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

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INTRODUCTION

The Santa Catarina Granulitic Complex (Hartmann et al. 1979) or Luiz Alves domain (Basei et al. 1992, Siga Jr. et al. 1979, Siga Jr. 1995) occurs over about 6000 km² in northern Santa Catarina and southern Paraná 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 Alves Microplate (Basei 1985), who studied the high-grade paragenesis 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.

LITHOGEOCHEMISTRY

This work uses a set of new geochemical data which complements that obtained by other authors (Moreira & Marimon 1980, Hartmann 1981, Silva 1984, Basei 1985), who studied the high-grade facies 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-charnoendebrites. 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.

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Selected analyses are given in Table 1. Determined by XRF spectrometry of pressed powder pellets. The new data were obtained at Memorial University of Newfoundland. The major elements were measured by AAS digestion in teflon bombs, while the trace elements were analysed in this study include examples of the Barra Velha pyroxenites (Table 1) which correspond to mixtures of higher-Al, Ca-rich, and lower-Al, Ca-poor pyroxenes, varying from clinopyroxene 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 cognetic differentiated sequence will be termed here as the Luis Alves sequence. The high-Fe and intermediate to felsic rocks define linear trends in many Barker diagrams. 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 (gabbroanorthosites), 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% Fe₂O₃) 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 cognetic with the main sequence, then they could also represent a cumulate stage for which the corresponding liquid differentiates are the more mafic nortites.

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

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**Figure 1 - Geotectonic sketch map of southeastern Paraná 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.

1988, Mantovani 1985, Marques 1988, Siga J. 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.
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 (Fig. 6) for the Luis Alves sequence (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 calc-alkaline pyroxenites (e.g. Arth & Hanson 1975, Fujimaki & Tatsumoto 1984). The range in REE contents allows the participation of some orthopyroxene, which largely rejectsREE, 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 HREE 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 basaltic 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, Nb and Ta 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 &
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 (McCulloch & 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 Mesoproterozoic (Hartmann et al. 1979, Kaul & Teixeira 1982, Basi 1985, Basi & Teixeira 1987, Mantovani et al. 1987), clearly indicating the polycyclic evolution of this complex. Table 2 presents a synthesis of the available Rb-Sr, U-Pb & Pb-Pb results for the granulite complex.
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% SiO₂) 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
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 TiO₂, 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% SiO₂) 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 plagioclase, 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 chemical 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

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It is widely recognised that high-grade metamorphism may not be isochemical, especially where anatexic conditions are reached. Furthermore, if the protoliths were 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, perhaps with different intensities for different rocks, is consistent with this process and indicates a large contribution from fractional crystallization in the derivation of these suites.

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 ocean 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 dehydration 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 chamo-enderbites of the Santa Catarina granulitic complex, correspond to a cummingtonite-calc-alkaline sequence, having as migmatic 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. XLRFRAC-modeling 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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