REE SIGNATURES IN PYROXENES FROM ESTATHERIAN PASSIRA META-ANORTHOSITIC COMPLEX, NE BRAZIL: FUTHER EVIDENCES FOR MASSIF TYPE ORIGIN.

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ABSTRACT: The Passira Meta-anorthosite Complex (PAC) in NE Brazil is a massif-type complex mainly composed of anorthosite with minor gabbro and lenses of pyroxenite rich in Fe-Ti oxide minerals, surrounded by a dyke complex of apatite-rich ferrodiorite. It is situated in the Rio Capibaribe terrain, north of the Pernambuco Lineament, Borborema Province. It was formed at 1.7Ga, and was subjected to two major tectono-metamorphic events. The PAC has a sigmoid shape, is hosted by gneiss-migmatite rocks, and was controlled by movements along the Paudalho and Limoeiro shear zones, branches of the Pernambuco Lineament. Most present textures developed during retro-metamorphism of granulite facies assemblages, but practically unmodified primary mineral assemblages are identified. Augite (sub-calcic augite in older terminology) is identified in the gabbros, and enstatite (bronzite) in the anorthosites. REE patterns in augite have strong light REE enrichment with LaN/YbN > 10, with high total REE contents (SREE) and are therefore different from those expected for augite crystallized from common basalt magmas. Bronzite from anorthosite has a flatter pattern with LaN about twice chondritic values and slight HREE enrichment. The patterns observed for pyroxene are attributed to crystallization from a LREE – enriched jotunitic magma, which may have been formed from enriched mantle, or by melting of mafic lower crust.

Keywords: Anorthosite, gabbro, REE, pyroxene, massif type anorthosite.

RESUMO: O complexo metanortosítico de Passira (CMAP) localiza-se no Estado de Pernambuco, Nordeste Brasileiro. Apresenta-se como um batólito de composição principalmente anortosítica constituindo um complexo do tipo Maciço. O CMAP situa-se no Terreno Rio Capibaribe, na Zona Transversal da Província Borborema, a norte do Lineamento Pernambuco. Apresenta-se como um sigmóide balizado pelas zonas de cisalhamento Paudalho e Limoeiro que são ramificações do Lineamento Pernambuco e acha-se encaixado em rochas gnáissicas-migmatíticas paleoproterozóicas. Subordinamente às rochas metanortosíticas ocorrem metagabros, metagabro-anortositos, e lentes de meta-ultramáficas enriquecidas em óxidos de Fe-Ti e uma série de diques de composição Fe-diorítica enriquecidos em P (apatita-metadioritos), Zr, Ba e elementos terras raras leves envolve o corpo batolítico. Os metanortositos foram datados através do método U-Pb em zircão convencional. A idade obtida de1,7 + 0,02 Ga é interpretada como de cristalização. As rochas do CMAP estiveram submetidas à pelo menos dois eventos tectono-metamórficos, cujas texturas observadas são tipicamente desenvolvidas durante retrometamorfismo sobre associações minerais do facies granulito. Entretanto fases minerais primárias são identificadas. O piroxênio nos gabros é augita (subcálcica) ao passo que enstatita (bronzita) é observada nos anortositos. Os padrões de ETR de augitas nos gabros mostram forte enriquecimento em elementos terras raras leves com LaN/YbN > 10, com altos teores de SETR. Estes padrões são diferentes daqueles esperados para clinopiroxênios derivados de líquidos de composição basáltica. Os piroxênios dos anortositos apresentam um padrão plano, pouco diferenciado com LaN da ordem de 2 vezes o condrito. A assinatura de ETR nos piroxênios dos anortositos quando comparada a do condrito mostra um enriquecimento anômalo em ETR pesados. Os diferentes padrões dos piroxênios das rochas do CMAP podem ser atribuídos a processos magmáticos de cristalização de magmas jotuníticos enriquecidos em elementos terras raras leves, que podem ter se formado a partir de líquidos provenientes de manto enriquecido envolvendo uma série de hipóteses geotectônicas para sua concepção, ou a partir de uma fonte de crosta inferior.

Palavras-chave: Anortosito, gabro, Elementos Terras Raras, piroxênio, anortosito tipo maciço

INTRODUCTION

The Passira Meta-anorthosite Complex (PAC), part of the Borborema Province, is located in eastern Pernambuco State, Northeast Brazil, cropping out around Passira town (Figure 1). A batholithic body mainly composed of meta-anorthosite with minor metagabbro, meta-leucogabbro, and lenses of meta-pyroxenite containing Fe-Ti oxide minerals. Meta-anorthosite is the dominant lithology. The banding locally observed corresponds to an alternance of foliated and massive including pegmatoids anorthosites. These lithological associations compose a typical massif-type complex. A dyke complex composed of apatite-rich ferrodiorite surrounds the PAC. Granitic magmas (orthogneisses) were intruded into, and were deformed together with the PAC. They include metaluminous alkaline, and meta- to peraluminous garnet-bearing types whose chemical characteristics have some features usually associated with orogenic granites, and others which are more typical of anorogenic granites. Their isotopic signatures show that they are unlikely to be genetically related to the PAC.

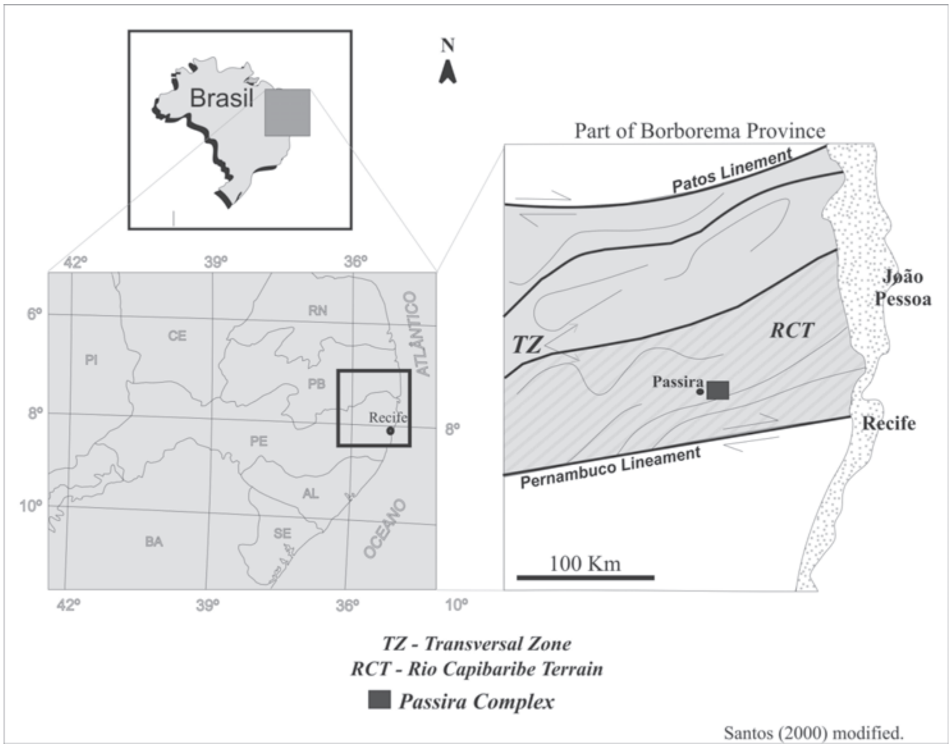

Figure 1 – *Regional geological context.*

In this paper we present data on the rare earth elements (REE) in minerals from rocks of the PAC, obtained by laser ablation, inductively coupled plasma source mass spectrometry (LAICPMS) at the Crystal Chemistry and Crystallography Study Centre of Pavia University, Italy. The procedure used follows that of Bottazi et al. (1994). Major element mineral compositions were obtained using the JEOL JXA-8600 electron microprobe at the Mineralogy and Geotectonic Department of the Geosciences Institute of the University of São Paulo. The accelerating voltage was 15 kV and the current was 10 nA. ZAF corrections were applied. The mineral compositions were used to constrain the possible compositions of the magma(s) involved in the formation of the complex following the line suggested by Bellieni et al. (1981), and to investigate the effects of the subsequent metamorphisms on mineral compositions. Studies of REE in minerals from basic rocks have been used for studies in many fields, including petrogenesis and metamorphism (Vannucci et al., 1995; Rivalenti et al., 1995; Szabó et al, 1995; Tribuzio et al., 1996, 1997; Tiepolo et al., 1997).

GEOLOGICAL SETTING

The PAC occurs within the Rio Capibaribe Terrain (Santos, 1996) and is bounded by the Limoeiro and Paudalho shear zones, both of which on branches of the Pernambuco Lineament. The inferred stratigraphy (Figure 2) places at the base a Paleoproterozoic high-grade gneiss-migmatite complex, which was consolidated in the 2.0Ga Transamazonic event (Barbosa, 1990; Hackspacher et al, 1991; Brito Neves et al, 1995; Accioly, 2000).

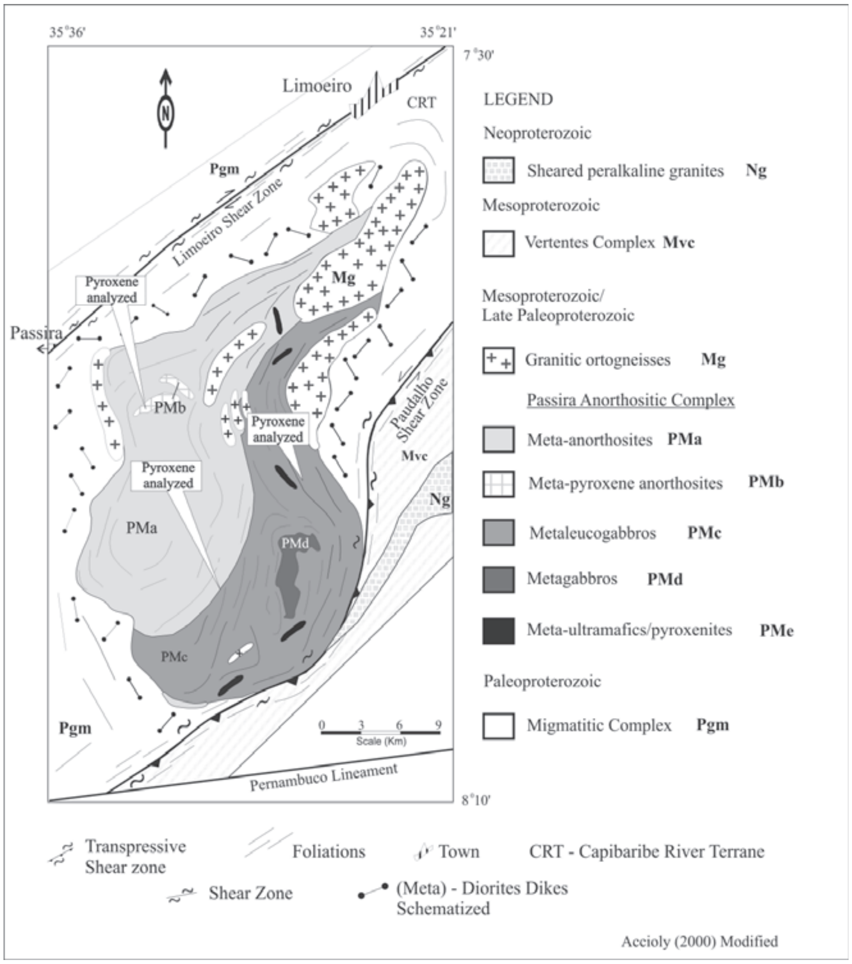

Figure 2 *– Simplified geological map of the Passira metaanorthositic complex.*

The PAC and accompanying granitic orthogneisses are penecontemporaneous with a Statherian age that was obtained in a metanorthosite sample dated of 1.7 U-Pb (Accioly, 2000). Our age data demonstrate that emplacement of the PAC occurred during Statherian-Calymmian period similar to that of the other most voluminous massif anorthositic Complexes in the world (e.g. Damiao complex, Kunene Complex, Lofoten Island, Hard Lake and others, see Ashwal, 1993). Metavolcano-sedimentary rocks of the Vertentes Complex (Santos & Medeiros, 1999), which occur both north of the Limoeiro shear zone and south of the Paudalho shear zone, are believed to be younger. Diorites intruded along the Pernambuco Lineamento and sheared peralkaline granites not represented in Fig. 2 complete the succession of rock types. The PAC is deformed and recrystallized by at least two tectonic/metamorphic events, which have produced two distinct structural elements. The first is a penetrative sub-horizontal foliation denoted by amphibole-rich bands and the second is a sub-vertical to sub-horizontal foliation, which corresponds to the steeply dipping foliation on rocks, mainly near the shear zones. Symplectitic reaction coronas around garnet were produced after the first tectonic metamorphic event (Accioly et al, 2003).

PETROGRAPHIC ASPECTS OF THE PAC

Sufficient original features have escaped the metamorphic effects to allow exact description of the facies present, and from now on the prefix "meta" will be dropped. The dominant anorthosite is present in three facies. Coarse pegmatitic anorthosite has large plagioclase crystals up to 10 cm long with adcumulate texture, containing zircon and opaque Fe-Ti mineral inclusions. Films and strings of antiperthite are metamorphic products. Large dispersed orthopyroxene and ilmeno-rutile crystals make up to about 10% of the rock. The former exhibits both calcic pyroxene and opaque mineral exsolution lamellae. Pyroxene-anorthosite (or intercumulus anorthosite) contains mafic aggregates in which orthopyroxene is predominant (Figure 3A), but cummingtonite, magnetite, ilmenite, biotite, chlorite and epidote are also present. The first three minerals in this list may be primary, while the last three are metamorphic. Foliated anorthosite (Figure 3B) is usually hololeucocratic, and is a transitional type between leucogabbro and anorthosite in the vicinity of the major shear zones.

Leucogabbro or gabbro-anorthosite, gabbro and garnet-bearing gabbro are the three main gabbro facies. The leucogabbro is porphyritic with pyroxene and minor opaque minerals involved in a mass of andesine-labradorite. Amphiboles are products of alteration of pyroxene (Figure 3C). Gabbros preserve a primary mineral assemblage of plagioclase, calcic clinopyroxene and opaque oxide minerals, but have overprints at higher and lower metamorphic grades. Assemblages of the former are represented by hornblende, biotite, titanite and quartz, while epidote, chlorite and carbonate minerals represent the latter. The garnet gabbros contain, apart from plagioclase, calcic clinopyroxene, opaque oxide and sulphide as primary minerals. Metamorphic minerals include rutile and garnet with coronas of symplectite formed of intergrowths of amphibole and plagioclase (Figure 3D). Reaction coronas around garnet might be attributed to metamorphic destabilization and substitution processes of original paragenesis. These processes are observed mainly in the vicinity of the major shear zones.

Most authors (Messiga et al, 1995 and references therein) deduce that these textures are formed during retro metamorphic episodes. For others authors (Ait-Djafer et al, 2003) coronas can be produced during the cooling of intrusions. In PAC this texture is interpreted according the first model. A Sm-Nd internal isochron using garnet and whole rock for-meta-gabbros yielded an age of 612 + 50 Ma, thus coronas were formed during the Brasiliano-Pan-African event (Accioly et al, 2003).

4. MAJOR ELEMENT MINERAL CHEMISTRY

Cores and rims of the plagioclases and pyroxenes from gabbros and anorthosites were analyzed and described below.

Pyroxene: The primary pyroxene in the anorthosites is enstatite according to Morimoto´s classification (1968) or bronzite in earlier classifications (Table 1; Figure 4). Subtle zoning with decrease in MgO from core to rim was detected in the analysed grains. A most important feature is that the present compositions are not those of the typical high-alumina orthoyroxene (HAOP) which are present as megacrysts in many massif-type anorthosites (Emslie, 1975), and which show that crystallization occurred under lower crustal pressures (Fram and Longhi, 1992). The primary pyroxene in garnet-bearing gabbro and gabbro-anorthosite is augite (sub-calcic augite in older classifications). Slight zoning from cores richer in Ca and Mg to borders richer in Fe is observed.

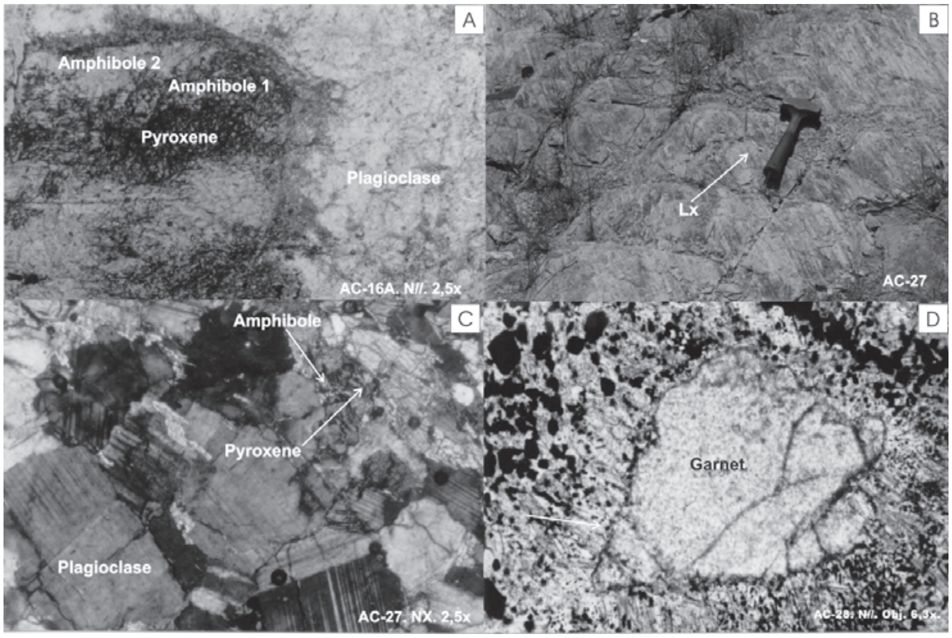

Figure 3 *– (A) Photomicrography of thin section showing pyroxene in contact with plagioclase in pyroxene-anorthosite. (B) Mineral lineation on foliated anorthosite. (C) Photomicrography of thin section presenting amphibole replacing pyroxene on gabbro-anorthosites (D) Photomicrography of thin section showing reactions coronas around garnet (symplectitic texture).*

Plagioclase: Plagioclase compositions (Table 2; Figure 5) in anorthosites range between labradorite and andesine, with zoning from more calcic cores to more sodic borders. Cores compositions of Labradorite occur in pyroxene-anorthosite and andesine in coarse pegmatitic anorthosite. In gabbros the compositions are labradorite.

REE CHEMISTRY OF MINERALS

The principal primary minerals from pyroxene anorthosite, garnet-bearing gabbro and leucogabbro were analysed for their REE content (Table 3). At least one analysis of either core or rim was made, and core and rim compositions were obtained for some samples. Concentrations were normalized to CI chondrite values presented by Evensen et al. (1978). Our conclusions are affected by the rather high limits of detection of the analytical method used, and some of the chondrite-normalized patterns for plagioclase and orthopyroxene presented here include segments which represent the maximum normalized values, while the real values could be much lower. Spiky patterns for minerals with low REE contents are probably a result of low precision of determination of concentrations of some of the elements when close to the detection limits. Nevertheless, it is possible to place some constraints on parent magma compositions.

Pyroxene: Sub-calcic augite from the gabbros has strong LREE enrichment and no Eu anomaly (Figure 6). The central segment of the pattern for bronzite from pyroxene-anorthosite is a maximum (Figure 7). Published compilations of distribution coefficients (e.g. Rollinson, 1993) suggest that these minerals must have been in equilibrium with LREE-enriched magmas.

***Table 1** Representatives pyroxenes chemical analyses of the gabbros and anorthosites from PAC. Structural formulae based on 6 oxygen atoms.*

	GARNET BEARING GABBRO		***GABBRO ANORTHOSITES***	***PYROXENE ANORTHOSITES***				
Sample	**AC25-1**	**AC25-2**	**AC86-1**	**AC16-1**	**AC16-2**	**AC16-3**	**AC16-5**	**AC16-6**
Remarks	**CORE**	**RIM**	**CORE**	**CORE**	**RIM**	**CORE**	**CORE**	**RIM**
SiO2	53,8	51,07	52,00	51,27	53,66	52,19	52,43	51,38
TiO2	0,21	0,07	0,06	0,03	0,13	0,06	0,03	0,01
AI2O3	3,65	5,3	3,75	2,50	3,21	1,70	1,97	2,04
FeO	11,82	13,23	12,8	23,40	18,18	23,43	23,73	23,71
MgO	16,85	15,93	17,02	22,00	20,76	21,75	21,56	21,27
CaO	12,66	11,62	12,73	0,10	1,36	0,68	0,36	0,42
Na2O	0,42	0,75	0,52	0,02	0,30	0,04	0,01	0,01
MnO	0,29	0,26	0,35	0,30	0,41	0,43	0,42	0,43
TOTAL	**99,7**	**98,23**	**99,23**	**99,62**	**98,01**	**100,28**	**100,51**	**99,27**
T Si	1,992	1,915	1,992	1,91	2,02	2,93	1,95	1,94
T Al	0,008	0,082	0,008	0,08	0,00	0,06	0,05	0,06
M1Al	0,151	0,152	0,151	0,03	0,14	0,02	0,04	0,03
M1Ti	0,006	0,002	0,006	0,00	0,00	0,00	0,00	0,00
M1Mg	0,84	0,839	0,84	0,00	0,00	0,00	0,00	0,00
M2Mg	0,091	0,052	0,091	0,97	0,85	0,98	0,96	0,97
M2Fe2	0,366	0,415	0,366	0,25	0,31	0,23	0,23	0,22
M2Mn	0,009	0,008	0,009	0,73	0,57	0,73	0,74	0,75
Ca	0,502	0,467	0,502	0,01	0,01	0,01	0,01	0,01
M2Na	0,03	0,055	0,03	0,00	0,06	0,03	0,01	0,02
M2K	0,002	0,002	0,002	0,00	0,02	0,00	0,00	0,00

Plagioclase: Patterns for plagioclase from gabbro are mostly maximum, while the LREE segment for plagioclase from anorthosite is real (Figure 8). In the absence of specific partition coefficient data, which allow the evaluation of the effect of temperature, a tentative explanation of the differences between gabbro and anorthosites would be a higher crystallization temperature for the gabbros, with consequently lower partition coefficients. The real part of the plagioclase REE patterns in anorthosites are comparable to that found in some other massif-type anorthosites (e. g. Wiszniewska et al., 2002), for which a LREE-enriched jotunite parent magma has been demonstrated.

DISCUSSION AND CONCLUSIONS

The origin of massif-type anorthosites is a much debated subject in which the nature of the parent magma(s) and their source(s), the physical processes responsible for their formation, and the relationships with granites and members of the charnockite suite (where present) represent cardinal points. Various high-alumina basalt types (Emslie 1978; Nolan and Morse, 1986) or Fe-Ti-P-rich jotunitic magma (e.g.Vander Auwera and Longhi, 1994) are competitors for the role of parent magma for the anorthosite, while crustal melts (Emslie et al., 1994) or differentiates from intermediate magmas (Vander Auwera et al., 1998) are proposed as parent magmas for the associated granites.

A mantle origin for the mafic magma(s), generated during the activity of mantle plumes, was a consensus view (Ashwal, 1993), and the trapping of basalt magma at the base of the continental crust

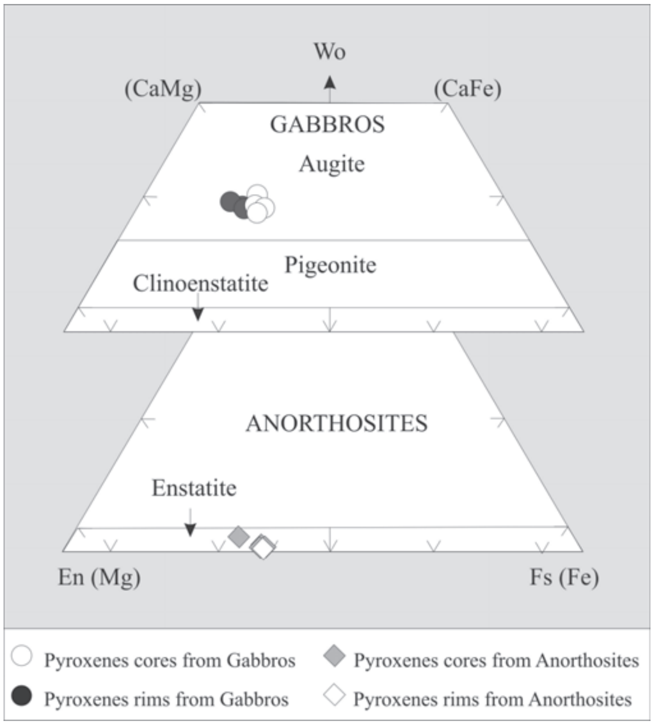

Figure 4 *– Pyroxene compositions from the Anorthosites and Gabbros plotted in the pyroxene polygon.*

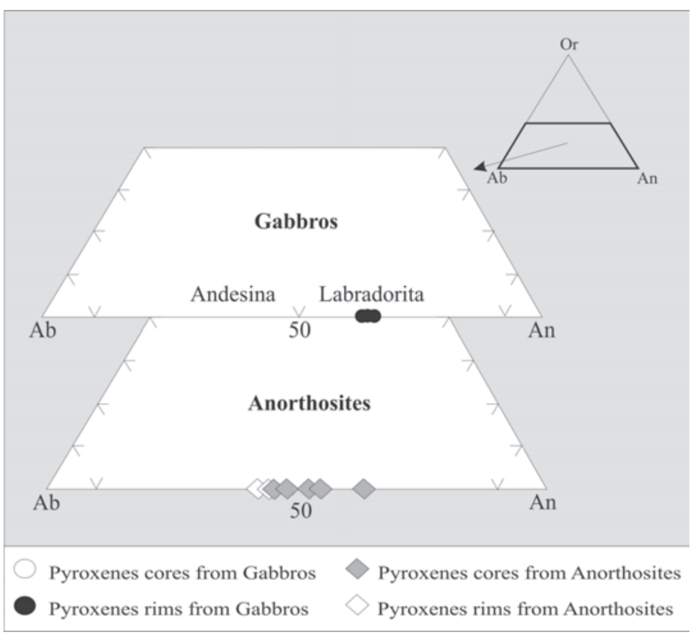

Figure 5 *– Plagioclase compositions from the Anorthosites and Gabbros*

***Table 2** – Representatives plagioclases chemical analyses of the anorthosites and gabbros from PAC, structural formulae based on 32 oxygen atoms and all iron is ferrous.*

Sample	*GARNET BEARING GABBROS*		*ANORTHOSITES*					
	AC25-26	**AC25-27**	**AC16-9**	**AC16-10**	**AC16-10b**	**AC27-1**	**AC-27-2**	**AC27-2b**
Remarks	**CORE**	**CORE**	**CORE**	**CORE**	**RIM**	**CORE**	**CORE**	**RIM**
SiO2	52,73	52,70	51,71	51,58	54,1	58,07	60,31	58,07
AI2O3	30,58	30,60	31	31,46	29,29	26,47	26,50	26,47
FeO	0,31	0,30	0,21	0,53	0,08	0,00	0,05	0,00
MgO	0,04	0,04	0,00	0,00	0,00	0,00	0,00	0,00
CaO	13,10	13,30	13,31	13,41	10,66	7,90	7,90	7,90
Na2O	3,80	3,80	4,36	4,15	5,52	6,90	6,70	6,90
MnO	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
K2O	0,00	0,00	0,02	0,02	0,03	0,19	0,20	0,19
BaO	0,00	0,00	0,06	0	0,1	0,00	0,00	0,00
TOTAL	**100,56**	**100,74**	**100,67**	**101,15**	**99,78**	**99,53**	**101,66**	**99,53**
Si	5,18	5,17	2,34	2,32	2,32	2,61	2,64	2,68
Al	3,53	3,50	1,65	1,669	1,669	1,40	1,37	1,32
Fe2	0,03	0,03	0,01	0,02	0,02	0,00	0,00	0,00
Mg	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00
Ca	1,38	1,38	0,65	0,65	0,65	0,38	0,37	0,31
Na	0,70	0,70	0,38	0,36	0,36	0,60	0,59	0,66
K	0,00	0,00	0,00	0,00	0,00	0,01	0,01	0,01

would have given rise to diversity of liquids involved. A contrary view that the mantle contribution is not as dominant as first thought has grown recently. Differences between the Sr and Nd isotopic compositions of magmas derived from the enriched mantle and mafic lower crustal sources are unlikely to be very large. A combination of sources involving contamination processes may have occurred, but the known models present in the literature may only imitate other processes, for example the same results can be obtained by crustal derived, assimilation and enriched mantle sources.

For those massif anorthosites for which an enriched jotunitic magma may be parental, a lower crustal origin has been proposed (Longhi et al., 1999), since the jotunitic magma cannot be generated from olivine-rich sources such as the upper mantle, but HAOP is typically formed by crystallization of jotunitic magma at lower crustal pressures. Convincing tectonic models have been presented for some occurrences (Duchesne et al., 1999; Wiszniewska et al., 2002).

The studied pyroxenes from both gabbros and anorthosites have different patterns from those expected for normal mafic rocks. REE signatures from pyroxenes of anorthosites and gabbros are different, but both have anomalous LREE enrichment. Longhi (2005) described that a majority of workers believe that massif anorthosites formed in two stages, with various pulses in a deep-seated chamber followed by intrusions of the suspensions into mid to upper crustal chambers, together with associated basaltic, gabbroic and granitic intrusions. Then the different signatures of these pyroxenes can be attributed to magmatic processes.

Our results favor the involvement of a LREE-enriched magma as the parent for the

Table 3 *– Rare Earth Elements analyses (ppm) for plagioclases and pyroxenes separated from Gabbros and Anorthosites.*

	GABBROS						*ANORTHOSITE*	
	PLAGIOCLASE		*PYROXENE*				*Plagioclase*	*Pyroxene*
Sample	**AC28**	**AC28**	**AC 86**	**AC 86**	**AC 86**	**AC 86**	**AC16-10**	**AC16-1**
Remarks	**Core**	**Core**	**Core**	**Rim**	**Core**	**Rim**	**Core**	**Core**
La	0,8	1,0	33,3	34,4	10,7	31,7	1,41	0,41
Ce	1,4	<1.0	107	121	11,7	98,0	2,08	0,68
Pr	<0.3	<0.6	14,7	17,6	0,76	13,8	0,18	0,09
Nd	<0.7	<2.3	65,2	79,1	1,4	57,2	<1.6	0,60
Sm	0,0	<1.7	11,8	17,6	<0.6	10,8	0,05	0,10
Eu	<0.7	<1.2	3,5	3,7	2,2	3,1	0,65	<0.2
Gd	<3.2	<7.8	8,4	10,9	<0.8	7,8	<1.5	<0.4
Tb	<0.3	<0.8	0,88	1,67	<0.2	0,93	<0.3	<0.1
Dy	<1.0	<1.4	5,4	8,8	0,00	4,5	0,00	0,37
Ho	<0.22	<0.55	1,06	1,56	<0.1	0,90	<0.1	0,09
Er	0,0	<1.4	2,34	2,65	0,00	3,7	<0.6	0,32
Tm	<0.28	<0.07	0,50	0,63	<0.09	0,42	<0.18	0,08
Yb	<1.2	<0.7	3,3	2,9	0,00	3,0	<0.2	0,43
Lu	<0.19	<0.05	0,45	0,47	<0.06	0,49	<0.3	0,07

mafic and anorthositic rocks. We cannot exclude a mantle (in the geometric sense) source, since subduction during the Transamazonian is believed to have been responsible for enrichments, which are seen in brasiliano-age granites (Ferreira et al (1997); Neves at al (2000)). A critical but unresolved question is whether subducted ocean crust can yield jotunitic magmas at shallow mantle, rather than lower crustal pressures. The compositions of the orthopyroxenes with low Al contents suggest that fractionation of the parent magma occurred within the upper or middle crust.

We conclude that the Passira anorthosite complex is a product of crystallization of enriched jotunitic magma, in common with many other massif anorthosites, which may have been formed from enriched mantle, or by melting of mafic lower crust. The preserved primary mineral assemblages appear to have formed during crystallization within the upper, rather than the lower crust.

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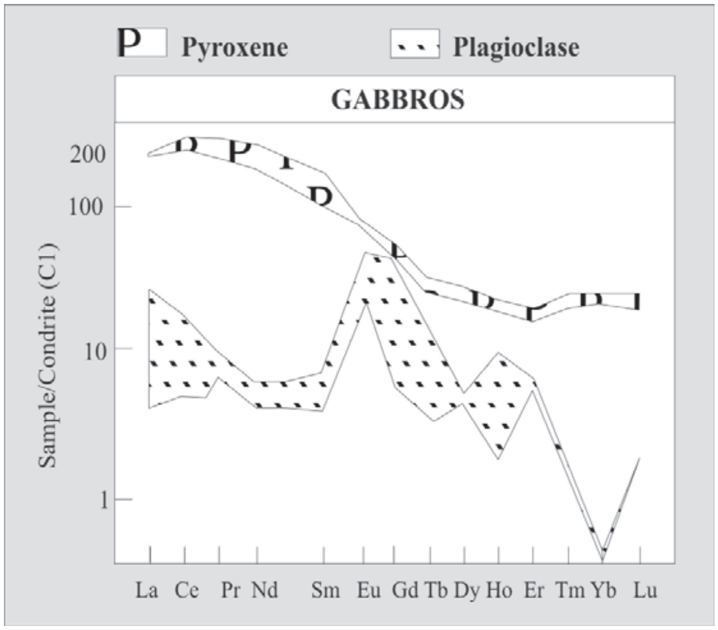

Figure 6 *– REE signatures for pyroxenes and plagioclases from Gabbros normalized for chondrite (C1 – Evensen et al, 1978).*

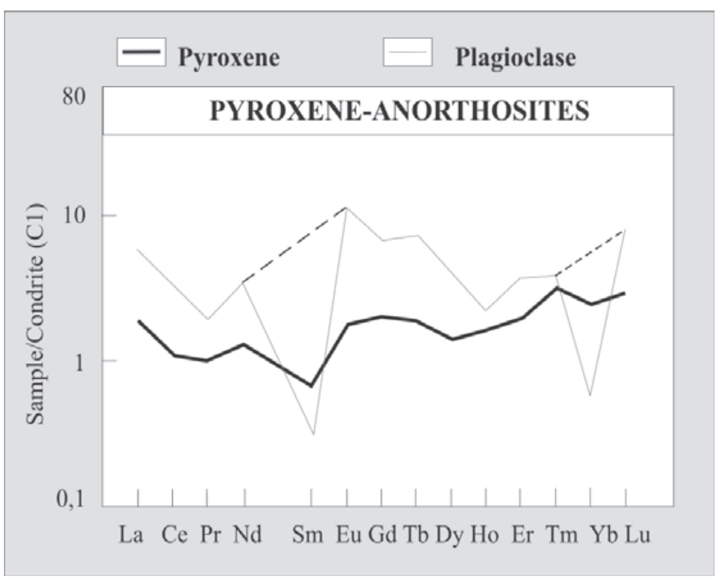

Figure 7 *– REE signatures pyroxenes and plagioclases from pyroxene-Anorthosites of the PAC, normalized for chondrite (C1 – Evensen et al, 1978).*

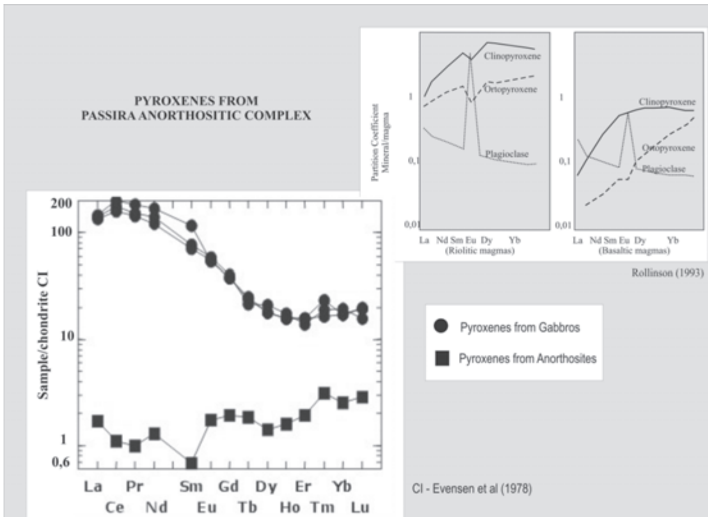

Figure 8 *– REE Spydergrams for pyroxenes from Pyroxene-anorthosites (black squares) and from Gabbros (black circles).*

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