989) and for typical xenolith, synplutonic enclave and metagabbronorite of Barro Vermelho. Normalization factors from Thompson et al. (1984).

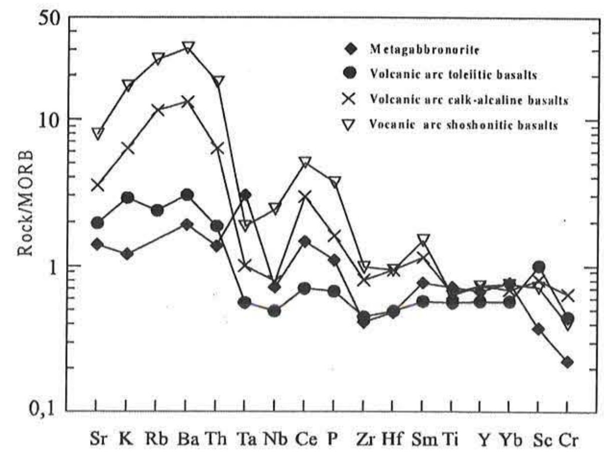

Figure 13 – MORB-normalized REE patterns for metagabbronorite of Barro Vermelho and island arc basalts. Note that the pattern for metagabbronorite (average of two samples) is similar to that showed by volcanic arc tholeiitic basalts. Values after Pearce (1982), including the normalization factors.

high Sm/Nd ratios ($^{147}Sm/^{144}Nd > 0.12$) yield anomalously high $T_{(DM)}$ model ages that should be ignored. As such, only samples OM-164A and OM-153B yield meaningful $T_{(DM)}$ model ages, 2.30 and 2.73 Ga, respectively. These data suggest that some older Archean crustal material was incorporated during the genesis of the 2.44 Ga tonalitic gneisses, while the mafic enclaves appear to

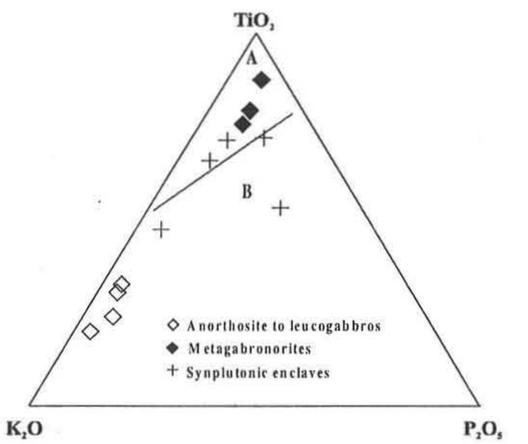

Figure 14 – Tectonomagmatic diagram after Pearce et al.(1975) that discriminates between oceanic basalts (field A) and continental basalts (field B). Note that the metagabbronorites, whose protholiths better represent the original magma of the mafic suite in terms of composition, fall in the field A.

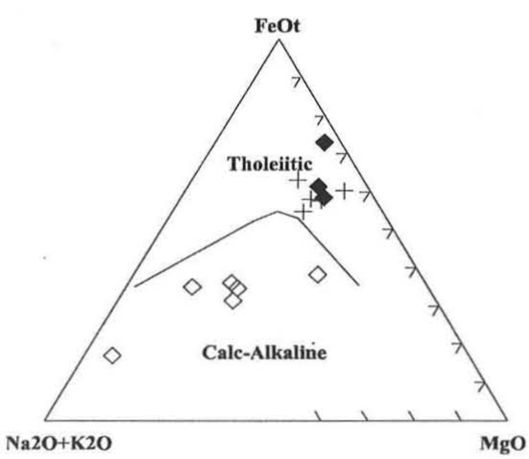

Figure 15 – AFM diagram, curve of Irvine & Baragar, (1971) for lithotypes of Barro Vermelho. Note that the metagabbronorites fall in the tholeiitic field. Symbols as in figura 14.

have been derived from a Paleoproterozoic source.

DISCUSSION During the detailed geologic mapping in the area surrounding the Barro Vermelho Fe-Ti body it was not possible to detect a well defined layered mafic complex or body related to the ore, as expected from information in the literature. As a matter of fact, only a large number of mafic enclaves with random distribution in a complex of granitized/migmatitized tonalitic gneisses were observed. Few enclaves reach sizes in the order of two or three hundred meters in length while the great majority ranges between a few decimeters to two or three decameters. Five types of enclaves formed by different mafic rocks were distinguished. Most of the

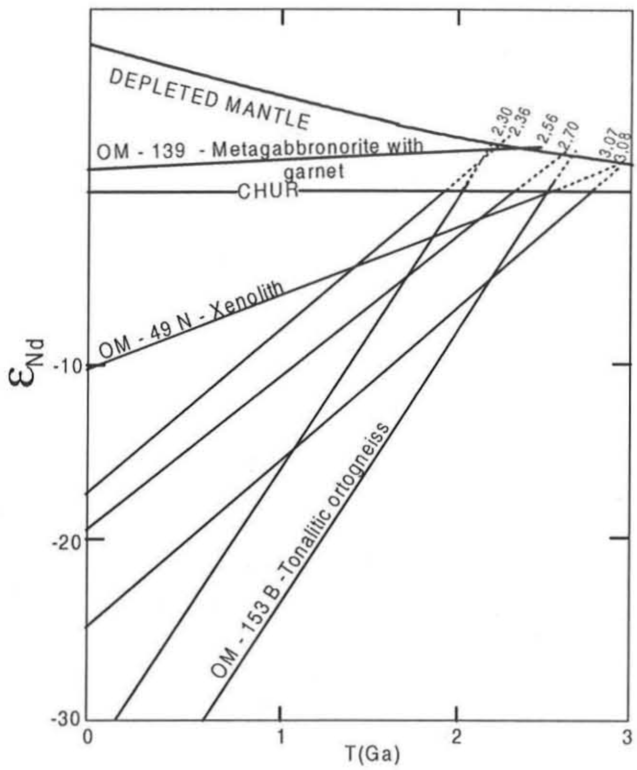

Figure 16 – Model ages (Sm/Nd - T_{DM}) of some lithotypes of Barro Vermelho. See numeric date in table 1 and comments in the text.

Table 1 – Isotopic date (Sm-Nd) and model ages for some lithotypes of Barro Vermelho.

Sample	Nd ppm	Sm ppm	^{147}Sm / ^{144}Nd	^{143}Nd / ^{144}Nd ± 2 σ	Epsilon Nd (today)	Epsilon Nd (600 Ma)	Epsilon Nd (1.000 Ma)	$T_{(DM)}$ Ga
OM - 49 N (Xenolith)	3,66	1,01	0,16714	0,512126 ± 9	- 10,0	- 7,7	- 6,2	3,08
OM - 164 A (Xenolith)	13,93	1,74	0,07560	0,510967 ± 11	- 32,6	- 23,3	- 17,1	2,30
OM - 139 Meta-gabbronorite with garnet	12,51	4,01	0,19371	0,512714 ± 12	1,5	1,7	- 1,9	2,56
OM - 46 A Synplutonic enclave	18,38	4,07	0,13407	0,511646 ± 8	- 19,4	- 14,6	- 11,4	2,70
OM - 153 B Tonalitic ortogneisse	12,37	1,50	0,07307	0,510544 ± 17	- 40,9	- 31,4	- 25,1	2,73
OM - 63 D (Calc-silicate)	27,71	5,94	0,12969	0,511374 ± 8	- 24,7	- 19,5	- 16,1	3,07
OM - 38 D (Troctolite)	14,42	3,11	0,13022	0,511755 ± 9	- 17,2	- 12,1	- 8,7	2,36

enclaves are composed of one single rock type, with only slight compositional or textural variations. One hectometric enclave includes the Fe-Ti ore and is the only where various rock types occur together. Four trenches cut through this enclave allowed to observe the common field relationships between gabbro-anorthositic xenoliths, synplutonic enclaves, ore, granitic gneisses and later dykes. Field relationships with the other types of mafic enclaves unfortunately were not observed. This situation required to resort to lithogeochemistry to try to understand the petrological relations between the different mafic rocks and their relationship to the ore. It is clear that the use of geochemical diagrams, mostly produced from unmetamorphosed Mesozoic or younger rocks, to understand Paleoproterozoic or Archean and metamorphosed rocks occurring as enclaves in migmatitized orthogneisses is somewhat tenuous. We emphasize, however, that it is the only tool presently available to help unravel this problem.

According to this approach and in agreement with the field relationships observed between ore, gabbro-anorthositic xenoliths, synplutonic enclaves and metagabbronorites. these lithotypes belong to the same mafic suite. The other mafic enclave types observed were either modified too much during metamorphism and migmatitization or do not belong to this suite

The geochemical characteristics and specially the REE patterns of gabbro-anorthositic xenoliths, synplutonic enclaves and metagabbronorite enclaves resemble those of massive anorthosite complexes (Laramie Range, Adirondack, etc.). Archean anorthosites have REE levels about three to five times lower than those observed at Barro Vermelho, although equally pronounced Eu anomalies (Figs. 10 and 11). Anorthosites of the Stillwater layered complex behave like the Archean anorthosites and have small or no Eu anomaly when they reach REE levels close to those of massive type anorthosites (Fig. 11, also). In the Bushveld layered complex no Eu anomaly is observed in the B2 magma from which the anorthosites derived (Harmer & Sharpe 1985). In addition, the anorthite content of the plagioclase of the Barro Vermelho anorthosites around 50% or less is distinctly lower than usually observed in Archean or layered complexes. In layered complexes large variations of the anorthite content in plagioclase from 55% to 80% would be expected. On the other hand, the REE level of the Barro Vermelho anorthosites is about four times lower than the observed in anorthosites and leucogabbros of jotunitic affiliation (Damaiffe & Hertogen 1981).

Some rocks of the jotunitic series at Rogaland-Norway (Duchesne *et al.* 1989) show chondrite-normalized spidergrams with conspicuous depletions of Rb, Th, Nb-Ta, Sr, Zr, Hf and Ti, in comparison with the other trace elements which form a plateau at 100 to 200 times chondrite values (compare Figs. 10 and 11). At first glance, this pattern resembles the distribution observed in synplutonic enclaves of Barro Vermelho, in which a strong depletion (at about 10 times that of chondrite) of Nb,Ta, Sr and Ti is also observed (Fig.12). However, an outstanding difference of the synplutonic enclaves is that the "plateau" is at the 20 to 50 times chondrite level, and not at 100 to 200, as in samples from Rogaland. In addition, Th and Zr show no depletion at Barro Vermelho and K forms a negative anomaly while in Rogaland K lies on the plateau. Therefore, it seems that the greatest geochemical similarity of the Barro Vermelho anorthosites is with massive anorthosites of tholeiitic affiliation such as Laramie, Ana Sira, Egerund, etc. One problem with this interpretation arises with the geochemical indication of a Volcanic Arc Tholeiitic Basalt (oceanic) affiliation for the Barro Vermelho anorthosites (Figs. 13 and 14) contrasting with the supposition of a thick continental crust setting for most massive anorthosite occurrences of the world (Ashwal 1993). However, the oceanic signature at Barro Vermelho could be explained easily if the source magma had formed along a plate margin setting, by melting of an oceanic crustal slab subducting or underplating a thick continental crust, in analogy to the model suggested by Duchesne *et al.* (1998) and Morgan *et al.* (2000). A second problem in accepting the Barro Vermelho anorthosites as being of the massif type is the minimum age of 2.44 Ga, well constrained by the U/Pb data on the host gneisses. This would be an unusually old age for a massif type anorthosite.

Other Fe-Ti ore occurrences of the Pajeú-Paraíba foldbelt in the Borborema Province include: the occurrence of Itatuba-PB where a Volcanic Arc Tholeiitic Basalt affiliation and a Paleoproterozoic age is also supposed (Almeida *et al.* 1997); the Fe-Ti ore in the middle Proterozoic (1.7 Ga, Accioly *et al.* 2000) massive anorthosite complex of Passira – PE; and the Fe-Ti ore deposits near Floresta–PE, hosted in ultramafic rocks of supposed ophiolitic affiliation (Beurlen 1988, Beurlen *et al.* 1992) and middle Proterozoic age (Santos 1995, 1996). The minimum age of 2.44 Ga for the Barro Vermelho anorthosites, constrained by U/Pb data in zircons of the tonalitic gneisses that host the anorthosite enclaves (Melo *et al.* 2002) suggest that this occurrence is older than those of Floresta and Passira and also older than those ages known for massif anorthosites elsewhere.

CONCLUSIONS The Barro Vermelho Fe-Ti ore body is part of one hectometric mafic enclave within granitic to tonalitic orthogneisses. Numerous decimetric to metric gabbro-anorthositic xenoliths, sinplutonic dykes/enclaves of banded amphibolites and various types of xenoliths (composed of mafic and calc-silicatic rocks) are also found as enclaves with random distribution in the orthogneisses. Geochemical analyses suggest that three types of enclaves, respectively gabbro-anorthositic xenoliths, banded amphibolitic sinplutonic dykes/enclaves (dioritic to trondhjemitic in composition) and gabbronoritic enclaves belong to the same mafic suite responsible for the ore formation. This mafic suite is interpreted to have been derived from a tholeiitic magma in Paleoproterozoic (Sm/Nd data) volcanic arc setting or by melting of similar mafic source rocks in a subducting or underplating crustal slab in a continental plate margin setting (based on trace and rare earth element patterns). The gabbronorites are the most primitive rocks of this suite and the gabbro-anorthosites the earliest differentiation products (floating cumulates). These early crystalization products were entrained as xenoliths by an ascending tonalitic intrusion at 2.44 Ga. Simultaneously the residual tholeiitic magma produced the synplutonic dykes of gabbroic-dioritic-trondhjemitic composition, including the Fe-Ti ore. The ore probably represents the most evolved (residual) melt of the same suite. At 2.01 Ga the already deformed tonalites and the enclaves underwent a migmatitization/granitization and a new phase of deformation

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