GEOCHEMISTRY OF PART OF THE SANTA CATARINA GRANULITIC COMPLEX, SOUTHERN BRAZIL: A MODEL OF DIFFERENTIATION FROM HIGH ALUMINA BASALT

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RESUMO GEOQUÍMICA DE PARTE DO COMPLEXO GRANULÍTICO DE SANTA CATARINA, BRASIL AUSTRAL: UM MODELO DE DIFERENCIAÇÃO DE BASALTO TOLEIÍTICO DE ALTO-AL Parte do Complexo Granulítico de Santa Catarina é composta de uma sequência cálcio-alcalina, básica a ácida e cogenética, bem como piroxenitos. Anortositos, trondhjemitos, anfibolitos e metassedimentos são subordinados. A sequência cálcio-alcalina compõe-se de noritos, enderbitos e charno-enderbitos. As composições do granulitos intermediários-ácidos assemelha-se as de tonalitos a alto-Al e granodioritos arqueanos, enquanto os granulitos básicos correspondem a toleítos alto-Al. Os piroxenitos de Barra Velha possuem composições augíticas e apresentam, localmente, texturas de cumulatos. Os dados de geoquímica sugerem que a sequência cálcio-alcalina formou-se através de cristalização fracionada de toleítos alto-Al. Plagioclásio, olivina ou ortopiroxênio e clinopiroxênio foram as fases principais. Os piroxenitos correspondem a cumulatos de piroxênio formados precocemente durante a cristalização fracionada de basalto a alto-Al, enquanto rochas com teores muito elevados de Al devem ser cumulatos de plagioclásio, e rochas com altos teores de Fe devem ser cumulatos de minerals ferro magnesianos. Essas observações demonstram que a subducção de crosta oceânica, fria e hidratada, seguida pela sua desidratação com invasão da cunha sobrejacente pelos fluidos liberados e fusão parcial do manto peridotítico dessa cunha, com geração de magmas máficos, pode ter occorido durante o Arqueano tardio. Nessa época, o processo mais comum era fusão direta de crosta oceânica quente e anidra, que durante a subducção produziu magmas tonalíticos e semelhantes.

Palavras chaves: Granulitos. petrogênese arqueana, suíte cálcio-alcalina, basalto toleiítico alto-Al

ABSTRACT Part of the Santa Catarina Granulitic Complex consists of a comagmatic calc-alkaline basic to acid sequence and pyroxenites. Subordinate anorthosites, trondhjemites, amphibolites and metasediments are also present. The calc-alkaline sequence is formed by norites, enderbites, and charno-enderbites. The composition of the acid- intermediate granulites is similar to Archaean high-Al tonalites and granodiorites, while the basic granulites correspond to high-Al tholeiites. The Barra Velha pyroxenites have augitic compositions and local cumulate textures. Geochemical data suggest that the Archaean calc-alkaline sequence was formed by crystal fractionation of high-Al tholeiites, with plagioclase, olivine or orthopyroxene and clinopyroxene as the main fractionating phases. The Barra Velha pyroxenites appear to correspond to pyroxene cumulates, formed early during differentiation of high-Al basalt. Rocks with very high Al contents are probably plagioclase cumulates and high-Fe rocks are ferromagnesian mineral cumulates. These observations show that subduction of cold, hydrated ocean crust followed by its dehydration, invasion of the overlying mantle prism by the released fluids and partial melting of mantle peridotite to yield mafic magmas could have occurred during the late Archaean, when the more common process was direct melting of the hot, anhydrous subducted slab to yield tonalites and related magmas.

Keywords: Granulites, Archaean petrogenesis, calc-alkaline suite, high-Al tholeiitic basalt

INTRODUCTION The Santa Catarina Granulitic Complex (Hartmann *et al.* 1979) or Luiz Alves domain (Basei *et al 1992,* Siga Jr. *et al* 7993, Siga Jr. 1995) occurs over about 6000 km^2 in northern Santa Catarina and southern Parana States (Fig. 1). Discussion of the geological constitution and evolution of the region have continued since Hasui *et al* (1975) defined the limits of the Joinville Massif. In the Neoproterozoic, the granulitic complex formed the Luis Alves Microplate (Basei *et al* 1992) or domain (Siga Jr. 1995) which was, as other gneiss terranes situated between the Ribeira and Dom Feliciano Belts, involved in the regional tectonic scenario related to the amalgamation of Gondwanaland.

Part of the granulitic complex is composed of a noritic-enderbitic-charno-enderbitic sequence with mafic to ultramafic rocks which occur mainly as small to mega-enclaves. The mafic rocks are mostly noritic while the ultramafic rocks are mainly pyroxenites, of which some of the most important bodies occur around Barra Velha town. Anorthosites, trondhjemites, amphibolites, iron-formations, calc-silicatic rocks and quartzites also occur. All these lithologies are gneissic and have a steep-dipping NE main foliation. Our attention is focused on the metaigneous component.

The basic-intermediate granulites are composed of plagioclase, orthopyroxene, clinopyroxene, quartz, amphibole, titaniferous biotite and occasional microcline. The common accessory minerals are zircon, apatite, rutile and magnetite. The granulite facies regional metamorphism was followed by an also regional amphibolite facies metamorphism, then by a greenschist facies event described by several authors (Minioli 1972, Hartmann *et al* 1979, Moreira & Marimon 1980, Hartmann 1981, Silva 1984, Basei 1985), who studied the high-grade parageneses and considered the medium- and low-grade assemblages to be formed by retrogression of the granulite facies minerals. Hartmann (1988), based on two-pyroxene geothermometry, calculated temperatures of about 800°C for the main granulite facies metamorphism.

The abundance of noritic granulites, which occur mostly as large lensoid to boudinaged bodies, and their field relations with the acid to intermediate rocks, with sharp contacts and angular shapes or as diffuse patches, suggest that there could have been some genetic relationship between the norites and the enderbite-charnoenderbites. The mega-enclaves, such as the Barra Velha pyroxenites and other smaller bodies, represent large igneous mafic-ultramafic bodies preserved during the superimposed tectonometamorphic processes.

LITHOGEOCHEMISTRY This work uses a set of new geochemical data which complements that obtained by other authors (Moreira & Marimon 1980, Hartmann 1981,

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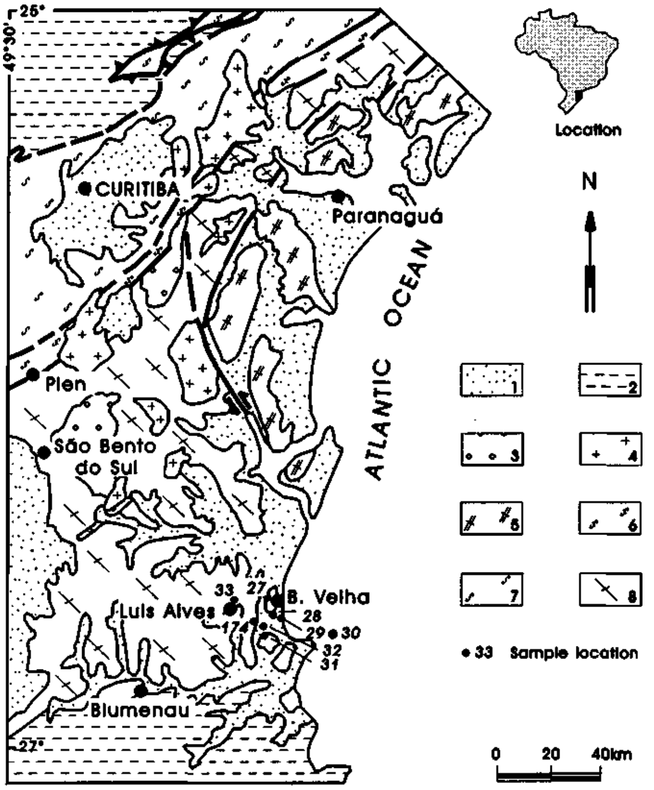

Figure 1 - Geotectonic sketch map of southeastern Parana and northeastern Santa Catarina States (after Basel et al. 1992, Siga Jr. 1995), with sample location. Symbols: ***1*** *= Phanerozoic cover;* ***2*** *= Ribeira (northwest) and Dom Feliciano (south) belts;* ***3*** *= Brasiliano-age volcanosedimentary basins;* ***4*** *= alkaline-peralkaline granitoids of post-orogenic extensional regimes; 5 = granitoids, gneisses, migmatites and schists of the Paranagud Tectonic Domain;* ***6*** *= high-Kcalc-alkaline granitoids; 7 - banded gneisses, migmatites and amphibolites of the Curitiba Tectonic Domain;* ***8*** *= granulitic orthogneisses intercalated with mafic-ultramafic bodies, quartzites, iron-formations and paragneisses of the Luis Alves Tectonic Domain.*

Figura 1 - Esboço geotectônico do Sudeste do Paraná e nordeste de Santa Catarina (segundo Basei *et al.* 1992, Siga Jr. 1995), com localização das amostras analisadas. Símbolos: 1 = cobertura fanerozóica; 2 = Cinturões de Ribeira (a Noroeste) e Dom Feliciano (a Sul); 3 = bacias volcanossedimentares brasilanas; 4 = granitóides alcalinos e peralcalinos de regimes extensionais pós-orogênicos;5 = granitóides, migmatitos e xistos do Domínio Tectônico Paranaguá; 6 = granitóides cálcio-alcalinos de alto-K; 7 = gnaisses bandados, migmatitos e anfibolitos do Domínio Tectônico Curitiba; 8 = ortognaisses granulíticos intercalados com corpos máfico-ultramáficos, quartzitos, formações ferríferas e paragnaisses do Domínio Tectónico Luis Alves.

1988, Mantovani 1985, Marques 1988, Siga Jr. 1995). The samples analysed in this study include examples of the Barra Velha pyroxenites, mafic rocks and intermediate to felsic gneissic granulites. The sample locations are shown in Fig. 1. The new data were obtained at Memorial University of Newfoundland. The major elements were measured by AAS after digestion in teflon bombs, while the trace elements were determined by XRF spectrometry of pressed powder pellets. Selected analyses are given in Table 1.

Major element chemistry The Santa Catarina granulites have a wide compositional range from ultrabasic to acid, with predominance of basic-intermediate compositions. The Barra Velha pyroxenites have chemical compositions (Table 1) which correspond to mixtures of higher-Al, Ca-rich, and lower-Al, Ca-poor pyroxenes, varying from clinopyroxenite to websterite. Alkali-element contents are low, which suggests that the primary compositions for these elements are largely preserved. If the observed concentrations of, for instance, K and Rb are wholly primary, these rocks are nearly pure cumulates, which retained little interstitial differentiated magma.

Most rocks from the Santa Catarina granulitic complex appear to retain their original compositions without important alterations, with the exception of depletion of some incompatible elements during granulite facies metamorphism. For instance, apart from the pyroxenites, the major element compositions largely conform to the standard igneous trends for unmodified igneous rocks, defined by Beswick & Soucie (1978). There is a tendency for the analyses to group towards the limits of the compositional envelopes and, since the rocks are generally aluminous, this distribution could result from accumulation of plagioclase.

Mafic rocks include mostly high-Al and subordinately high-Fe compositions. The mafic-intermediate-acid terms which appear to represent a cogenetic differentiated sequence will be termed here as the Luis Alves sequence. The high-Al mafics, and intermediate to felsic rocks define linear trends in many Barker diagrams (Fig. 2). Such trends are, however, features which can be produced by various primary and secondary processes, although we consider more probable that they were formed by magmatic differentiation processes. The high-Fe mafic rocks (CAN-30a and CAN-30b) usually lie off the linear trends defined above. Once again, there could be a number of motives for such a divergence. Apart from the Luis Alves high-Al trend, other samples have very high-Al contents and may result from plagioclase accumulation (gabbro-anorthosites), while other samples have lower Al contents and at least some of them may represent "basaltic liquids" from which plagioclase was removed by flotation, while others could have been formed by accumulation of ferromagnesian minerals by sinking. Two samples have high K contents and appear to correspond to monzonitic rocks, while two others have very high Fe (30-40% Fe_2O_3t) contents and may represent iron-formations.

In the R1-R2 diagram (De La Roche *et al.* 1980), the Luis Alves sequence plots in the gabbro-tonalite-granodiorite fields, usually associated with sub-alkaline rocks. Compared with Palaeozoic suites from known tectonic environments (Batchelor & Bowden 1985), the Luis Alves sequence is closely comparable with pre-collisional calc-alkaline granitoids and associated mafic rocks, related to subduction zones (Fig. 3).

In the AFM diagram (Fig. 4) most rocks of the Luis Alves sequence conform to a trend similar to those of the Phanerozoic calc-alkaline granitoids from Peru, Central America and California (in Brown 1982). Some of the mafic rocks have tholeiitic tendencies. The overall chemical features of the two high-Fe samples CAN-30a and CAN-30b, which also lie off the AFM trend, suggest that they are ferromagnesian mineral cumulates. They may not be directly related to the main Luis Alves differentiation sequence, or they could represent part of a more complete differentiation trend, as yet incompletely sampled, which includes a strong inflection.

The Barra Velha pyroxenites may also not be directly related to the proposed differentiation sequence. If they are cogenetic with the main sequence, then they could also represent a cumulate stage for which the corresponding liquid differentiates are the more mafic norites.

Trace *element chemistry* The Barra Velha pyroxenites have low contents of most incompatible trace ele-

Table 1 - Compositions of rocks from the Santa Catarina granulite complex, selected from 22 new analyses.
Tabela 1 - Composições de rochas do complexo granultício de Santa Catarina, selecionadas de 22 novas análises.

	CAN-28B	CAN-29B	CAN-30B	CAN-30A	SCMB-174RB	CAN-33G	CAN-31	CAN-33E	CAN-33B	CAN-33C	CAN-33A
SiO_2	49.5	49.6	40.9	42.0	48.5	52.0	55.9	61.8	67.7	70.7	73.8
TiO_2	0.35	0.30	1.18	0.84	1.42	0.86	0.69	0.67	0.49	0.20	0.31
Al_2O_3	4.92	4.00	15.5	15.8	13.3	17.7	16.9	15.6	14.8	14.4	13.5
$Fe_2O_3^t$	11.19	11.53	16.14	15.50	15.92	9.45	7.96	6.24	4.16	2.47	1.55
MnO	0.19	0.22	0.19	0.18	0.22	0.13	0.17	0.08	0.06	0.04	0.03
MgO	19.90	19.65	9.80	8.80	5.94	4.69	3.34	2.69	1.67	0.99	0.96
CaO	11.46	13.40	10.42	11.24	8.80	7.80	5.66	4.72	4.32	4.16	3.58
Na_2O	0.63	0.32	1.96	1.80	2.83	4.13	4.09	4.14	3.99	4.02	3.63
K_2O	0.24	0.03	0.63	0.56	1.08	1.17	1.76	1.30	1.36	1.05	1.08
P_2O_5	-	-	0.17	0.17	0.26	0.21	0.17	0.25	0.15	0.13	0.03
LOI	1.96	1.27	1.72	1.74	0.24	0.73	2.13	0.94	0.91	0.85	0.67
Total	100.34	100.32	98.61	98.63	98.51	98.87	98.77	98.43	99.61	99.01	99.14
Cr	1495	962	33	36	131	18	11	21	22	14	5
Ni	270	240	17	17	62	7	-	-	-	-	-
V	195	204	430	366	258	151	105	65	45	27	10
Ba	51	22	453	294	234	731	599	1226	607	607	693
Rb	-	9	11	8	8	6	35	-	2	2	3
Sr	67	36	431	480	241	563	603	622	638	638	588
Nb	7	9	8	7	21	14	12	9	8	6	7
Zr	2	6	39	37	102	175	74	193	324	101	33
Y	13	15	40	36	64	49	23	20	14	14	6
La	25	25	13	4	41	32	14	36	9	15	1
Ce	36	-	37	59	91	107	91	134	82	103	71

ments, especially probably immobile Zr confirming the major element .features already noted. They did not suffer from introduction of incompatible elements, especially the large ion lithophile elements (LILE) during the metamorphic evolution. They have relatively high values of Ni and V and very high contents of Cr. The Ni contents are crudely positively correlated with MgO and negatively correlated with CaO, features which suggests that the pyroxenites retain the main features of original igneous trace element distributions, in which orthopyroxene preferentially concentrates Ni. It is, therefore, highly probable that websterite was present in the protoliths, and that orthopyroxene cannot be simply a metamorphic reaction product. Less mobile, high field strength trace element (HFSE - e.g. Zr) contents are also low, strengthening the hypothesis that these ultramafic rocks are nearly pure cumulates.

The Luis Alves calc-alkaline sequence has relatively low contents of Rb, Th, U, Nb and Ta and high contents of Ba, Sr, light rare earth elements (LREE) and Nd. In the Nb-Y diagram (Fig. 5), the Luis Alves enderbites and charno-enderbites plot in the field of modern volcanic arc granitoids. This also occurs in the Ta-Yb diagram, where the only three samples which have Ta analyses (Marques 1988) also plot in the field of volcanic arc granitoids, with Ta contents of 0.11 to 0.26 ppm and Yb values ranging from 0.49 to 0.80 ppm. Therefore, in terms of the HFSE, the Luis Alves intermediate and felsic rocks have compositions quite similar to those of tonalites and granodiorites from modern magmatic arcs associated with subduction of oceanic crust.

The REE patterns of the pyroxenites (Fig. 6) analysed by Hartmann (1988) show an arcuate shape with higher contents of intermediate REE and lower contents of LREE, Eu and heavy rare earth elements (HREE), resembling the common patterns of calcic clinopyroxenes (e.g. Arth & Hanson 1975, Fujimaki & Tatsumoto 1984). The range in REE contents allows the participation of some orthopyroxene, which largely rejects REE, in the mineralogical composition of these rocks. The total REE contents of the pyroxenites is relatively high, suggesting that these rocks have indeed been formed from REE-rich basaltic liquids, such as the those which formed the basic rocks of the Luis Alves sequence.

The REE patterns (Fig. 7) for the Luis Alves sequence (Hartmann 1988) are strongly fractionated with the norites having slightly positive Eu anomaly and lower LREE contents, while the enderbites and charno-enderbites have slightly negative Eu anomaly and higher LREE values. The fact that the basic granulites are already highly fractionated in terms of REE (with La contents of about 100 times chondrite) suggests that a high-Al basalt magma, precursor of the basic granulite, was formed by partial melting of garnet peridotite, and that crystal fractionation did not involve garnet or amphibole, in agreement with the fractional crystallization model discussed below. One sample of low-Al, high-Fe basic granulite (CGSC-9) analysed by Hartmann (1988) presents an almost flat REE distribution which strengthens the hypothesis of accumulation of ferromagnesian minerals already proposed for these rocks.

Primitive mantle normalised spidergrams (Fig. 8) for the Luis Alves enderbites show strong depletion in Rb, Th, U and K relative to Andean tonalites, a behaviour similar to that of the Lewisian enderbites (Weaver & Tarney 1980), although not so highly depleted. For less incompatible elements, the Luis Alves rocks show a general similarity with both Andean and Lewisian rocks, but they are not as depleted in Y and HREE as the Lewisian and other Archaean rocks. Marked depletion of Ta and Nb, as well as of Ti, is a common, but not exclusive characteristic of modern calc-alkaline and island-arc magmas and has been explained by retention of these elements in the magma source region by some accessory minerals (Saunders *et al.* 1980, Weaver & Tarney 1980), but could equally be caused by the fact that although Nb and Ta are as incompatible as, for instance, U and K (Sun &

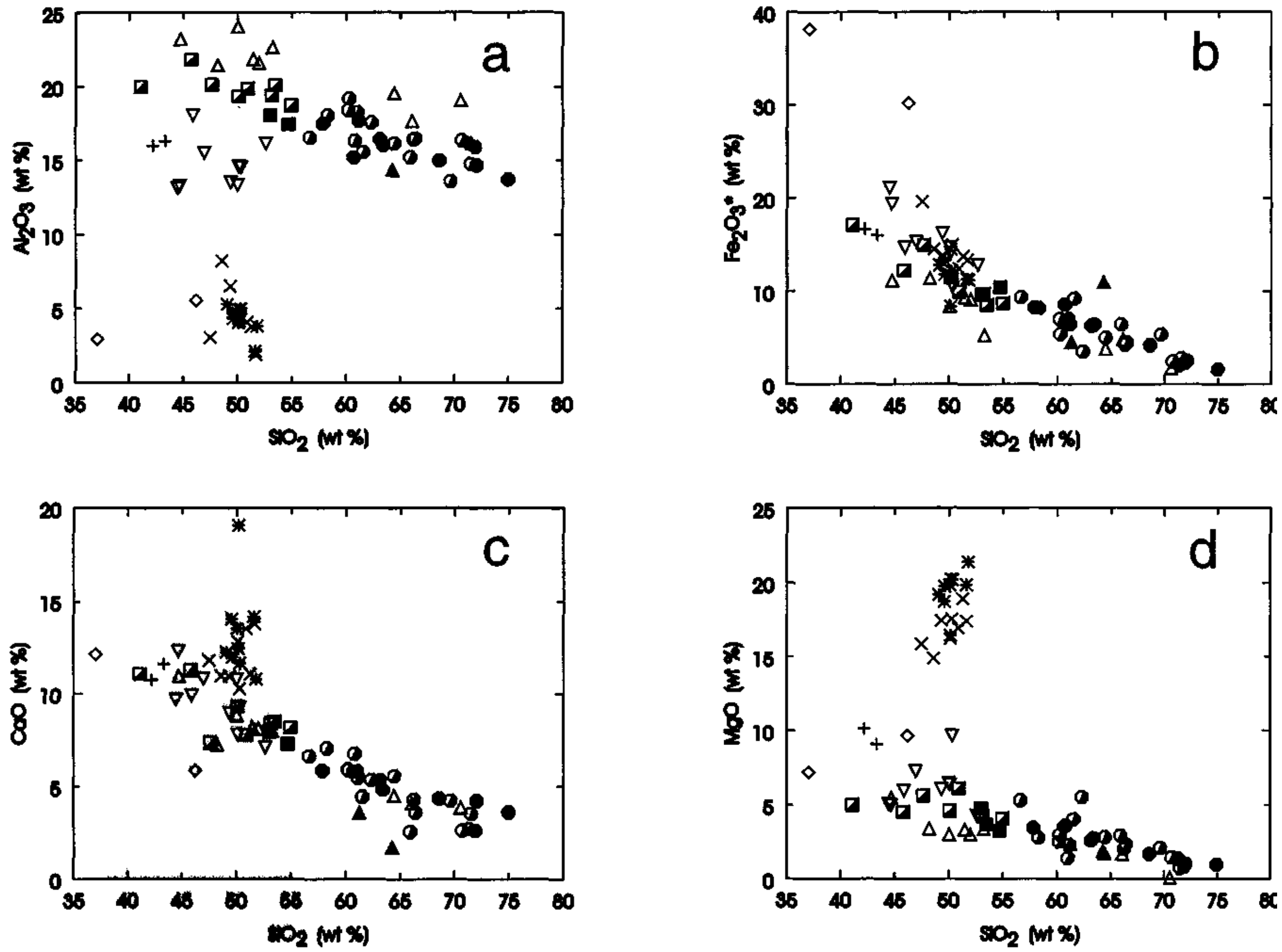

Figure 2 - Marker diagrams for the Santa Catarina granulitic complex: Al_2O_3 (a), $Fe_2O_3^t$ (b), CaO (c) and MgO (d). Symbols: basic granulites (filled squares for data from this work, and half-filled squares for data from other sources) and intermediate-acid granulites (filled circles for d&tafrom this work, and half-filled circles for data from other sources) from high-Al calc-alkaline sequence; "very high""Al rocks (open triangles, data from other sources); "low"-Al rocks (filled inverted triangle for sample SCMB-174RB from this work, and open inverted triangles for data from other sources); samples CAN-30a and CAN-30b from this work (crosses); monzonitc rocks (filled triangles, data from other sources); iron-formations (diamonds, data from other sources); pyroxenites (asterisks for data from this work, and exes for data from other sources). Other sources of data: Moreira & Marimon (1980), Hartmaw (1981, 1988), Marques (1988), and Siga Jr. (1995).

Figura 2 - Diagramas de Barker para rochas do complexo granulftico de Santa Catarina: Al_2O_3 (a), $Fe_2O_3^t$ (b), Cao © e MgO (d). Símbolos: granultios básicos (quadrados cheios, este trabalho; quadrados semi-cheios, da literatura); granulitos intermediários e ácidos da sequência cálcio-alcalina a alto-Al (círculos cheios, este trabalho; círculos semi-cheios, da literatura); rochas a Al muito alto (triângulos abertos, da literatura); rochas a baxio-Al (triangulo invertido cheio, amostra SCMB 174RB deste trabalho; triângulos invertidos abertos, da literatura); amostras CAN30a e CAN 30b, deste trabalho, cruzes; rochas monzoníticas, triângulos cheios da literatura; formações ferríferas (lozângulos, da literatura); piroxenitos, asteriscos deste trabalho, Xs da literatura; Fontes da dados: Moreira & Marimon (1980), Hartmanft (1980,1988), Marques (1988) e Siga Jr. (1995).

McDonough 1989) in oceanic basalt genesis and evolution, they are not mobile in hydrated fluids formed by dehydration of a subducted slab, and are derived exclusively from the mantle wedge without additional enrichments from the slab (McCullock & Gamble 1992), Considering that depletions of these elements also occur in the Luis Alves and Lewisian rocks, it is apparent that it also applies to the generation of some Archaean calc-alkaline magmas.

ISOTOPES Ages of the rocks of the granulitic complex range from Archaean to Meoproterozoic (Hartmann *et al.* 1979, Kaul & Teixeira 1982, Basei 1985, Basei & Teixeira 1987, Mantovani *et al* 1987), clearly indicating the policyclic evolution of this complex. Table 2 presents a synthesis of the available Rb-Sr, U-Pb &nd Pb-Pb results for the granulite complex.

Archaean whole rock Rb-Sr isochron and U-Pb (zircon) upper intercept ages were interpreted (Basei 1985, Mantovani *et al.* 1987, Basei *et al* 1988) as being the age of generation of the igneous precursors, while the granulite facies metamorphism probably occurred around 2.1 Ga during the Transamazonian cycle. This model is supported by the trace element patterns, particularly the LILE depletion, as discussed above, and is in agreement with Hartmann's (1988) interpretation for the Santa Maria Chico granulites in Rio Grande do Sul State, in southern Brazil.

The low initial $^{87}Sr/^{86}Sr$ ratios and μ1 values associated with the Transamazonian ages can be explained if the granulite facies metamorphism acted on rocks which already had very low Rb/Sr ratios, of the order of 0.02, as well as low U/Pb ratios.

In several of the isochrons, both acid-intermediate and basic granulites from the same outcrops were used. Field

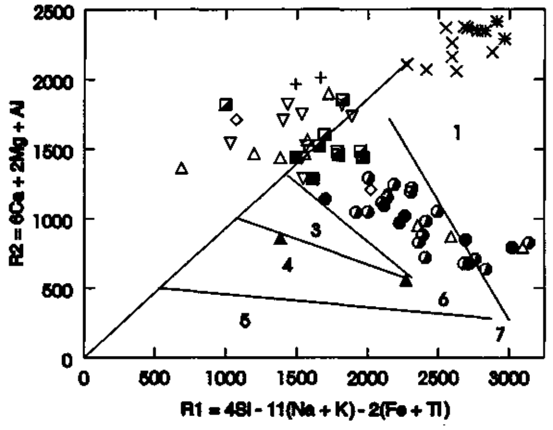

Figure 3 - Santa Catarina granulitic complex rocks plotted in the R1-R2 diagram (De La Roche et al 1980) with the tectonic discrimination fields by Batchelor & Bowden (1985). 1 = mantle fractionates; 2 = pre-plate collision; 3 = post-collision uplift; 4 = late-orogenic; 5 = anorogenic; 6 = syn-collision; 7 = post-orogenie. Same symbols as in Fig. 2.
Figura 3 - O complexo granulítico de Santa Catarina no diagrama R1-R2 (De La Roche *et al,* 1980) incluindo-se os campos de discriminação tectônica de Batchelor & Bowden (1985). 1 = fracionados mantélicos; 2 = pré-colisão; 3 = soperguimento pós-tectônico; 4 = tarde-orogênico; 5 = anorogênico; 6 = sin=colisão; 7 = pós-orogênico. Símbolos, ver Fig. 2.

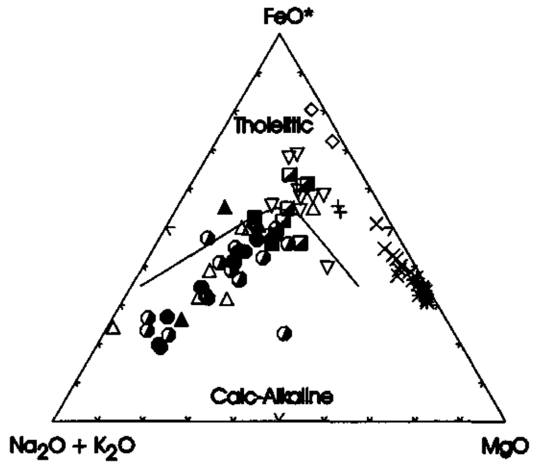

Figure 4 - Santa Catarina granulitic complex rocks plotted in the AFM diagram with the fields of tholeiitic and calc-alkaline rocks (Irvine & Baragar 1971). Same symbols as in Fig. 2.
Figura 4 - O complexo granulítico de Santa Catarina no diagrama AFM com os campos de rochas toleiíticas e cálcio-alcalinas (Irvine & Baragar 1971) Símbolos, ver Fig. 2.

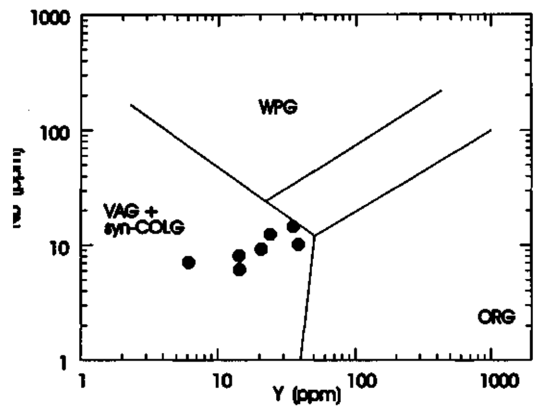

Figure 5 - Luis Alves calc-alkaline intermediate-acid granulites (data from this work) plotted in the Nb-Y diagram (Pearce et al 1984). VAG = volcanic arc granitoids, syn-COLG - syn-collisional granitoids, WPG = within-plate granitoids, and ORG = ocean ridge granitoids.
Figura 5 - Graulitos cdlcio-alcalinos, intermedidrios a ácidos, no diagrama Nb-Y (Pearce *et al.* 1984). Dados deste trabalho. VAG = granitóides de arcos volcânicos; syn-COLG = granitóides sin-colisionais; WPG = granitóides itraplacas; e ORG = granitóides de cordilheiras meso-oceânicas.

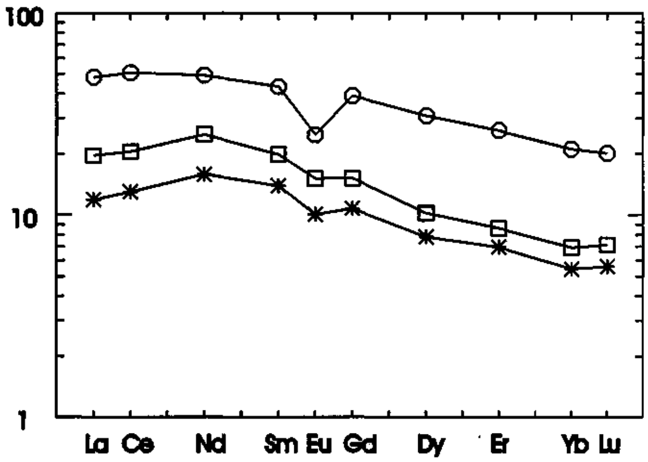

Figure 6 - Chondrite normalised (Evensen et al. 1978, values multiplied by 1.27) REE patterns forBarra Velha pyroxenites (ICP data from Hartmann, 1988).
Figura 6 - Padrões dos elementos terras raras, normalizados aos valores de Evensen *et al.* (1978) multiplicados por 1,27, para os piroxenitos de Barra Velha (dados por ICP de Hartmann 1988).

relationships suggest that the compositional terms are at least chronocorrelated, but the isotopic data do not rule out the possibility that the different terms are not cogenetic.

DISCUSSION In Harker diagrams for major elements the relationship between the compositions of pure cumulate, a parent magma (in the case illustrated, mafic) and differentiated liquid products of fractional crystallization is linear. Where denser, mafic minerals are preferentially accumulated and lighter, felsic minerals such as plagioclase remain in suspension or float in the differentiated liquids, the geometrical distribution of the theoretical points is modified.

In the Luis Alves sequence, some of the mafic rocks appear to be cogenetic with the intermediate and acid types and the trends show an inflexion (at about 51 wt% SiO_2) which is considered as typical of crystal-liquid differentiation processes (e.g. Cox *et al.* 1979). It is therefore probable that the Luis Alves calc-alkaline sequence was formed either by fractional crystallization of the high-Al basalts, or by progressive partial melting. The presence of pyroxenites, anorthosites and cumulate textures, suggest that fractional crystallization was a dominant mechanism.

Approximate step-wise major element mass balance tests of possible differentiation trends were performed using the programme XLFRAC (Stormer & Nicholls 1978). The initial magma composition and intermediate points (Tab. 3) were identified from Harker diagrams, while suitable mineral compositions were selected from Deer *et al.* (1963, 1982). No

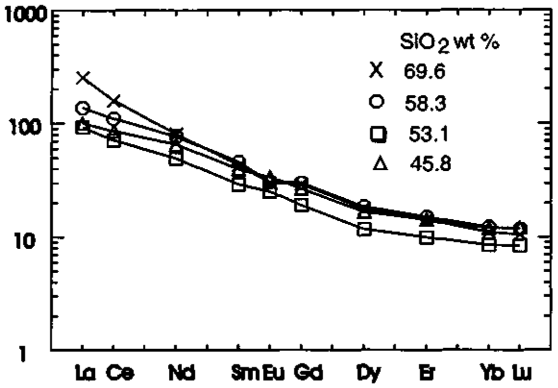

Figure 7 - Chondrite normalised (see Fig.6) patterns for Luis Alves basic to acid granulites (ICP data from Hartmann, 1988).

Figura 7 - Padrões dos elementos terras raras, normalizados conforme em Fig. 6, para granulitos básicos a ácidos de Luis Alves (Dados por ICP de Hartmann 1988).

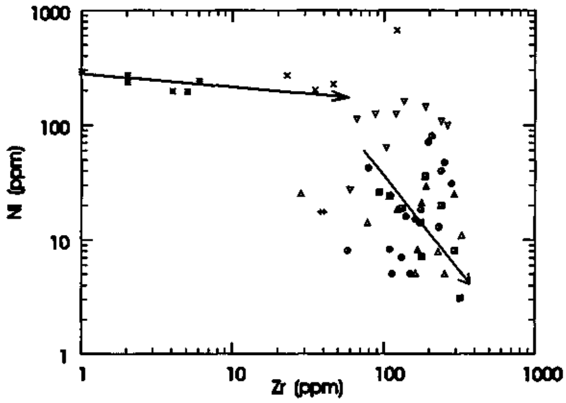

Figure 8 - Log-scale Zr-Ni diagram for Santa Catarina granulitic complex rocks. Same symbols as in Fig. 2.

Figura 8 - Diagrama Zr-Ni em escala lograítmica para rochas do complexo granulítico de Santa Catarina. Símbolos, ver Fig. 2.

attempt was made to continue the fractionation scheme further than tonalite, since more felsic compositions are very variable. A small range of major mineral compositions was allowed for each step, and mineral compositions were systematically varied between steps. Olivine was permitted only for the initial step of the differentiation. The compositions of clinopyroxene-orthopyroxene pairs obeyed reasonable tie-line relationships. Accessory minerals allowed in the initial tests were Ti-magnetite and apatite, and single analyses of these minerals were chosen. Poor results were common for minor elements, especially TiO_2, probably because the concentrations of Ti in augite and Fe-Ti oxides are controlled by the magma composition and will vary substantially during the fractionation. New tests were carried out with the exclusion of these elements from the magma compositions, and the accessory minerals from the model fractionated assemblages, although in the real fractionation they must be present.

The results of the second tests showed that the fractionated solid evolves from (olivine) gabbro-norite for the mafic-intermediate (-54% SiO_2) step, through leucocratic gabbro-norite to leuconorite for the more siliceous steps. The presence of olivine in the early fractionated solid is not essential, since adequate mass balance can be achieved in its absence. A dominant role in the fractionation model is played by plagio-

*Table 2 - Summary of isotopic and geochronological data available for the studied area. * Lower intercept age of 1040 ± 320 Ma*

Tabela 2 - Resume de dados isotópicos e geocronlógicos para a área estudada. * intersepto inferior com idade de 1,040 ± 320 Ma

Locality	Age (Ma)	Error	Initial ratio	Source
Rb/Sr isochrons		1 sigma	$^{87}Sr/^{86}Sr$	
Luiz Alves	2663	72	0.7040	Hartmann et *al.* 1979
Pomerode	2478	37	0.7013	Siga Jr. 1995
Luis Alves	1914 (leucos)	112	0.7046	Basei (1985)
Luis Alves	2829 (mesos)	339	0.7026	Basei (1985)
Blumenau	2169	52	0.7015	Basei 1985
Pomerode	1970	36	0.7024	Siga Jr. 1995
Jaragua do Sul	2184	48	0.7026	Siga Jr. 1995
Pien	2067	199	0.7024	Girardi *et al.* 1974
São Bento do Sul	2107	69	0.7028	Machiavelli *et al* 1993
Camboriá	2587	344	0.7007	Basei 1985
Pb-Pb isochrons		*2 sigma*	μ_I	
Luis Alves	2094	500	8.88	Basei 1985
Presidente Nereu	2388	100	8.61	Basei 1985
U/Pb upper intercept Zircon ages		*2 sigma*		
Luis Alves	~2400	50		Basei 1985
Luis Alves*	~2800	170		Basei 1985
Dona Francisca	2200	2		Siga Jr. 1995
Dona Francisca	2247 (pink)	18		Siga Jr. 1995
Dona Francisca	2360 (brown)	100		Siga Jr. 1995

Table 3 - Compositions of magmas along the liquid line of descent

Tabela 3 - Composições de magmas ao longo da linha de ascendência líquida

	1	2	3	4
SiO_2	50.0	54.5	56.0	64.0
Al_2O_3	17.0	18.6	17.5	17.4
FeOt	11.0	9.3	9.0	5.0
MgO	6.3	4.1	4.0	2.4
CaO	8.9	8.0	6.5	4.9
Na_2O	3.4	4.0	4.2	4.4

clase, extracted in proportions from 54 to 68 wt.% of the total solid.

The theoretical distribution of rock compositions in logioX vs. logioY diagrams (where X is an incompatible element, and Y is a compatible element) could range between the two extremes of pure, unfractionated cumulates forming a cluster off the liquid line of descent to products of crystallization of pure differentiated liquids grouped along a straight line.The resulting ideal distribution of compositions would be fan-shaped. Selective accumulation of mafic phases in the cumulates and retention of plagioclase crystals by the differentiated liquids results in a modified distribution pattern, but chemcal compositions should still lie in a fan-shaped area.

Of the chemical elements analysed in this study, Zr is chosen as the incompatible element, since precipitation of a Zr-rich mineral, which would radically modify the effective weighted partition coefficient, is likely to occur only at the end of the differentiation. Ni was chosen as the compatible

Table 4 - Compositions of fractionated solids. Path: see compositions in Table 3; For path 1→ 2, two options were tested, (a) and (b). W(s) is total of solid removed during the step, W(t) is the total weight separated from 1 to the end of the step in question. In italics, range of compositions of minerals used, with a cut level at MSWD = 2.0. Clinopyroxene compositions maintain the same Mg/(Mg+Fe) as the orthpyroxene or olivine, and have Wo = 45.

Tabela 4 - Composições de sólidos fracionado. Caminho, ver composições em Tabela 3; para a etapa *1→ 2*, foram testradas duas possibilidades, (a) e (b). W(s) representa a soma dos pesos extraidos em cada etapa, W(t) representa o peso total separado, incluindo-se as etapas anteriores. Em italicas, composições do minerais usados, com nível de corte para MSWD = 2,0. Os clinopiroxênios mantém as mesmas razões Mg/(Mg+Fe) dos ortopiroxênios ou da olivina, e contém Wo = 45.

Path	Plag	Cpx	Opx	Ol	W(s)	W(t)
1 → 2 (a)	*(An 75-85)* 54	20	*(En70-80)* 26	-	60	60
1 → 2 (b)	*(An75-85)* 55	18	-	*(Fo70-80)* 27	52	52
2 → 3	*(An65-75)* 66	9	*(En50-60)* 72	-	72	(a) 89/(b) 87
3 → 4	*(An45-55)* 68	11	*(En40-50)* 21	-	86	(a) 98/(b) 98

element (Fig. 9). The scatter of ponts about a steeply-inclined line may be caused by the accumulation processes previously discussed. For the most mafic rocks, however, the scatter may also reflect the presence of various parent magmas, perhaps derived by different degrees of partial melting of the source rocks. These parents magmas result in slightly different intermediate-felsic suites. The steep slope is compatible with an important contribution from fractional crystallization in the derivation of these suites.

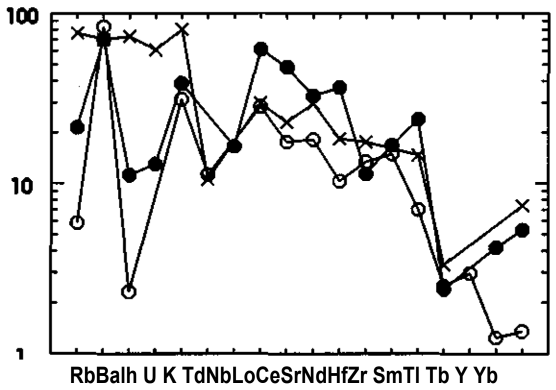

Figure 9 - Primordial mantle normalised distribution of incompatible elements (Wood et al. , 1979) of Luis Alves enderbite (closed circles), Lewisian enderbite (open circles) (Weaver & Tarney, 1980) and Andean tonalite (exes) (sample G18; Lopez-Escobar et al., 1979). For the Luis Alves enderbite: U, Th and Hfare NAA data from Marques (1988); REE are ICP data from Hartmann (1988); other elements are from this work.

Figura 9 - Elementos incompatíveis normalizados ao manto primoridal de Wood *et al.* (1979) para enderbitos de Luis Alves (cículo cheio), do Lewisiano (circulo aberto: Weaver & Tarney, 1980) e tonalito andino (X - amostra G1 8 - Lopez-Escobar *et al.*, 1979). Para o enderbito de Luis Alves, U, Th e Hf foram analisados por NAA (Marques, 1988); dados para elementos terras raras por ICP (Hartmann, 1988); outros elementos, este trabalho.

It is widely recognised that high-grade metamorphism may not be isochemical, especially where anatectic conditions are reached. Furthermore, if the protoliths wer formed under low pressures, there would be every chance that the rocks passed through a prograde metamorphic sequence with ample possibility of open-system conditions prevailing at various stages, perhaps with different intensities for different rocks. The fact that the compositions of the Luiz Alves sequence do conform reasonably well to a fractional crystallization model suggests that the original compositions of the rocks have not been radically modified, except for the LILE.

The petrogenetic model of crystal fractionation starts from a low-K, high-Al tholeiitic mafic magma. The pyroxenites could represent early cumulates formed during this differentiation, while the Fe-rich and Al-very rich basic samples could represent heavy and light cumulates, respectively. The suite formed by intermediate and felsic members is typically calc-alkaline.

Archaean calc-alkaline intermediate rocks are generally considered as formed predominately by partial melting of the subducted slab (e.g. Weaver & Tarney 1980), while modern analogues would be produced mostly by fractionation of basalts formed by partial melting of the mantle wedge modified by the introduction of subduction zone components by hydrated fluids and/or small-fraction partial melts coming from the subducted slab (e.g. Gill 1981). On the other hand, just as the "Archaean" model appears to be feasible to explain the modern adakites, which could be produced by partial melting of young and relatively hot oceanic crust (e.g. Defant & Drummond 1990), so it is proposed here that the petrogenetic process usually considered to be more characteristic of modern subduction zones may have locally occurred in Archaean terranes. Subduction, far from the ocean ridge, of a relatively old and cold slab would be accompanied by dehydrate before melting. The Luis Alves calc-alkaline sequence would be an example of this process. It is of interest to note that the Luis Alves enderbites are not as depleted in Y and HREE (see Fig, 9) as most Archaean intermediate igneous rocks, believed to be produced by partial melting of garnet and/or amphibole-bearing mafic rocks, being similar in this respect to more modern rocks such as the Andean ones.

The Santa Catarina granulitic complex plutonic protoliths may have been formed in an intra-oceanic island arc environment, considering its relatively immature subduction-related composition and the absence of known older terranes which could have acted as a continental margin, as suggested by Figueiredo *et al.* (1991).

CONCLUSIONS The geochemical data suggest that most of the norites, enderbites and charno-enderbites of the Santa Catarina granulitic complex, correspond to a comagmatic calc-alkaline sequence, having as magmatic precursors high-Al tholeiites, high-Al tonalites and granodiorites. The Barra Velha pyroxenites have augitic compositions.

When plotted in variation diagrams, the calc-alkaline sequence data show inflections which are characteristic of crystal-liquid differentiation processes. The presence of pyroxenites, anorthosites and cumulate textures suggests that crystal fractionation had a dominant role. XLFRAC-modelling is consistent with this process and indicates a large predominance of plagioclase, followed by Clinopyroxene, olivine and/or orthopyroxene, Ti-magnetite and apatite as fractionated phases.

Isotope data are consistent with a close genetic link between the basic and acid-intermediate granulites. The igneous component of the Santa Catarina Granulite Complex corresponds to an arc-related Archaean unit submitted to granulite facies metamorphism during the Paleoproterozoic, which promoted LIL element depletion.

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