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Amphibole-rich clots in calc-alkalic granitoids in the Borborema province, northeastern Brazil

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Abstract — Metaluminous granodioritic–tonalitic plutons intruded low-grade metaturbidites of the Cachoeirinha–Salgueiro terrane and low- to intermediate-grade metasediments of the Macururé terrane, northeastern Brazil, around 630 Ma ago. Four types of amphibole-rich polycrystalline clots, up to 20 cm long, are found within mafic microgranular enclaves or in their granodioritic–tonalitic hosts. Type-I clots are usually angular, with granoblastic textures, composed of amphibole with patchy actinolite cores and magnesiohornblende margins, in polygonal packing where grains commonly display near-120° triple junctions. Interstitial biotite and calcic clinopyroxene are the other component phases. Magnesiohornblende + biotite cumulates form the type-II clots that sometimes constitute an external layer around type-I clots. Actinolite pseudomorphs after clinopyroxene-rich restites form the type-III. A fourth type, texturally similar to type-I clot, contains pyrite as an additional accessory phase and is found only in plutons in the Macururé terrane. Amphibole cores in clots of types I and IV are actinolite with SiO_2 around 55%, MgO (6.5%, FeO 10.5% and Al_2O_3 around 2%, while margins are magnesiohornblende with SiO_2 around 50%, FeO $\approx$ 12%, MgO $\approx$ 14.5%, and $Al_2O_3 \approx 5\%$). Amphibole aggregates in type-II clots display compositions identical to those in the granodiorite hosts. Biotite in types I and IV clots show SiO_2, TiO_2, K_2O and CaO equivalent to those in the granodiorite host, but are about 4% lower in FeO and about 3% higher in MgO. Although all studied plutons are oxidized I-type granites, those from the Cachoeirinha–Salgueiro terrane display quartz-corrected w.r. $\delta^{18}O$ (+11 to +13‰$_{SMOW}$) in the range for S-type granites, while in the Macururé terrane values from +9 to +10‰ are observed. Amphibole-rich clots usually have $\delta^{18}O$ values 1.5‰ lower than those observed in their corresponding hosts. Initial Sr ratios for plutons and their mafic microgranular enclaves are 0.70598 in the Cachoeirinha–Salgueiro terrane. Host plutons show εNd (0.6 Ga) values from −1.0 to −3.0 and −4.6 to −6.7, respectively in the Cachoeirinha–Salgueiro and Macururé terranes, and $\delta^{34}S$ from +1 to +9‰CDT in the Cachoeirinha–Salgueiro terrane. Whole-rock δD values for amphibole clot-bearing granodiorites, mafic microgranular enclaves and clots vary from −69 to −114‰$_{SMOW}$, a variation much broader than for corresponding $\delta^{18}O$ values. Partial fusion of low-T altered basaltic source (amphibolites) generated the calc-alkalic granodioritic–tonalitic magmas in the Cachoeirinha–Salgueiro terrane. Type-I clots are probably fragments or restites of melting of this source. High $\delta^{18}O$ in amphibole-rich clots and granodiorite hosts support this hypothesis. Actinolite pseudomorphs after calcic clinopyroxene (type-III clots) attest to the incorporation of extraneous H into host magmas, causing a wide δD isotopic range. In the Macururé terrane, type-IV amphibole-rich clots are restite remnants of dehydration melting of an amphibolite source.

Keywords: Clot, Calc-alkalic, Restite, Amphibole, northeastern Brazil

INTRODUCTION

The Cachoeirinha–Salgueiro terrane (CST) constitutes a NE-trending structural unit (II in Fig. 1) in the Borborema province, central portion of the states of Pernambuco and Paraíba, northeastern Brazil. This terrane is dominated by low-grade metamorphic rocks (marine turbidites), intruded by oval to elongate magmatic epidote-bearing granodioritic to tonalitic stocks, mostly at 5 kbar pressure or slightly deeper.

Similar plutons have intruded low- to intermediate-grade metasediments (thick, deep-water sequence of greywackes, siltstones and shales) of the Sergipano Foldbelt (V in Fig. 1) in the states of Sergipe and Bahia. These late to post-kinematic plutons (Davison and Santos 1989) are referred to by Santos and Silva Filho (1975) as the Coronel João Sá-type for their type-area. Plutons of the Coronel João Sá-type are restricted to the Macururé terrane (MT) in this belt, south of the São Francisco river.

Rounded to elliptical mafic microgranular enclaves up to 1 m in diameter are common in all of these plutons. Amphibole-rich clots (ARC) of different types and size, up to 30 cm long, mostly angular, are found in both mafic microgranular enclaves and in their granodioritic–tonalitic hosts.

Attempts to explain the origin of amphibole-rich clots led Castro and Stephens (l992) to the following possibilities: (a) they represent mineral cumulates; (b) xenoliths (cognate/accidental); (c) restites; (d) remnants of mingled magmas; or (e) polycrystalline pseudomorphs of phenocrysts and crystal agglomerations

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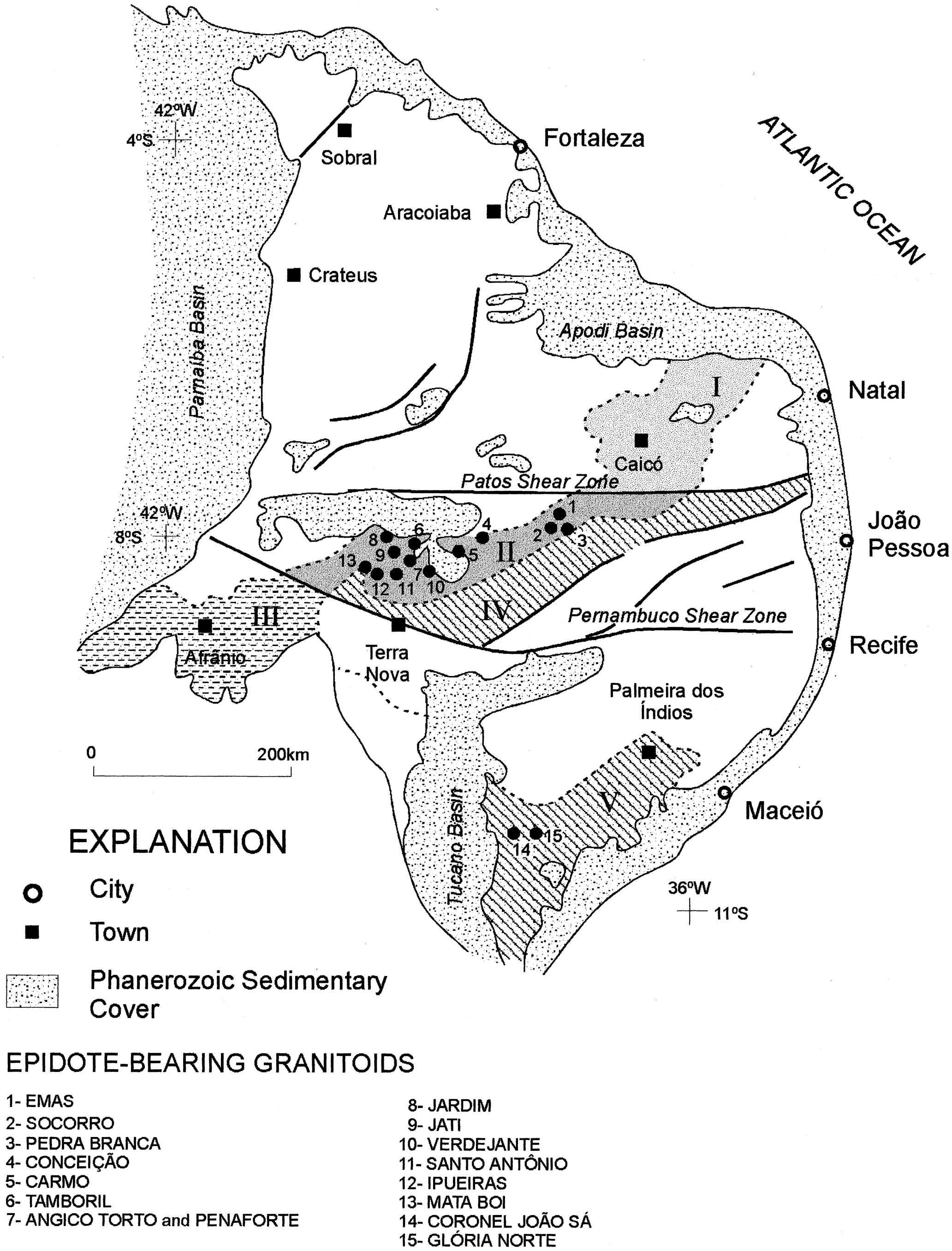

Fig. 1. Simplified geological map of northeastern Brazil indicating locations of calc-alkalic granodioritic–tonalitic plutons which carry amphibole-rich clots (ARC), distributed in two tectonostratigraphic terranes (II = Cachoeirinha–Salgueiro, V = Macururé terranes). Other tectonostratigraphic terranes shown in this map are: I = Seridó, III = Riacho do Pontal, and IV = Alto Pajeú.

with effects of recrystallization. Stephens (1997), in examining the composition of amphibole-rich clot aggregates from the Strontian pluton, Scotland, which are common in many I-type granodioritic–tonalitic plutons, identified them as potential candidates for I-type restites.

The possibility that some of the amphibole-rich clots in the CST and MT granodioritic–tonalitic plutons could represent fragments from the source or restites from melting is examined in the present study in the light of mineralogy, chemistry and isotopic behavior of both the clots and hosts.

FIELD ASPECTS AND PETROGRAPHY OF ARC-HOSTS

Among the ARC-bearing plutons studied in the CST, the medium-grained biotite-hornblende granodioritic- to tonalitic Conceição, Emas, Boa Ventura and Riacho Santo Antonio batholiths and the São José do Bonfim stocks are the best known examples (Goist, 1989; Sial, 1993; Cunha, 1994; Medeiros *et al.*, 1994). These plutons are composed of intermediate plagioclase (An_{35}), K-feldspar, quartz, magnesiohornblende, biotite, epidote (Ps_{19-24}), titanite and very rare iron oxide minerals. Epidote is found in different textural relationships (Sial, 1990), some of them of magmatic origin. Abundant calcic clinopyroxene is found in the Pedra Branca ARC-free pluton, as crystals up to 3 cm long, which often show margins partially transformed into hornblende, suggesting disequilibrium with the host melt.

Thermal aureoles have been identified around some of these plutons (e.g. Riacho Santo Antônio and Angico Torto plutons, Sial *et al.*, 1996) and around granodioritic–tonalitic plutons near Itaporanga town in the state of Paraíba (R. Caby, 1998, written communication). They are kyanite-bearing thermal aureoles (medium-pressure, garnet–staurolite–kyanite–white mica–late biotite metapelites), a relatively rare type, probably equilibrated at about 7–8 kbar, a pressure equivalent to hornblende solidification in some of these plutons (Sial, 1993). This kind of thermal aureole implies that these plutons probably intruded relatively cold middle crust.

Mafic microgranular enclaves in granodioritic–tonalitic plutons in the CST usually display a large number of small amphibole-rich clots (Fig. 2). In many cases, ARC form swarms and probably resulted from disruption of larger amphibolite fragments.

The rounded to elliptical mafic microgranular enclaves in these plutons are of three types: (a) quartz diorites; (b) tonalites; and (c) porphyritic tonalites, composed of plagioclase, biotite, hornblende, magmatic epidote, titanite, apatite and rare iron oxide minerals. They are evenly distributed over the plutons and not all of them carry amphibole-rich clots. In the Emas pluton in the CST, some mafic microgranular enclaves show numerous, homogeneous, millimetric ARC and less abundant, angular quartz lumps up to 5 cm long, also present in granodiorite hosts.

Idiomorphic amphiboles are only observed in mafic microgranular enclaves, and occur especially in the quartz dioritic. There is no correlation between the presence of idiomorphic amphiboles in these enclaves and the presence of amphibole-rich clots. The abundance of clots is not apparently related to higher modal amphibole, except in a few mafic microgranular enclaves where amphibole is locally found as aggregates.

Most mafic microgranular enclaves have seriate texture and comprise plagioclase, amphibole, biotite, quartz, acicular apatite, titanite and opaque minerals. Tourmaline, although rare, has been observed in some of them (e.g. Emas and São José do Bonfim stocks in the CST).

The Boa Ventura pluton carries the largest number of amphibole-rich clots among the studied plutons in the CST. In some places, angular to subrounded clots are numerous and lend an agmatitic aspect to the outcrop (Fig. 3). As in the Emas pluton, ARC are found within quartz diorite and tonalite microgranular enclaves or in the granodiorite hosts.

In the three granodiorite stocks near São José do Bonfim town, ARC seem to be pseudomorphs after pyroxene. Usually, this type of clot is of millimetric size and is often observed in mafic, microgranular enclaves.

In the Macururé terrane, the Glória Norte and the Coronel João Sá granodioritic–tonalitic plutons carry a large quantity of ARC and less abundant, angular quartz lumps. These two plutons are texturally and mineralogically similar to each other and were petrographically described by Santos *et al.* (1988) and Chaves (1991). They contain plagioclase, K-feldspar, hornblende, biotite, clinopyroxene (up to 3 cm long at Coronel João Sá pluton) besides quartz and magmatic epidote. Likewise in the calc-alkalic granitoids in the CST, iron oxide minerals are rare to absent. Magmatic epidote, up to 0.5 mm in length, occurs in three textural relationships: (a) euhedral, zoned, included in plagioclase; (b) with a zoned allanite core; or (c) euhedral to subhedral, included or rimmed by biotite. This mineral is more abundant in the Glória Norte pluton, Clinopyroxene is more common in the Coronel João Sá pluton, in which ARC are also more abundant. This situation contrasts with those observed in ARC-bearing plutons in the CST where calcic clinopyroxene is present only in ARC-free plutons (e.g. the Pedra Branca pluton).

ARC included in mafic microgranular enclaves in the Coronel João Sá and Glória Norte plutons are smaller than those found in their granodiorite hosts. A darker, external layer composed of biotite and hornblende commonly armors clots.

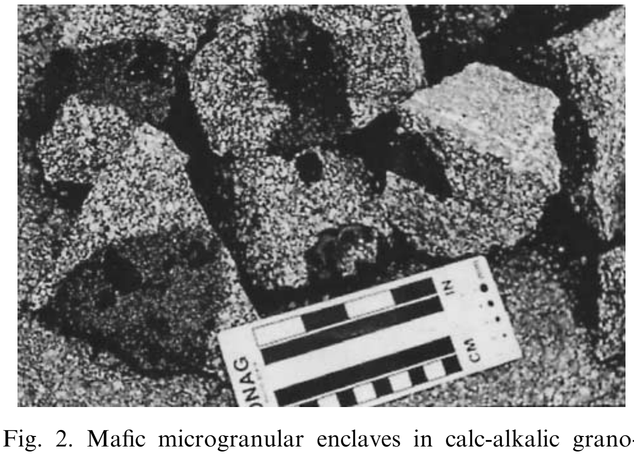

Fig. 2. Mafic microgranular enclaves in calc-alkalic granodioritic–tonalitic plutons in the Cachoeirinha–Salgueiro terrane exhibit, sometimes, many small amphibole-rich clots which are probably disaggregates from larger amphibolite fragments.

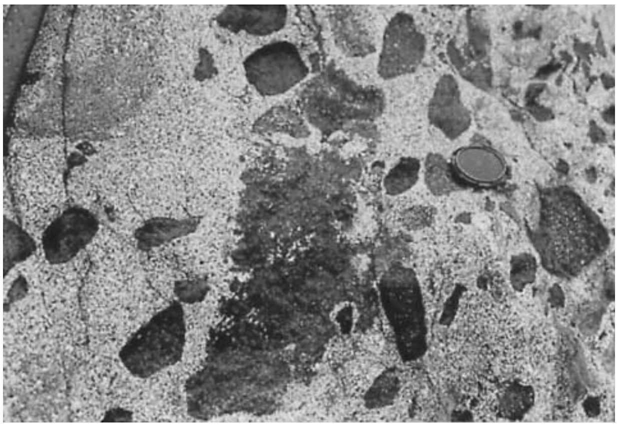

Fig. 3. Angular to subrounded fragments of amphibole-rich clots (ARC) lend to the outcrop, sometimes, an agmatic feature (Boa Ventura pluton, state of Paraíba).

ARC abundance is variable and tends to be evenly distributed throughout some plutons and localized in others, exhibiting a larger size when clustering to form swarms. In the plutons under consideration, ARC of a small size tends to be preferentially concentrated in microgranular tonalite enclaves. The more abundant this type of mafic enclave, the higher the abundance of clots. Similar behavior has been noticed in other calc-alkalic granitic plutons such as in the Central System batholith of Spain (Castro *et al.*, 1991) and in the Sierra Nevada batholith, western United States (Presnall and Bateman, 1993).

TEXTURES AND PETROGRAPHY OF ARC

Four types of textures are observed in the clots. Type-I ARC are found in granodioritic–tonalitic plutons in both the Cachoeirinha–Salgueiro and Macururé terranes. They are composed predominately of reversely or patchy zoned amphiboles, whose grains commonly meet at 120°-triple junctions, ±clinopyroxene and interstitial biotite. They exhibit granoblastic texture in their interior and are generally armored by an outer zone composed of hornblende + biotite whose textural arrangement suggests crystallization directly from host magma.

In these clots, the predominant amphibole is actinolite with a light green core, which is surrounded by marginal hornblende with deeper pleochroic colors (Fig. 4a). Clinopyroxene occurs as pale-green anhedral grains, at low abundance. Pale-brown mica is typically an interstitial phase and either crystallized from the host magma that penetrated interstices of the clot, or from the reaction between the host magma and clot amphibole, being found, in this case, along amphibole cleavages. Most biotites, however, are observed near the rims of the clots, intergrown with the outermost amphibole crystals. Less often, biotite forms triple junctions with amphibole, perhaps due to growth in the solid state. This type of ARC is usually angular, regardless of whether the host rock is deformed or not. In some cases, however, round to oval shapes are observed. The textural relationships in this type of ARC are difficult to explain by crystallization from a silicate melt. Instead, they can be interpreted either as fragments derived from deep amphibolite crust or as pieces from a basaltic source, metamorphosed under P–T conditions of the amphibolite facies.

Type-II ARC are characterized by aggregates of amphibole + biotite, which crystallized from host magma and sometimes surround the type-I ARC (Fig. 4b) armoring it and preventing further interaction with the host magma. Individual amphibole crystals are, generally, even grain-sized. Usually ARC of this kind are of millimetric size, evenly distributed within mafic microgranular enclaves.

Type-III ARC have external shapes that approach that of a euhedral pyroxene section (Fig. 5), being interpreted here as pseudomorphs after early-crystallized pyroxene phenocrysts or pyroxene restites. They are generally composed of actinolite + chlorite, sometimes externally armored by biotite + hornblende, which prevented further interaction with the host magma. In some cases clinopyroxene seems to have dominated the mafic restites. Grain-boundary diffusion from the melt promoted recrystallization of clinopyroxene to actinolite. This type of ARC has been

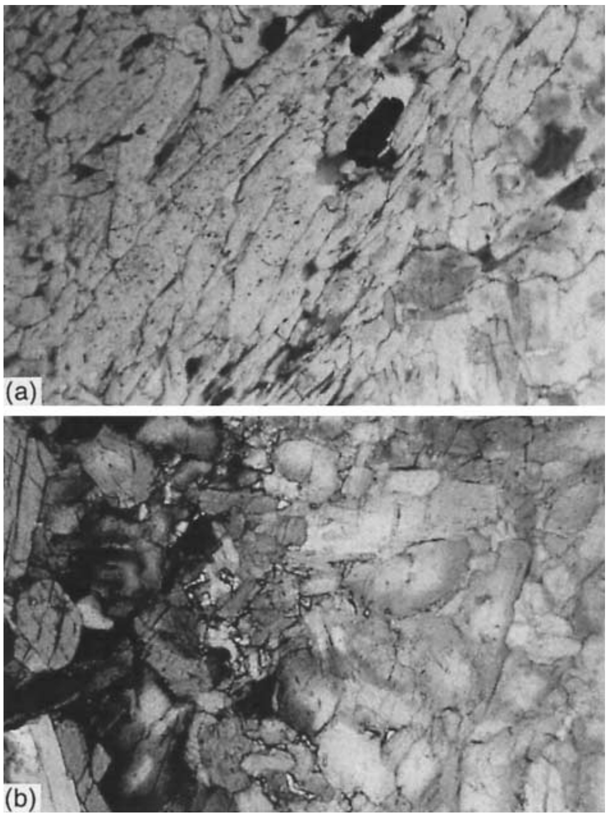

Fig. 4. (a) Aggregates of amphibole with actinolite cores and magnesiohornblende margins (type-I ARC) where grains exhibit a preferential orientation; and (b) Type-II amphibole-rich clots (magnesiohornblende aggregates) surrounding type-I ARC, forming an armoring layer. Nicols not crossed; 63 X.

observed only in the São José do Bonfim stocks in the CST.

Type-IV ARC are only observed in the Coronel João Sá pluton in the Macururé terrane. These clots are texturally and mineralogically very similar to the type-I ARC, but contain small, euhedral, disseminated crystals of pyrite (Fig. 6) and are observed as angular to subrounded xenoliths (Fig. 7). They are usually armored by a layer of amphibole or amphibole + biotite similar to type-I ARC in the CST.

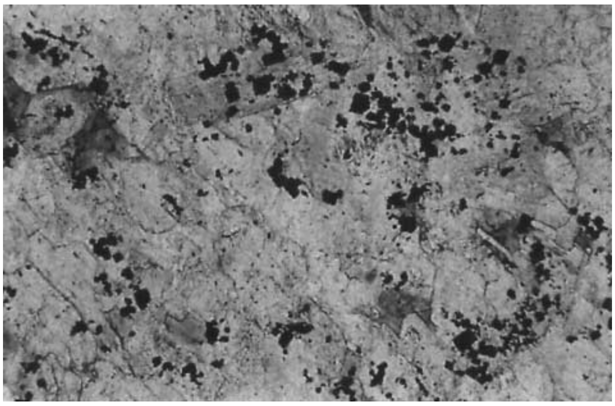

Fig. 6. Type-IV amphibole-rich clot formed by actinolite, interstitial biotite and small pyrite cubes, in the Coronel João Sá pluton, Macururé terrane, state of Bahia. Nicols not crossed; 63 X.

MINERAL CHEMISTRY

Amphibole, biotite, pyroxene, plagioclase and epidote from granodiorite hosts and amphibole and biotite from ARC were analyzed by electron microprobe at the Federal University of Bahia, Salvador, Brazil, totaling about 230 analyses performed. Analyses were carried out with a CAMECA SX50, using a beam current of 20 μA and an acceleration potential of 15 kV. Counting time was 5 s and routine corrections were done using the ZAF program.

Amphibole

Representative analyses of amphiboles from ARC-bearing granodiorite hosts (Conceição, Emas, Boa Ventura and São José do Bonfim granitoids) and the ARC-free Pedra Branca pluton in the CST can be found in Table 1. Structural formulae were calculated on the basis of 23 oxygen atoms. Amphibole compositions have Si atoms per formula unit (afu) ranging from 6.2 to 7.9 atomic formula units (afu) and can be classified in the IMA nomenclature (Leake *et al.*, 1997) as magnesiohornblende to edenite. Representative core analyses of amphiboles of type-I (sample BV-16 in Table 2) and type-IV ARC (CJS in Table 2) confirm the presence of actinolite patches, whereas analyses of margins of amphiboles in these clots display magnesiohornblende composition (BV-17-B, Table 2).

The (Na + Ca + K) vs Si plot (Fig. 8) allows chemical discrimination between metamorphic and igneous amphiboles (Leake, 1971). Type-I ARC amphiboles from Boa Ventura display a compositional trend entirely in the metamorphic field of the diagram, a behavior interpreted as an indication that type-I ARC amphiboles are mostly metamorphic actinolite to magnesiohornblende. Their chemistry has been partially affected by reaction with the host magma. Typical magmatic amphiboles with lower Si in this diagram are from granodiorite hosts. Amphiboles from the Boa Ventura and Conceição plutons, including type-II ARC and granodiorite host, form a continuous trend, mostly in the igneous field, slightly transgressing the boundary between the igneous and metamorphic fields.

The total Al content of amphibole can be used to estimate the pressure of solidification of this phase. Successive empirical and experimental calibrations slightly improved the error of this barometer from ± 3 kbar (Hammarstrom and Zen, 1986) to ± 0.5 kbar (Johnson and Rutherford, 1989) or ± 0.6 kbar (Schmidt, 1992). Johnson and Rutherford's calibration was obtained by performing experiments on natural

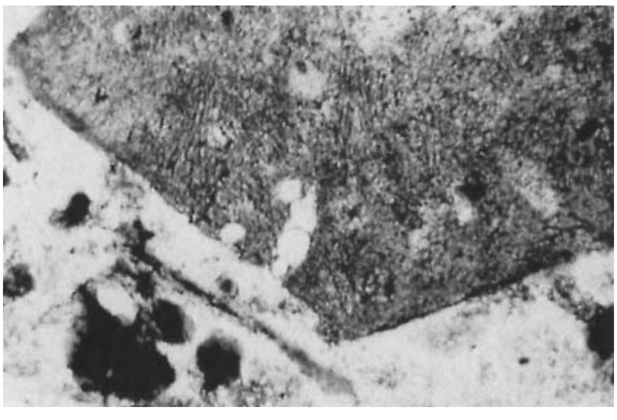

Fig. 5. Amphibole pseudomorphs after pyroxene (type-III ARC) in one of the São José do Bonfim stocks in the Cachoeirinha–Salgueiro terrane. Nicols not crossed; 160 X.

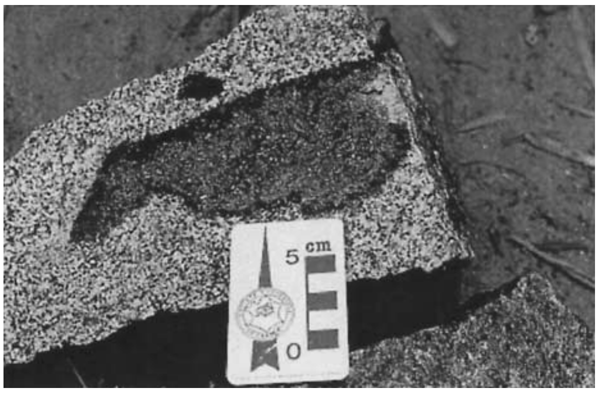

Fig. 7. Large amphibole-rich clot rimmed by a layer of magnesiohornblende + biotite, in the Coronel João Sá pluton, Macururé terrane, state of Bahia.

Table 1. Representative chemical analyses of amphiboles from ARC-bearing granodiorites and ARC-free Pedra Branca pluton in the Cachoeirinha–Salgueiro terrane and from the Coronel João Sá pluton in the Macururé terrane

	Cachoeirinha–Salgueiro terrane									Macururé terrane	
	ARC-bearing plutons							ARC-free plutons		ARC-bear. plutons	
	Boa Ventura		Conceição		Emas		Bonfim	Pedra Branca		Coronel João Sá*	
SiO_2	44.08	45.18	44.21	43.90	42.71	42.22	44.00	42.98	42.67	42.73	41.78
TiO_2	0.68	0.63	1.40	1.41	1.91	1.22	1.26	1.02	1.06	1.31	1.48
Al_2O_3	12.08	11.67	11.07	11.11	10.91	11.36	11.03	11.17	11.55	11.00	10.72
FeO	13.98	14.22	16.91	16.66	17.76	17.94	16.20	17.09	17.29	18.73	18.64
MnO	0.34	0.30	0.33	0.41	–	0.39	0.41	0.36	0.35	0.39	0.40
MgO	10.91	10.66	9.13	8.79	10.30	10.51	9.93	8.51	8.46	8.22	8.39
CaO	11.40	11.55	11.40	11.53	11.60	11.64	12.20	12.91	12.62	11.13	11.02
Na_2O	1.73	1.59	1.67	1.63	1.45	1.68	1.41	1.21	1.44	1.48	1.56
K_2O	1.50	1.37	1.21	1.26	1.32	1.72	–	1.59	1.70	1.46	1.49
Cr_2O_3	0.09	0.01	0.28	0.08	–	–	–	0.06	0.04	–	–
SrO	0.05	0.08	0.04	0.07	–	–	–	–	–	–	–
Total	100.84	99.28	99.69	98.76	97.76	98.75	96.49	98.86	98.45	96.46	95.48
Structural Formulae (23 oxygens)											
Si	6.59	6.71	6.64	6.65	6.35	6.26	6.69	6.56	6.51	6.54	6.47
Al(IV)	1.41	1.29	1.36	1.35	1.65	1.74	1.31	1.44	1.49	1.46	1.53
T	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al(VI)	0.72	0.75	0.60	0.63	0.040	0.25	0.66	0.67	0.58	0.53	0.43
Fe	1.75	1.77	2.12	2.11	2.27	2.29	2.04	2.18	2.21	2.39	2.41
Ti	0.08	0.07	0.16	0.16	0.012	0.14	0.14	0.18	0.12	0.15	0.17
Mg	2.43	2.36	2.05	1.98	2.21	2.32	2.16	1.93	1.92	1.88	1.94
$\mathbf{M_1+M_2+M_3}$	4.98	4.95	4.93	4.88	5.00	5.00	5.00	4.96	4.83	4.95	5.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.04	0.04	0.04	0.05	0.00	0.05	0.05	0.05	0.05	0.00	0.05
Ca	1.83	1.84	1.84	1.87	1.92	1.88	1.98	2.11	2.06	1.83	1.83
Na	0.13	0.12	0.12	0.13	0.08	0.07	0.00	0.00	0.00	0.17	0.17
$\mathbf{M_4}$	2.00	2.00	2.00	2.00	2.00	2.00	2.03	2.16	2.11	2.00	2.00
Na	0.37	0.34	0.37	0.35	0.41	0.41	0.49	0.36	0.43	0.27	0.30
K	0.29	0.26	0.23	0.24	0.31	0.33	–	0.31	0.33	0.29	0.29
A	0.66	0.60	0.60	0.59	0.72	0.74	0.49	0.67	0.76	0.56	0.59

* = from Castellana 1998,

samples under CO_2+H_2O volatile pressure. Presence of magmatic epidote implies a low-CO_2 activity during crystallization of the host magma (Ghent *et al.*, 1991) and, therefore, Schmidt's calibration seems to be more appropriate for plutons in the present study.

The Al(t) in amphiboles of ARC-bearing plutons varies from 1.67 to 2.13 in the Boa Ventura, from 1.65 to 1.98 in the Conceição, from 1.89 to 1.97 in the São José do Bonfim plutons, and from 2.01 to 2.18 in the ARC-free Pedra Branca pluton. All of these bodies show the mineralogical assemblage appropriate to buffer the Al content in hornblende. If all the aluminum in this phase is ascribed to pressure and Schmidt's equation is used, pressures of solidification in the 4.8–7.0 kbar range are obtained for amphiboles from the Boa Ventura pluton, 4.7 to 6.3 kbar for Conceição pluton, and 5.5–6.5 kbar for the São José

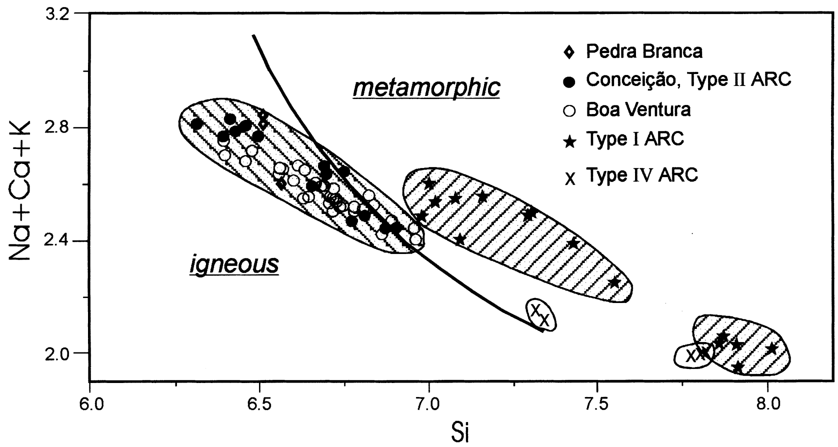

Figure 8

Fig. 8. Compositions of amphibole from ARC-free pluton (Pedra Branca), ARC-bearing plutons (Conceição and Boa Ventura) and type II ARC plot in the igneous field of the Na + Ca + K vs Si diagram, while amphibole cores of types I (Boa Ventura) and IV ARC (Coronel João Sá) plot in the metamorphic field (modified from Leake, 1971).

Table 2. Representative electron microprobe analyses of amphiboles in types-I and II ARC from Boa Ventura pluton in the Cachoeirinha–Salgueiro terrane and of type-IV ARC in the Macururé terrane

	Cachoeirinha–Salgueiro terrane						Macururé terrane			
	BV-16 (type-I ARC)			BV-17-B (type-II ARC)			CJS-20 (type-IV ARC; Castellana 1998)			
	15	16	18	24	29	26	1	2	3	4
SiO_2	51.66	55.30	54.93	43.00	42.02	42.13	55.09	54.45	50.73	50.85
TiO_2	0.16	0.06	0.01	0.83	2.19	0.94	0.13	0.11	0.46	0.37
Al_2O_3	3.27	0.68	0.82	11.23	11.65	11.45	2.02	2.32	5.59	5.02
MgO	16.80	19.59	18.44	9.59	8.60	9.42	16.81	16.31	14.49	14.51
CaO	12.22	12.57	12.23	9.59	8.60	9.42	12.11	12.49	11.80	12.15
MnO	0.54	0.49	0.48	0.40	0.32	0.47	0.41	0.34	0.42	0.33
FeO	8.98	7.46	8.12	16.89	16.50	16.34	10.46	10.48	12.24	11.79
Na_2O	0.95	0.42	0.45	1.54	1.73	1.64	0.52	0.31	1.02	0.66
K_2O	0.49	0.06	0.10	1.39	1.23	1.51	0.22	0.21	0.56	0.64
Cr_2O_3	0.61	0.13	0.06	0.13	0.05	0.13	–	–	–	–
NiO	0.06	0.09	0.02	0.03	0.07	0.05	–	–	–	–
SrO	–	–	–	0.02	0.01	0.02	–	–	–	–
BaO	–	–	–	0.00	0.11	0.00	–	–	–	–
H_2O	2.05	2.11	2.08	1.97	1.95	1.95	–	–	–	–
Si	7.55	7.85	7.91	6.55	6.45	6.47	7.81	7.81	7.34	7.44
Ti	0.02	0.01	0.00	0.09	0.25	0.11	0.01	0.01	0.05	0.04
Al	0.56	0.11	0.14	2.02	2.07	2.11	0.34	0.39	0.95	0.04
Cr	0.07	0.01	0.01	0.02	0.01	0.02	–	–	–	–
Mg	3.66	4.15	3.96	1.18	1.96	2.16	3.55	3.49	3.12	3.17
Ca	1.91	1.91	1.89	1.91	1.92	1.94	1.84	1.92	1.83	1.91
Mn	0.07	0.06	0.06	0.05	0.04	0.06	0.05	0.04	0.05	0.04
Fe	1.09	0.88	0.98	2.15	1.12	2.10	1.24	1.26	1.48	1.45
Ni	0.01	0.10	0.03	0.00	0.01	0.01	–	–	–	–
Sr	–	–	–	0.00	0.01	0.00	–	–	–	–
Ba	–	–	–	0.00	0.01	0.00	–	–	–	–
Na	0.08	0.01	0.02	0.46	0.51	0.49	0.14	0.08	0.17	0.09
K	0.08	0.01	0.02	0.27	0.24	0.30	0.04	0.04	0.10	0.12
Total	15.29	15.14	15.09	15.50	15.63	15.62	15.02	15.04	15.09	15.13

do Bonfim stocks. Amphiboles precipitated from melt in the Pedra Branca granodiorite yielded solidification pressures slightly greater than 6 kbar (6.4–7.2 kbar). Fifty percent of the analyzed amphiboles from the Boa Ventura pluton solidified at 6 kbar pressure or slightly deeper, while in the Conceição pluton, 80% of the analyzed amphiboles yielded pressures slightly < 6 kbar.

Amphiboles in type-I ARC (which may represent source fragments or restites) appear to have re-equilibrated with the host magmas, since both tend to yield pressures in the same range. The attempt to estimate crystallization pressures for amphiboles in type-I ARC, however, was discarded since assemblages in this type of clot do not correspond exactly to that for which the barometer was calibrated. Amphiboles (edenite) from type-II ARC in the CST, supposedly crystallized from the host magma, yielded pressures between 5.5 and 7 kbar.

According to Silva Filho and Guimarães (1994), hornblende in the Coronel João Sá granodiorite in the MT solidified around 4.2 ± 0.5 kbar while hornblende in the Glória Norte pluton solidified around 3.4 ± 0.5 kbar, using Johnson and Rutherford's (1989) barometric equation. Utilizing Schmidt's calibration, however, pressures around 6 and 5 kbar are obtained, respectively, for the Coronel João Sá and Glória Norte plutons.

Amphiboles of type-IV ARC in the Coronel João Sá pluton are magnesiohornblende and actinolite (Table 2). Magnesiohornblende shows average SiO_2 of 50%, FeO = 12%, Al_2O_3 = 5.5%, MgO = 14.5% and Na_2O = 0.5%, whereas the actinolite displays SiO_2 of 54.5%, Al_2O_3 = 2%, FeO = 10%, MgO = 16.5%, CaO = 12.5% and Na_2O = 0.35% (Table 2).

Nabelek and Lindsley (1985) calibrated a thermometer for mafic metamorphic rocks or granulites based on the chemistry of amphiboles. Type-I ARC amphiboles in the CST yielded temperatures in the 670–690°C range while in type II, temperatures in the 740–770°C range were found.

Clinopyroxenes

Elongate clinopyroxene crystals, up to 3 cm long, are common in the ARC-free Pedra Branca pluton in the CST and in one of the three facies of the ARC-bearing Coronel João Sá and Glória Norte plutons in the MT. Sometimes, they show borders partially transformed into amphibole which differ optically from amphiboles precipitated from the host melt.

Clinopyroxene from the Pedra Branca pluton displays a narrow compositional variation, from $Wo_{54}En_{31}Fs_{18}$ to $Wo_{54}En_{33}Fs_{13}$ and in the largest phenocrysts only little compositional variation is observed from core to margin. They display optical characteristics of diopside but their high Wo contents ($>50\%$) make their compositions plot in the pyroxenoid field, right above the area for the salite composition in the pyroxene quadrilateral. Their Fe/(Fe + Mg) ratios are around 0.10, the alumina varies from 0.7 to 1.5%, with Al almost totally in the T site in the structural formula, Al^{VI} being in most cases absent. Kushiro (l960) proposed that during magmatic crystallization, the proportion of Si increases in the pyroxene structure whereas that of Al in the tetrahedral site decreases. The situation where $Al^{IV} > Al^{VI}$ (Thompson, 1947) is somewhat typical for minerals formed at high temperature. These two characteristics combined suggest that this pyroxene probably crystallized at relatively high temperature.

In contrast, clinopyroxenes of the Coronel João Sá pluton in the Macururé terrane exhibit lower alumina variation (0.2–1.0 %) and show no Al in the tetrahedral site. Their Fe/(Fe + Mg) ratios are higher, between 0.35 and 0.40.

Clinopyroxene cores in type-I amphibole-rich clots from one of the São José do Bonfim stocks in the Cachoeirinha–Salgueiro terrane show $SiO_2 \cong 49\%$, $Al_2O_3 \cong 8\%$, total $FeO \cong 12\%$, $CaO \cong 12.5\%$, $MgO \cong 14\%$ and $Na2O \cong 1\%$, with K_2O practically absent. The Al_2O_3 content is slightly higher than the average observed for chrome-diopsides (6%) from upper mantle spinel–lherzolite nodules in Tertiary basaltic plugs in NE Brazil (Sial, 1977), supposedly crystallized at depths of 60–70 km and most likely resulted from interaction with the host magma.

Clinopyroxenes in type-III clots are usually partially or almost totally transformed into actinolite (chlorite), precluding analysis of their original chemical composition.

Biotites

This phase is widespread in the plutons under consideration, occupying up to 22% by volume in the Boa Ventura batholith, 21% in the Conceição, and 18% in the Pedra Branca plutons in CST and occupies about 15–20% by volume in the ARC-bearing granodiorite plutons in the MT. There is no substantial variation in the biotite chemistry of the granodiorite plutons, which usually shows FeO in the 15–18% range, MgO = 11–13%, $Al_2O_3 = 14–16\%$ and TiO_2 in the 1.5–3% range (Table 3).

According to experiments of Wones and Eugster (1965), biotite crystallizing in the presence of K-feldspar and magnetite can follow a trend rich in Fe or in Mg, depending upon the partial pressure of oxygen during the cooling of the melt. In the case of crystallization under oxidizing conditions, biotite is rather Mg-enriched and there is a considerable amount of modal magnetite, whereas in crystallization under reducing conditions, biotite crystallizes preferably enriched in Fe, and magnetite is scarce.

Although biotites in the plutons from CST and MT are not as Fe-enriched, Fe-oxide minerals are usually absent in all of the studied samples, a fact that leads to the assumption that Fe^{3+} is preferentially tied to the structure of the coexisting magmatic epidote. According to the biotite chemistry, these plutons crystallized at relatively high oxygen fugacity. However, since the Fe/Mg ratios in biotites from the Conceição and Boa Ventura plutons are low (< 1.3) relative to other plutons in the CST of the same kind (e.g. Pedra Branca (1.6), it seems that the prevailing fO_2 during crystallization experienced significant variation from pluton to pluton.

Interstitial biotites in amphibole-rich clots of types I and IV exhibit SiO_2, TiO_2, Al_2O_3 and CaO contents similar to those in the granodiorite hosts (Table 3). FeO, however, is about 4% lower than in biotites in the granodiorite hosts and MgO is about 3% higher.

Table 3. Representative electron microprobe analyses of biotite from types I and II ARC in the Boa Ventura pluton in the Cachoeirinha–Salgueiro terrane and from type-IV ARC from the Macururé terrane. Cations based on 23 oxygens

	Cachoeirinha–Salgueiro terrane							Macururé terrane		
	Type-I ARC			Type-II ARC			MBV-20-A	Type-IV ARC*		CJS-25*
	1	2	3	4	5	6	7	8	9	10
SiO_2	39.15	39.15	38.97	38.59	38.70	38.89	38.58	38.26	37.55	36.29
TiO_2	1.68	1.59	1.53	2.01	2.16	2.08	2.00	2.07	2.02	1.90
Al_2O_3	15.36	14.96	15.06	15.98	15.69	15.60	15.97	13.72	14.90	14.37
MgO	11.14	11.27	11.20	11.97	12.00	11.81	11.97	13.71	12.36	11.90
CaO	0.02	0.00	0.04	0.02	0.00	0.03	0.02	0.03	1.43	0.11
MnO	0.24	0.17	0.19	0.26	0.30	0.32	0.26	0.26	0.25	0.29
FeO	18.22	18.01	17.77	16.59	16.94	17.73	16.59	15.82	15.86	19.32
Na_2O	0.03	0.05	0.07	0.09	0.07	0.08	0.09	0.04	0.05	0.10
K_2O	9.18	9.44	9.75	9.79	9.43	9.16	9.79	9.56	8.64	0.15
H_2O	3.80	3.96	3.95	4.00	4.00	4.01	3.99	–	–	–
Total	99.02	98.60	98.53		99.29	99.70	99.29	93.46	93.06	93.43
Si	5.90	5.93	5.92	5.79	5.80	5.82	5.78	5.85	5.76	5.66
Ti	0.19	0.18	0.18	0.23	0.24	0.23	0.22	0.24	0.23	0.22
Al	2.73	2.67	2.69	2.82	2.77	2.75	2.82	2.47	2.69	2.64
Mg	2.50	2.55	2.53	2.68	2.68	2.63	2.67	3.12	2.83	2.77
Ca	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.23	0.02
Mn	0.03	0.02	0.02	0.03	0.04	0.04	0.03	0.03	0.03	0.04
Fe	2.30	2.28	2.26	2.08	2.12	2.22	2.08	2.02	2.03	2.52
Na	0.01	0.01	0.02	0.03	0.04	0.04	0.03	0.01	0.01	0.03
K	1.77	1.82	1.89	1.87	1.80	1.75	1.87	1.86	1.94	1.82
Total	15.43	15.47	15.51	15.53	15.48	15.46	15.53	15.60	15.75	15.72

*From Castellana 1998

This chemical behavior of clot interstitial biotites is interpreted here as an indication that they probably crystallized from the host melt that invaded the clots during their upward transport.

Plagioclase

Semi-empirical evaluation of the available experimental data on plagioclase + amphibole assemblages led Blundy and Holland (1990) to propose a thermometer that yields temperatures with uncertainties of around $\pm75^{\circ}$C for rocks equilibrated at temperatures in the 500–1000°C range. This thermometer was later refined by Holland and Blundy (1994) and can be applied to assemblages where plagioclase contains Si < 7.8 afu. Plagioclase compositions in granodiorite vary from An_{46} to An_{20} (average An_{35}) in the Boa Ventura pluton, An_{60} to An_{32} (average An_{36}) in the Conceição pluton, and An_{40} to An_{16} (average An_{34}) in the Pedra Branca pluton.

Temperatures of crystallization of hornblende–plagioclase pairs in the Boa Ventura pluton, estimated utilizing Blundy and Holland's thermometric equation, are in the 650–770°C range (from 13 pairs, 11 yielded temperatures in the 700–770°C interval). In the Conceição pluton, temperatures estimated by this approach range from 685 to 715°C and from 735 to 745°C in the Pedra Branca pluton. The latter is less hydrated than the other plutons examined in this study and the narrow temperature range estimated suggests that amphibole is a near-solidus phase. Therefore, the minimum pressure estimated for solidification of hornblende in this pluton corresponds, approximately, to that of the depth of emplacement ($\cong$6.4 kbar).

Epidote

Microprobe data indicate that the atomic Fe^{3+} $(Fe^{3+}+Al)$ ratio (Ps content) of euhedral to subhedral magmatic epidote in the Boa Ventura and São José do Bonfim plutons lies between Ps_{20} and Ps_{24}, a variation equivalent to that of epidote phenocrysts ($Ps_{19–24}$) in high-K calc-alkalic dikes of the Front Range of Colorado (Dawes and Evans, 1991) one of the strongest examples of magmatic epidote. Similar compositional range is found in magmatic epidote in granodioritic–tonalitic plutons in the Macururé terrane. Compositions for some epidotes in Farrow and Barr (1992), Rogers (1988) and Owen (1991) also lie in this range.

In the present study, compositions of epidote lie outside the field limited by the stability curves for epidote + quartz for the NNO and HM buffers (Ps content of epidote respectively of 25 and 33%; Liou 1993). This suggests that the prevailing fO_2 during crystallization in these plutons probably followed the NNO buffer curve or a fO_2–T curve between that and the QMF buffer curve.

MAJOR AND TRACE ELEMENT CHEMISTRIES

Almost 70 complete whole-rock analyses (major, trace and rare-earth elements) of magmatic epidote-bearing granitoids in the Cachoeirinha–Salgueiro terrane are available, including samples from granodioritic–tonalitic plutons, mafic microgranular enclaves and amphibole-rich clots. Microgranular enclaves and hosts exhibit an overall SiO_2 variation from 56 to 71% with Al_2O_3 around 15%, Na_2O usually $> K_2O$ ($<$ 4%), and MgO varying from 0.4 to 4%. Most of these plutons are metaluminous to slightly peraluminous and show high Ba (650–1500 ppm), moderate Sr (250–500 ppm), and intermediate Zr (180 ppm) contents.

Almost 50 bulk chemical analyses of the Coronel João Sá and Glória Norte plutons are available. Detailed discussion on the major and trace-element chemistries can be found in Fujimori (1989), Santos *et al.* (1988), Chaves (1991) and Castellana (1998). These plutons, in a similar fashion to the granodioritic–tonalitic plutons of the CST, are metaluminous to slightly peraluminous. They show an overall variation of Sr from 540 to 930 ppm, Zr from 280 to 550 ppm, Rb from 100 to 320 ppm, Ba from 900 to 1500 ppm and F from 160 to 2300 ppm (with most values >700 ppm). They are slightly K-enriched, $FeO/Fe_2O_3 > 1$, Na_2O < 5%, $K_2O <$ 4% with normative hypersthene and diopside.

The granodioritic–tonalitic hosts in the Cachoeirinha–Salgueiro terrane are enriched in REE relative to chondrite abundance, depleted in HREE relative to LREE and display a variable negative Eu anomaly (Eu/Eu* varies from 0.75 to 0.90) and total REE from 116 to 166 ppm. The REE abundance patterns for host and mafic microgranular enclaves are parallel and almost coincident, suggesting that fractional crystallization only happened to a limited extent.

Normalized REE-patterns for the Coronel João Sá and Glória Norte plutons are similar to those in plutons in the CST, being LREE-enriched and strongly fractionated. La/Yb varies from 30 to 40 (Eu/Eu* = 0.8–0.9), total REE (180–270 ppm in the Coronel João Sá and around 180 ppm in the Glória Norte pluton) and decreases with SiO_2 increase.

Type-I ARC in calc-alkalic plutons in the Cachoeirinha–Salgueiro terrane (Table 4) display an overall SiO_2 of 48–53%, Al_2O_3 (6–9%), CaO (7–12%), MgO (13.7–15.9%), FeO (11–13%), K_2O (1.3–2.6%), and Na_2O (0.4–0.75). Trace elements (Th, Y, Zr, Nb and Sr) are usually low. Ba varies from 99 to 700 ppm, with the highest values correlating with higher amounts of biotite. Chondrite-normalized REE patterns are LREE-enriched and HREE-depleted with a discrete negative Eu anomaly; they are very similar to the REE patterns of the granodiorite host with lower total REEs.

Table 4. Bulk chemical analyses of type-I ARC from calc-alkalic granitoids in the Cachoeirinha–Salgueiro terrane

			Boa Ventura			Conceição	
	MBV-17	AMPH-1	AMPH-2	AMPH-3	AMPH-4	MAF-1	MAF-2
SiO_2	55.30	53.10	50.60	52.20	48.00	52.20	51.60
TiO_2	0.31	0.22	0.47	0.21	0.64	0.30	0.29
Al_2O_3	6.80	5.60	6.40	5.50	9.10	5.60	6.20
Fe_2O_3	4.00	2.70	3.20	2.90	4.50	1.90	2.80
FeO	7.40	8.00	9.20	7.80	8.10	8.10	7.60
CaO	10.90	12.30	10.10	11.00	7.40	9.70	9.10
MgO	12.40	13.70	15.00	15.90	14.40	17.00	16.00
Na_2O	0.90	0.72	0.65	0.63	0.42	0.36	0.35
K_2O	0.55	1.30	2.10	1.40	2.60	2.30	2.80
MnO	0.31	0.26	0.26	0.27	0.22	0.30	0.29
P_2O_5	0.05	< 0.05	< 0.05	< 0.05	0.28	< 0.05	0.05
H_2O+	0.67	1.41	1.65	1.58	2.83	0.30	0.36
H_2O-	0.13	0.18	0.12	0.08	0.34	1.65	1.65
F	–	0.30	0.26	0.30	0.36	0.24	0.28
CO_2	< 0.05	< 0.05	–	–	< 0.05	< 0.05	–
Cr_2O_3	–	0.35	0.15	0.34	0.22	0.30	0.36
Ni	–	0.047	0.018	0.021	0.041	–	–
Ba	210	700	220	99	190	110	120
Th	< 5	< 10	< 10	< 10	< 10	< 10	< 10
Sr	36	48	27	26	24	20	17
Zr	56	44	58	49	46	54	64
Y	15	11	29	6	20	10	13
Rb	10	11	–	–	–	–	–

In a MORB-normalized elemental concentration diagram (not shown), amphibole-rich clots in some granodioritic–tonalitic plutons in the Cachoeirinha–Salgueiro terrane show a relatively homogeneous behavior, with Sr, P, Zr and Ti and Yb depletion and K, Rb, Ba, Nb, Ce and Sm enrichment. Ba, Ce and Sm are the most enhanced.

ISOTOPE GEOCHEMISTRY

Oxygen isotopes

Oxygen isotope analyses were performed by the conventional method at the Stable Isotope Laboratory, Federal University of Pernambuco, Brazil, reacting silicate samples with fluorine gas overnight at 550–600°C. The released O_2 was converted to CO_2 by reaction with pure carbon rod at 400°C. Isotope ratios were measured with a VG SIRA II, double inlet, triple collector mass spectrometer.

All analyzed samples from granodioritic–tonalitic plutons in the CST exhibit high whole-rock $\delta^{18}O$ (+11 to +13 ‰$_{SMOW}$) and even quartz-corrected values are high (Table 5, Fig. 9), a behavior typical for S-type granites in Australia (O'Neil *et al.*, 1977). Since these rocks are typical oxidized I-type granites, this unexpected behavior suggests that the I-type source was ^{18}O-enriched before the partial melting took place.

Mafic microgranular enclaves display $\delta^{18}O$ in the range of the granodiorite hosts at Conceição and Emas plutons (Table 5). ARC values exhibit values from +10.1 to +11.6‰$_{SMOW}$, an isotopic composition attributable to the source of these magmas, unless they have been badly contaminated by high

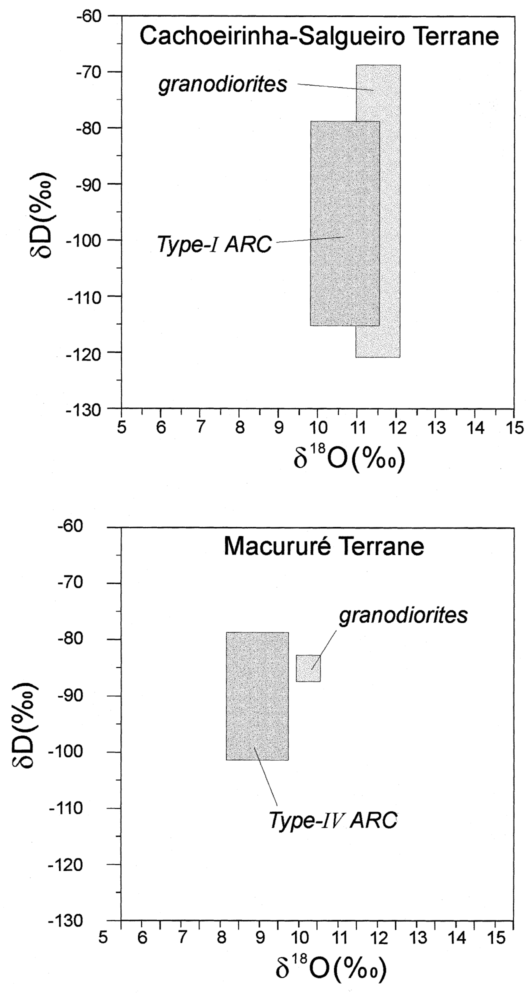

Fig. 9. (a) Type-I amphibole-rich clots and granodiorite hosts in plutons in the Cachoeirinha–Salgueiro terrane exhibit high $\delta^{18}O$ values and a wide range of δD that lie, in a $\delta^{18}O$ vs δD diagram, in adjacent fields. (b) $\delta^{18}O$ and δD variation for type-IV ARC and granodiorite host, Macururé terrane.

Table 5. Oxygen and hydrogen isotopes for ARC-bearing and ARC-free granodiorite hosts, mafic micrograne enclaves and ARC in the Cachoeirinha–Salgueiro terrane and Macururé terrane

Pluton	Sample	$\delta^{18}O_{SMOW}$	δD_{SMOW}	H_2O^+ μmolesmg^{-1}	Rock type
		(a) Cachoeirinha–Salgueiro terrane			
	MBV-17	+12.0	−98	0.7	mEpG
	MBV-18	+11.0	−104	0.9	mEpG
Boa Ventura	MBV-20	+11.3	−69	0.5	mEpG
	MBV-20B	+10.1	−83	1.1	ARC
	MBV-21	+11.1	−114	1.2	ARC
	MBV-23	+11.5	−114	0.5	ARC
	MBV-23A	–	−79	0.8	ARC
	MBV-22	–	−88	0.6	MME
	MBV-22	+11.4	−120	0.7	mEpG
Conceição	MC-1	+11.0	−90	0.6	MME
Emas	E-1	+10.4	−84	0.7	MME
	SJB-1	+11.1	–	–	mEpG
	SJB-2	+11.6	–	–	mEpG
São José do Bonfim	SJB-5F	+12.5	–	–	mEpG
	SJB-7F	+9.6	–	–	mEpG
	SJB-C1	+9.9	–	–	ARC
	SJB-7 M	+8.7	–	–	MME
	PB-1	+11.6	−7.6	0.6	mEpG
Pedra Branca	PB-2	+11.8	−104	0.8	mEpG
(ARC-free)	PB-30	+11.8	−89	0.6	mEpG
	PB-31	+12.0	−109	0.5	mEpG
	PB-33	+11.8	−95	0.4	mEpG
		(b) Macururé terrane			
	GN-1	+9.0	−79	1.38	ARC
	GN-2	+9.6	−85	0.48	mEpG
Glória Norte	GN-3	–	−87	1.77	biot. (ARC core)
	GN-4	–	−87	1.04	amph. (ARC core)
	GN-5	–	−79	1.85	biot. (clot arm.)
	GN-6	–	−81	1.50	amph. (clot arm.)
	CJS-01	–	−64	0.64	mEpG
Coronel	CJS-02	–	−52	1.40	mEpG
João Sá	CJS-03	+7.7	−101	0.87	ARC

mEpG = magmatic epidote-bearing granodiorite.
ARC = amphibole-rich clot.
clot arm. = clot armoring layer, mainly composed of amphibole.
MME = mafic microgranular enclave

δ^{18}O-crustal rocks, which does not seem to be the case.

In the MT, the Glória Norte pluton exhibits δ^{18}O close to + 10‰$_{SMOW}$, while type-I ARC values of +9‰$_{SMOW}$ have been found in the Glória Norte pluton and values of +7.7‰$_{SMOW}$ were found in type-IV ARC in the Coronel João Sá pluton.

Hydrogen isotopes

Twenty five D/H determinations were done by conventional methods (Fallick *et al.*, 1987) at the Scottish Universities Research and Reactor Centre (SURRC), East Kilbride, Scotland. These data include whole-rock analyses of Boa Ventura, Conceição, Emas, São José do Bonfim and Pedra Branca granodiorites, some quartz–diorite enclaves and amphibole-rich clots in four plutons, along with analyses of mineral separates from clots from one pluton (Table 5). Nine of these D/H analyses were done on types-I and IV ARC and granodiorite host samples, respectively from the Glória Norte and Coronel João Sá plutons in the MT.

δD values obtained for CST plutons vary from −69 to −114‰$_{SMOW}$ with no apparent correlation with corresponding sample H_2O which might have suggested vapor phase exsolution (i.e. degassing) as a mechanism for lowering δD. Among four samples analyzed from the Boa Ventura granodiorite, three of them lie outside the 'normal igneous' δD values (−50 to −85‰$_{SMOW}$; Taylor 1978) and among four samples of ARC analyzed, two lie inside the normal igneous values and two are < −85‰$_{SMOW}$. These data do not allow us to distinguish between types-I and II ARC based solely on hydrogen isotopes. δD variation obtained for ARC and host are plotted in Fig. 9.

This wide δD range lies mostly outside the δD variation for most terrestrial rocks according to values reported in the review by Taylor and Sheppard (1986). An interpretation is that most of the samples with δD < −85‰ represent alteration by meteoric hydrothermal systems; it is difficult to estimate whether this occurred before or after magma generation.

The preferred hypothesis is that the source for the CST calc-alkalic magmas was a low-T altered-basaltic crust with δD values below −70‰. Some ARC-free granodiorites show a very homogeneous behavior of whole-rock oxygen isotopes (for example, Pedra Branca, average +11.8 ± 0.2 for five analyses), but a broad variation of hydrogen isotopes. This suggests that H and O isotopes in some of these plutons probably experienced decoupled histories of fractionation.

The presence of actinolite pseudomorphs after pyroxene in type-III ARC resulted, perhaps, from the reaction between pyroxene and grain-boundary diffused hydrogen.

It is known that hydrogen can have diffused from the melt (OH...) into pyroxene-grain boundaries promoting its recrystallization to actinolite (Castro and Stephens, 1992). Actinolite in this case represents a transient state, intermediate between the precursor pyroxene and hornblende of the host magma. This requires that hydrogen, extraneous to the source, has been incorporated into the magma, causing a wide δD isotopic range as attested by the present δD data for some ARC and respective granodiorite hosts.

In the Macururé terrane, a type-I ARC found in the Glória Norte pluton, along with biotite and amphibole separates from the clot itself and from the biotite and hornblende armoring layer, show a more limited δD variation (−79 to −98‰, Fig. 9). Hornblende in the armoring layer shows typical igneous values (−81‰) as well as biotite (−79‰). Amphibole in type-I ARC displays a value of −98‰ and biotite, −87‰. The δD for granodiorite host (−85‰) behaves as 'normal' igneous rock. The Coronel João Sá granodiorite shows typical igneous δD values (−52 and −64‰) while values for the type-IV ARC analyzed (−101‰) is lower, likewise for those ARC in the Boa Ventura pluton in the CST.

Sulfur isotopes

Only two samples of whole-rock granodiorites from the Cachoeirinha–Salgueiro terrane are available. Analyses were performed at the Geological Survey of Japan and have been reported by Sial *et al.* (1996). These samples are from the Santo Antonio and Emas plutons, which exhibit similarly high $\delta^{18}O$ values, but discrepant $\delta^{34}S$ (+9.3‰ for the Santo Antonio and +1.0‰ for the Emas pluton).

Although the two $\delta^{34}S$ values are very different, it is important information that both are positive and that they are exactly the extreme value characteristics for the magnetite-type granites (Sasaki and Ishihara, 1979) which roughly correspond to the I-type granites of Chappell and White (1974). This positive trend argues for the introduction of isotopically heavy sulfur, probably of seawater origin, into a mantle-derived environment.

Sr isotopes

Whole-rock analyses of Sr and Rb isotopes in samples of quartz diorite enclaves and magmatic-epidote-bearing granodiorite host rocks from the Emas, Conceição and Santo Antonio plutons of the CST were performed in the University of Texas at Austin by Leon E. Long. If we use the hornblende Ar–Ar age (625 Ma; Dallmeyer *et al.*, 1987) and present day $^{87}Sr/^{86}Sr$ and Rb/Sr in these samples as a basis to calculate initial Sr ratios, the average is 0.70596 ± 0.00004 (2σ). Alternatively, the Conceição Rb-Sr data (two granodiorite host rocks and one quartz diorite enclave) may be regressed together in an isochron calculation, assuming that quartz diorite enclaves and granodiorite host rocks share the same age (which is likely) and initial ratio (which is not proven). Excellent co-linearity of the data points (MSWD = 0.08) is permissive evidence that the three Conceição samples belong to the same Rb-Sr isotope system. The calculation provides an initial Sr ratio of 0.70589 ± 0.00001 (2σ), and an age of crystallization of 633 ± 0.9 Ma, attesting that their Rb-Sr systems are similar. Therefore, Sr isotopes in calc-alkalic plutons in the Cachoeirinha–Salgueiro terrane suggest that quartz diorites are products of fractional crystallization from the same magma which generated the granodioritic–tonalitic hosts.

In their study of the Coronel João Sá pluton, McReath *et al.* (1993) postulated the existence of two isotopically distinct magmas dated at 619 ± 21 Ma and 614 ± 9 Ma, but with different $^{87}Sr/^{86}Sr$ initial ratios (0.71008 versus 0.70814) that did not equilibrate with each other. Futhermore, the initial $^{87}Sr/^{86}Sr$ ratios observed by McReath *et al.* (1993) are significantly higher than those of the CST plutons. McReath *et al.* (1993) concluded from their study that the mafic rocks were derived from an enriched-mantle source, with variable contamination. Although these granodioritic–tonalitic plutons are very similar to those in the CST under consideration, they show different initial ratios which suggests a slight difference in their source or contamination.

Nd isotopes

Van Schmus *et al.* (1995) carried out a preliminary Nd isotope study in granitoids from the Borborema province, in an attempt to do terrane mapping. In that study, they used the Nd isotopic signatures of granitoids as clues to the age and isotopic composition of the underlying crust. They included some of the granodioritic–tonalitic plutons among the granitoids they analyzed in the Cachoeirinha–Salgueiro terrane. Some of their results relevant to the present study are given in Table 6.

These calc-alkalic plutons yielded similar model ages (tDM, calculated following the model of DePaolo, 1981) between 1.2 and 1.4 Ga, with Nd (0.6 Ga) of −2.0 for the Emas and Nova Olinda plutons and −1.2 for the Conceição pluton. Van Schmus *et al.* (1995) chose 0.6 Ga as the main reference time for Nd compositions in the past to eliminate possible effects of Sm-Nd fractionation during magma genesis, considering that some granitoids could be much younger than their source terranes. This approach allowed them to estimate the ages of the crustal sources.

Table 6. Sulfur and Nd isotopes in calc-alkalic granitoids in the Cachoeirinha–Salgueiro and Macururé terranes

Pluton	C(ppm)*	S(ppm)*	$\delta^{34}S_{CDT}$*	εNd(0.6)**	t_{DM}(Ga)**
		Cachoeirinha–Salgueiro Terrane			
Santo Antônio	160	51	+9.3	–	–
Emas	40	56	+1.0	−2.0	1.30
Conceição	–	–	–	−1.2	1.23
Nova Olinda	–	–	–	−2.0	1.41
São José do Bonfim	–	–	–	−3.3	1.34
		Macururé Terrane			
Coronel João Sá***	–	–	–	−4.6 to −6.7	1.47 to 1.71
type-IV ARC***	–	–	–	−6.3	2.60
Glória Norte**	–	–	–	−4.2	1.46

* = from Sial *et al.*, 1990; ** = from Van Schmus *et al.*, 1995; *** = from Castellana, 1998

Castellana (1998) found εNd (0.6 Ga) values of −4.5 to −6.7 for ARC granodiorite hosts in the Coronel João Sá pluton, with a Nd model age of 1.5 Ga. No country rock of such an age is known in this geographic area. The ARC yielded a Nd model age of 2.6 Ga, which suggests that perhaps Archean crustal material represented by ARC xenoliths served as one of the sources for this magma.

An important conclusion reached by Van Schmus *et al.* (1995) was that no Transamazonian or Archean basement underlies large parts of the terranes in the Borborema province. Their data support a model in which rifting around 1.1–1.3 Ga was an important tectonic and crust-forming event, and therefore, Mesoproterozoic crust was a major feature in the Borborema province. It is possible, then, that basalt filled a rift system that later accomodated CST marine turbidites, and was probably the source for the granodiorite/tonalite magmas under consideration.

CONCLUSIONS

Small hornblende aggregates (type-II ARC) found in calc-alkalic granitoids in the CST likely crystallized from the granodiorite host magmas. However, actinolite-rich clots (type-I ARC) had a different history. According to Helz (1976), tremolite–actinolite, an Al-poor amphibole, does not crystallize from a basaltic magma, since it is unable to coexist with liquids of normal 10–25% Al_2O_3 content. Moreover, granoblastic textures in the type-I ARC, in the CST, and type-IV in the MT, suggest a metamorphic origin.

At present, there is no unequivocal model to explain the origin of types I and IV ARC. Two possibilities emerge from the present study:

Hypothesis 1

They could be fragments of an amphibolite (metamorphosed basalt that underwent low-temperature alteration) whose partial melting generated CST magmas of tonalitic–granodioritic composition. In this case, they represent patches of mafic phases, either unmodified or modified after recrystallization, in equilibrium with the host magma. This hypothesis is supported by high $\delta^{18}O$ values for clots and granodiorite hosts and εNd values for the granodiorite hosts. The presence of type-I ARC in almost every calc-alkalic pluton in the Cachoeirinha–Salgueiro terrane and type-IV ARC in the Macururé terrane reinforces the assumption of an origin for amphibole-rich clots connected to the host-magma source.

Oxygen isotope values for the Glória Norte granodiorite and related amphibole-rich clots, although slightly lower than values found for CST analogues, are still higher than ‘normal’ values for I-type granites. Therefore, the assumption that they underwent some kind of low-temperature alteration can also be applied to type-IV ARC found in the Macururé terrane calc-alkalic granitoids under consideration.

In the melting of amphibolite, fH_2O controls the relative proportions of plagioclase vs amphibole in the residuum (Beard and Lofgren, 1991). At high fH_2O, the residuum consists of amph + cpx + plag. Magmas derived through this process contain high SiO_2, low MgO + FeO, and no Eu anomaly, in contrast to magma generated at low fH_2O, for which the residuum contains plag + cpx + opx. In the Cachoeirinha–Salgueiro plutons, ARC (representing solid residuum) are composed mostly of amph + minor cpx + brown mica, corresponding to melting at high fH_2O. Petrological diversity of these I-type granitoids is due probably to variation in fH_2O during melting of amphibolite, as proposed for the Chiliiwak batholith, U.S.A. (Tepper, 1992).

Hypothesis 2

Clots are subsolidus, formed after calcic pyroxene, as discussed in Castro and Stephens (1992). In this case, the clinopyroxene could be either a residual phase which survived melting, or an early-crystallized phase from the magma.

This hypothesis, however, explains only the origin of the type-III ARC in the present study, especially if we consider that pyroxene aggregates are rather rare and have been observed only in the Coronel João Sá and Glória Norte plutons, and actinolite pseudomorphs after pyroxene, only in the São José do Bonfim stocks in the CST. In this case, early crystallized or restitic calcic-clinopyroxene was probably the precursor that gave rise to these types of clots by grain-boundary diffusion from the host melt, promoting recrystallization of clinopyroxene to actinolite.

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