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Magmatism and Metallogeny in the Crustal Evolution of Rio Grande do Sul Shield, Brazil

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Abstract - The State of Rio Grande do Sul has a complex Precambrian/Cambrian shield, which has been investigated for four decades. This complexity involves ages ranging from 2.55 Ga (possibly 3.3 Ga) to 550 Ma (and even 470 Ma). The three major juvenile accretionary episodes occurred at 2.55 Ga, 2.26-2.02 Ga and 900-700 Ma, while a continental-scale crustal reworking (collisional) orogeny occurred from 780 to 550 Ma. The three accretionary orogenies are known as the Jequié, Transamazonian and Brasiliano Cycles, respectively. The Brasiliano Cycle includes the collisional orogeny. Magmatism was tholeiitic low-K bimodal basic-acid in the Archean (Santa Maria Chico granulites), and evolved to tonalitic-trondhjemitic-granodioritic in the Paleoproterozoic (Encantadas Complex). During the Paleoproterozoic/Archean transition, komatiites and basalts were formed in greenstone belts (Passo Feio Sul Formation). The end of the Transamazonian Cycle was the beginning of a long period of tectonic quiescence, and the region remained in the interior of the Atlantica Supercontinent until the beginning of the Brasiliano Cycle at ca. 900 Ma (Passinho Diorite). This Neoproterozoic cycle displays two classical orogenic types, namely the São Gabriel accretionary orogeny in the western part of the State and Dom Feliciano collisional orogeny in its eastern part. Accretion generated juvenile tonalite-trondhjemite-granodiorite associations with related ophiolites (Cerro Mantiqueiras Ophiolite), while the collision formed the voluminous and mostly peraluminous and high-K calcalkaline granites of the Dom Feliciano orogeny. The waning stages of the orogeny were responsible for the outpouring of a very expressive silica-saturated volcanism and eventually finished with the Rodeio Velho basalts at 470 Ma.

Comparable Paleoproterozoic/Neoproterozoic Precambrian terranes surround the shield in Uruguay, in Santa Catarina and in western Africa. Comparable Neoproterozoic juvenile and reworked terranes occur in NE Africa.

Widespread indications of metals are a good sign of possible deposits, but the two major types of deposits are the orogenic epizonal Bossoroca gold deposit and the distal magmatichydrothermal Lavras/Camaquã copper-gold deposits.

INTRODUCTION

Magmatism in the Precambrian/Cambrian shield of Rio Grande do Sul State in southernmost Brazil is varied in terms of ages, tectonic settings, compositions, types of mineralizations and post-magmatic alteration (Carvalho 1932; Leinz *et al.* 1941; Ribeiro & Fantinel 1978; Figueiredo *et al.* 1990; Fragoso Cesar *et al.* 1986; Hartmann & Nardi 1983; Porcher & Fernandes 1990; Remus *et al.* 1999a; Silva *et al.* 1997). Some of these characteristics have been known for many years (Table 1). Recently, the use of the electron microprobe at UFRGS led to the understanding of magmatic processes in detail while work in isotopic facilities abroad established time constraints for major crustal processes.

This paper summarizes this body of work, evaluating the geological and metalogenetic evolution of the Precambrian/Cambrian shield of Rio Grande do Sul.

AGES

Well-defined ages of magmatic rocks from the shield range from 2.55 Ga to 470 Ma (Table 2; Fig. 1). Older xenocrysts about 3.3 Ga have been identified in the Caçapava Granite and surrounding Passo Feio Formation metassediments by the U-Pb zircon SHRIMP method (Remus *et al.* 1997a), but the magmatic ages of about 2.55 Ga of the Santa Maria Chico Granulitic Complex make it the oldest outcropping unit in the State of Rio Grande do Sul. This age had been identified previously by Sm-Nd T_{DM} models at ca. 2.6 Ga (Hartmann 1998), and is now confirmed in cores of zircons by SHRIMP. High-grade deformation occurred at 2.07 Ga (Hartmann *et al.* 1999a).

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Table 1. Scientific discovery periods in the investigation of Precambrian / Cambrian geology of Rio Grande do Sul. *Ref.* = references.

Scientific period	Dates	Description of period	Ref.
pioneer	1930-1960	Au/Cu mining and reconnaissance; recognition of Lavras granite, Caçapava granite, Camaquã basin, limits of shield	1
Escola de Geologia / UFRGS	1961-1972	Senior undergraduate field mapping and Faculty work; mapping of major geological units	2
Curso de Geologia / UNISINOS	1973-1983	Work by Faculty and senior undergraduate field mapping of granulites, alkaline gneisses, alkaline and K-granites; discovery of crustal reworking in the Pelotas Batholith	3
Curso de Pós-Graduação em Geociências / UFRGS (I)	1981-1994	Work by Faculty and postgraduate students; discovery of shoshonite suite, komatiite suite, study of granites; plate tectonic theory applied to shield evolution	4
Curso de Pós-Graduação em Geociências / UFRGS (II)	1995-1999	Mineral chemistry and geophysics at UFRGS; geochronology, isotope geochemistry and experimental petrology (abroad); papers in international journals; discovery of accretionay and collisional orogenies; discovery of orogenic origin of Bossoroca and Camaquã ores; significance of shear zones	5
Other Universities	1970-1999	Doctoral theses	6
Brazilian Geological Survey (CPRM)	1990-1999	Geological mapping of several major units and structures	7

[1] Carvalho, 1932; Leinz *et al.*, 1941.

[2] Goñi, 1961; 1962; Goñi *et al.*, 1962; Villwock & Jost, 1966; Tessari & Picada, 1966; Jost, 1966; Jost & Villwock, 1966; Ribeiro *et al.*, 1966; Formoso, 1973, Ribeiro & Fantinel, 1978.

[3] Nardi & Hartmann, 1979; Hartmann & Jost, 1980; Jost & Bitencourt, 1980; Hartmann & Nardi, 1982, Lima *et al.*, 1983; Nardi, 1989

[4] Altamirano, 1981; Vieira, 1981; Garcia & Hartmann, 1981; Rego, 1981; Chemale Jr., 1982; Licht, 1982; Jost, 1981; Furtado, 1980; Oliveira, 1982; Badi, 1983; Frantz, 1984; Jost & Hartmann, 1984; Nardi, 1984; Silva Filho, 1984; Naumann *et al.*, 1984; Naumann, 1985; Lima, 1985; Zarpelon, 1986; Naime, 1988; Koppe & Hartmann, 1990; Machado *et al.*, 1990; Wildner, 1990; Remus, 1990; Gomes, 1990; Philipp, 1990; Mexias, 1990; Mesquita & Fernandes, 1990; Mexias *et al.*, 1990; Mesquita, 1991; Nardi & Bonin, 1991; Tommasi, 1992; Barros, 1992; Menegat, 1992; Hartmann *et al.*, 1992; Fernandes *et al.*, 1992; Gastal *et al.*, 1992; Frantz & Nardi, 1992; Porcher, 1992; Nardi & Frantz, 1992, 1995; Bitencourt & Nardi, 1993; Remus *et al.*, 1993; Sommer, 1994; Oliveira, 1994; Barros & Nardi, 1994; Tommasi et al., 1994; Fernandes *et al.*, 1995; Koester, 1995; Schmitt, 1996.

[5] Fragoso-Cesar *et al.*, 1986; Chemale *et al.*, 1995; Fernandes *et al.*, 1995; Babinski *et al.*, 1996, 1997; Gresse *et al.*, 1996; Hartmann, 1998; Hartmann *et al.*, 1998; Lima & Nardi, 1998; Leite *et al.*, 1998; Gastal & Lafon, 1998; Soares, 1998; Soares *et al.*, 1999; Remus *et al.*, 1999, Marques,1996; Costa, 1997.

[6] Bettencourt, 1972; Formoso, 1973; Soliani Jr., 1986; Beckel, 1990; Fragoso-Cesar, 1991; May, 1990; Paim, 1994; Remus *et al.*, 1996; Frantz, 1997; Philipp, 1998; Philipp *et al.*, 1998.

[7] Ramgrab *et al.*, 1988; Porcher *et al.*, 1991; Ramgrab *et al.*, 1997; Orlandi Filho & Pimentel, 1998; Porcher & Lopes, 1999; Szubert, 1978, 1980; Santos *et al.*, 1990.

Shortly after the accretion of the Santa Maria Chico Complex, an important event of juvenile accretion generated the granitic Neto Rodrigues gneisses and probably also the enclosing Passo Feio Sul Formation greenstone belt. The greenstone terrain contains ultramafic, mafic and felsic volcanics.

Often seen as the oldest unit in the State, the Encantadas Complex was actually accreted to the crust at 2.26 Ga (zircon U-Pb SHRIMP) at its type locality (Santana da Boa Vista); no Sm-Nd isotopic data are available, but the tonalite-trondhjemite-granodiorite association is more likely of juvenile origin. Orthogneisses mapped 50 to 200 km to the north and northeast (as far as Porto Alegre), formerly known as Arroio dos Ratos gneisses, also yield magmatic U-Pb zircon SHRIMP ages > 2.0 Ga and thus show that the Encantadas Complex is a major unit in the Precambrian of Southern Brazil (Leite *et al.* 1999; Silva *et al.* 1999a).

Amphibolites enclosed in the Razzera marbles (southeast of Caçapava) yield a magmatic age of 2.1 Ga for the contained zircons, confirming (together with the Neto Rodrigues gneisses) the pre-Transamazonian Cycle origin of the Passo Feio Sul Formation supracrustals.

Although the Cambaí Complex seems to be dominated by 750-700 Ma tonalite-trondhjemites, the 900 Ma old (U-Pb SHRIMP) Passinho diorites were discovered by Leite *et al.* (1998). This magmatism constitutes a small volume but is widespread in the basement of the western portion of the shield and represents the oldest magmatic accretion of the Brasiliano Cycle in the region.

The Brasiliano Cycle is of major expression in South America (Brito Neves & Cordani 1991) and also in Rio Grande do Sul. At ~780 Ma it caused the partial melting of the Paleoproterozoic rocks, possibly corresponding to the Encantadas Complex, generating

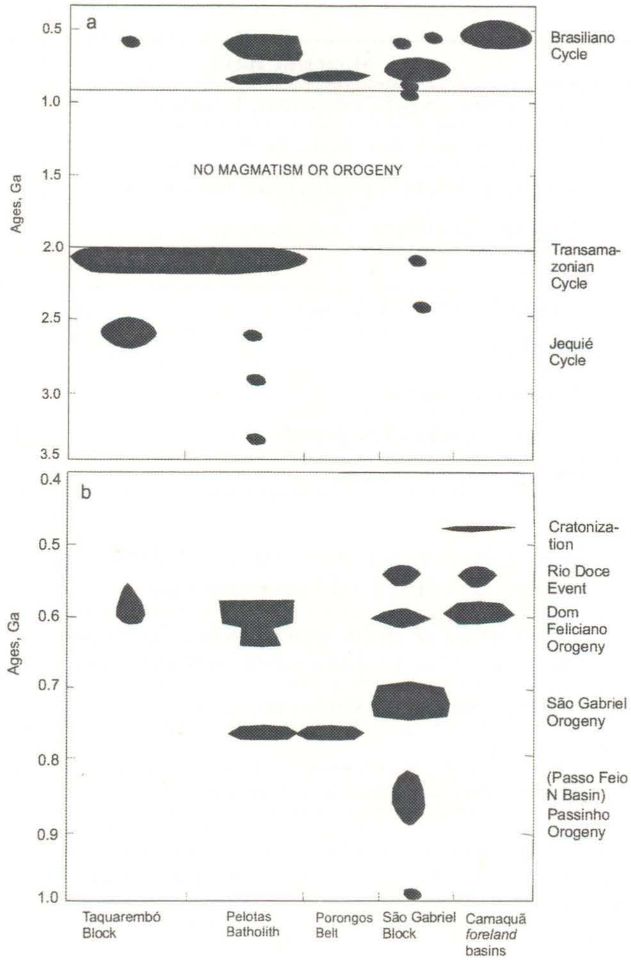

Figure 1. Timing of major magmatic events in the Precambrian / Cambrian of the main crustal provinces of Rio Grande do Sul. a – Three major magmatic events correspond to three major orogenic cycles; magmatic, and probable tectonic, quiescence between ~2.0 Ga and ~900 Ma. b – Magmatic events in the orogenies of the Brasiliano Cycle. Age close to 1.0 Ga is inherited zircon in Bossoroca belt. Rio Doce event after Campos Neto and Figueiredo (1995).

the Piratini gneisses and the volcano-sedimentary Porongos Complex. A possible geotectonic interpretation of the Piratini gneisses and the Porongos Complex is in a continental back-arc positioned to the east of the juvenile island arc represented by the Cambaí Complex plutonic rocks and the Vacacaí Group volcanics, because all these units have similar ages.

The thermal peak of the Brasiliano Cycle is represented by the voluminous 610-590 Ma old K-granites and minor Na-granites of the Dom Feliciano Orogeny scattered across the basement. At the same time, the main volcanic sequence was forming in the Camaquã Basin. The waning stages of the cycle originated shear-zone related and postectonic granites. As in many orogenies, it seems that the Brasiliano Cycle ended with the extrusion of tholeiitic basalts in the molassic stage of the foreland basin (~470 Ma).

We now turn to the tectonic settings prevailing during each of these events.

TECTONIC SETTINGS

The Rio Grande do Sul shield is made up of several tectonic units (Fig. 2) characterized by juvenile accretion in the Vila Nova Terrane of the São Gabriel Block (Babinski *et al.* 1996) and intense crustal reworking in the Dom Feliciano Belt (Babinski *et al.* 1997). The oldest magmatic rocks (Archean) occur in the western portion of the shield while Paleoproterozoic rocks are more abundant in the eastern sector (Hartmann *et al.* 1998). A sequence of geotectonic scenarios is proposed for the region (Figs. 3, 4 and 5).

The Late Archean had an island-arc tectonic environment, forming the Santa Maria Chico Complex (Hartmann, 1998). Abundant low-K depleted tonalites-trondhjemites of tholeiitic affinity were formed and consolidated in a continental crust. The geochemistry of the TTG rocks remained largely unaffected by the high-grade metamorphism. It is likely that the same type of setting originated the Neto Rodrigues granodioritic rocks and associated komatiites and basalts.

Rocks formed in the Paleoproterozoic are abundant (Encantadas Complex); in the absence of geochemical data, we postulate a tectonic setting of accreting island arcs that consolidated onto an older continent. This Transamazonian Cycle was responsible for the amalgamation of the Atlantica Supercontinent (Rogers 1996) that remained undeformed from 2,020 to 900 Ma in the region because the large data-base has not sampled magmatic or metamorphic rocks from this time interval.

The active continental margin of the Rio de La Plata Craton (local name for fragments of the Atlantica Supercontinent) was situated to the west of the cratonic region (Dalla Salda *et al.* 1988). The oldest granitic rocks of the Brasiliano Cycle were formed in subduction zones which dipped to the east beneath the continent. This juvenile granitic magmatism formed and accreted to the continent in several episodes during an accretionary orogeny, constituting the Cambaí Complex. Associated ophiolites were also thrusted over the continent (Cerro Mantiqueiras Ophiolite). The related volcanic arc contains andesites of the Vacacaí Group.

Table 2. Timing of magmatism and metallogeny in Rio Grande do Sul shield; zircon U/Pb SHRIMP ages, Ma.

Ages	Geologic unit	Magmatic rocks
2,550[1]	Santa Maria Chico Granulitic Complex	Trondhjemites, basalts, pyroxenites, K-syenites
2,450[2,3]	Neto Rodrigues Gneisses	Tonalites, granodiorites, monzogranites
	Passo Feio Sul Formation	Komatiites, basaltic komatiites, andesites, rhyolites
2,260[4]	Encantadas Complex	Tonalites, granodiorites, monzogranites
2,100[5]	Razzera amphibolites	Diabase
900[6]	Passinho Diorites	Diorites, tonalites, trondhjemites
780[7,8]	Porongos Complex	Rhyolites
	Piratini Gneisses	Tonalites, granodiorites
750-700[6,9]	Cambaí Complex	Tonalites, trondhjemites, granodiorites
	Vacacaí Group	Basalts, andesites, rhyolites
700[10]	Bossoroca gold deposit	
610-590[6,11,12]	Dom Feliciano K-granites	Granodiorites, monzogranites, syenogranites. Many plutons in the São Gabriel Block and Dom Feliciano Belt.
	Saibro Na-granites	Saibro peralkaline perthite granite plutons in São Gabriel Block; Bela Vista peralkaline granites in Dom Feliciano Belt
	Hilário Formation	Basalts, traqui-basalts, shoshonites, rhyolites
580[12]	Camaquã Cu (Au) and Santa Maria (Pb/Zn) deposits	
560[6,10]	Caçapava and São Sepé Granites	Granodiorites, monzogranites, syenogranites
470[12]	Rodeio Velho Formation	Basalts

[1] Hartmann *et al.*, 1999a; [2] Hartmann *et al.*, 1998; [3] Hartmann *et al.*, 1999c; [4] Porcher *et al.*, 1999; [5] Hartmann *et al.*, 1999; [6] Leite *et al.*, 1998; [7] Porcher *et al.*, 1999; [8] Silva *et al.*, 1999a; [9] Machado *et al.*, 1990; [10] Remus *et al.*, 1999b; [11] Chemale *et al.*, 1995; [12] Remus *et al.*, 1997b.

At approximately the same time (~750 Ma), the continental crust was activated to the east; partial melting of the old Paleoproterozoic crust led to the intrusion of the Piratini gneisses and the extrusion of the Porongos Complex rhyolites in a continental back-arc setting.

100 Ma later, the eastern region of Rio Grande do Sul was reactivated by the Dom Feliciano Orogeny and many of the rock units were partially remelted, including the Encantadas Complex and the Piratini gneisses. The most voluminous granitic magmatism in the State was generated by this collisional orogeny, mostly along the eastern portion but also in some circumscribed plutons in the western portion. Sm-Nd isotopic data indicate strong Paleoproterozoic contribution to the melts, but also several Mesoproterozoic ages (Mantovani *et al.* 1987; May 1990; Babinski *et al.* 1997). These Mesoproterozoic model T_{DM} ages are considered a result of rare-earth element fractionation during the Neoproterozoic melting event, because zircon U-Pb SHRIMP dating of some rocks (Silva *et al.* 1999b) show only two ages, magmatism in the Paleoproterozoic and metamorphism in the Neoproterozoic.

Late manifestations of the Brasiliano Cycle (ca. 550-560 Ma) occurred in the western portions, including the Caçapava granite and the São Sepé granite, and correspond to the distal tectonics of the Rio Doce Orogeny that was active in Rio de Janeiro and SW Africa (Campos Neto & Figueiredo1995). The Dom Feliciano Orogeny evolved in its waning stages into a foreland basin; zircons from a basalt stratigraphically high in the basin yielded an age ~470 Ma. This is the final manifestation of the Brasiliano Cycle in the State.

COMPOSITIONS

Magmatic compositions of rocks in this complex shield vary from komatiites to basalts and peralkaline rhyolites and their plutonic equivalents such as gabbros and abundant granitic rocks. Magmatic suites are well represented, such as komatiitic, tholeiitic, calcalkaline, alkaline and shoshonitic suites.

Komatiites

Volcanic features of ultramafic rocks have been erased by deformation and metamorphism, but

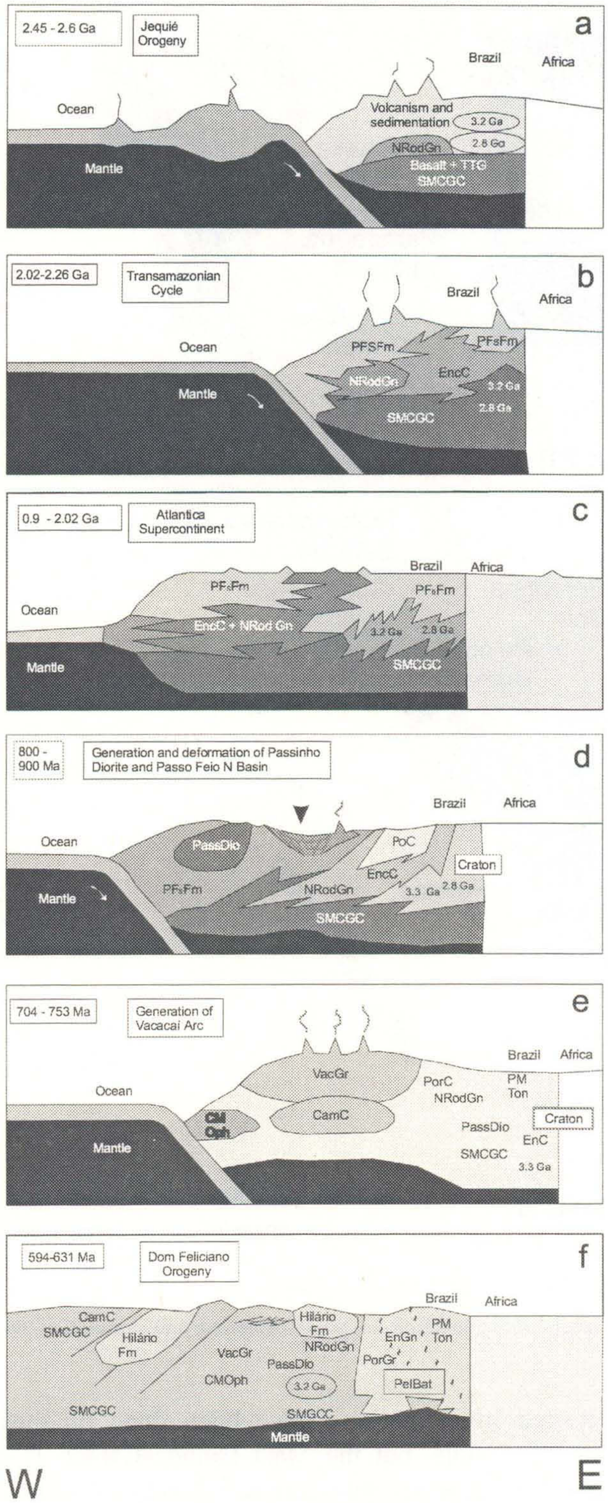

Figure 2. Cartoons showing the possible geoctectonic environments of magmatism in the Precambrian / Cambrian evolution of Rio Grande do Sul. NRodGn = Neto Rodrigues gneisses; TTG = tonalite-trondhjemite-granodiorite; PFsFm = Passo Feio S Formation; EncC = Encantadas Complex; SMCGC = Santa Maria Chico Granulitic Complex; PassDio = Passinho Diorite; PoC = Porongos Complex; VacGr = Vacacaí Group; PMTon = Pinheiro Machado Suite tonalite; CamC = Cambaí Complex; CMOph = Cerro Mantiqueiras Ophiolite; Hilário Fm = Hilário Formation; PelBat = Pelotas Batholith.

there is abundant evidence for the presence of komatiitic lava flows in the shield. Metamorphism tends to obscure original structures and textures, due to the ready transformation of olivine, pyroxene and glass into serpentine, talc, olivine, tremolite, anthophyllite, chromite, magnetite, and even clino- and orthopyroxene in magnesian schists. What can be said of the paleo-volcanic record of these rocks?

Field evidence in the Cambaizinho and Ibaré regions, Passo Feio Sul Formation and near Votorantim cement industry in Pinheiro Machado show a sequence of 1 to 20 m thick magnesian schists intercalated rather regularly with supracrustal rocks such as meta-rhyolites, BIF, meta-graywackes and meta-andesites. Detailed geochemistry of two such layers in the Cambaizinho region (Remus *et al.* 1993) demonstrated the magmatic origin and komatiitic chemistry of the rocks; more recently, we obtained a T_{DM} age of ~1700 Ma for an intercalated amphibolite. The Passo Feio Sul Formation is another example of komatiitic chemistry of the talc-chlorite-tremolite schists (Bitencourt, 1983; Bitencourt & Hartmann 1984); the zircon U-Pb SHRIMP dating at ~2.45 Ga of the Neto Rodrigues granodiorite (Remus *et al.* 1997a) and of the Razzera amphibolite (~2.1 Ga - Hartmann *et al.* 1998) demonstrate that this is a Paleoproterozoic greenstone belt.

These low-grade metakomatiites still preserve the original chemistry in less metassomatized domains (Fig. 6). It is possible that higher grade remnants may be preserved in the Encantadas Complex and in the Santa Maria Chico Complex, but these require special investigation for determination of their komatiitic affinity.

Basalts

Basalts and their metamorphosed equivalents (amphibolites and mafic granulites) are abundant in all supracrustal belts of the shield, particularly in its western portion such as the Cambaizinho belt, Vacacaí Group, Passo Feio N/S Formation, and even Cambaí Complex and Santa Maria Chico Complex. In the eastern portion of the State, amphibolites do occur but are less abundant, such as in the Porongos Complex and Encantadas Complex, and occur in small volumes in the Dom Feliciano Belt.

Outstanding pillow lavas are encountered in the Arroio Mudador region south of Caçapava (Campestre Formation).

Figure 3. Geotectonic provinces of Uruguay and southern Brazil; insets show location in South America and correlation with southwestern Africa.

The basalts are mostly of tholeiitic affinity such as in the Palma region (Garcia 1980), but transitional alkaline rocks are also found, such as in the Passo Feio Formation. Komatiitic basalts occur in the Cambaizinho belt. The amphibolites of the Cerro Mantiqueiras Ophiolite may correspond to deformed high-Ti ocean floor basalts (Leite 1997).

Gabbros

Layered gabbroic intrusions are common in the shield albeit small (100-5,000 m in diameter). No detailed investigations have been done on these important units, but the Mata Grande Gabbro is of Neoproterozoic juvenile accretion because it yields a Nd T_{DM} age ~800 Ma. Several such bodies occur in the Passo do Salsinho region (Oliveira 1981; Porcher *et al.* 1991). The Pedras Pedras mega-xenolith (Rego 1980) shows strong evidence of contact metamorphism by the enclosing São Sepé Granite (Mattos, 1997). Small gabbros occur in the Cambaizinho region; small bodies are abundant in the Pinheiro Machado-Pelotas region as the Passo da Fabiana gabbros.

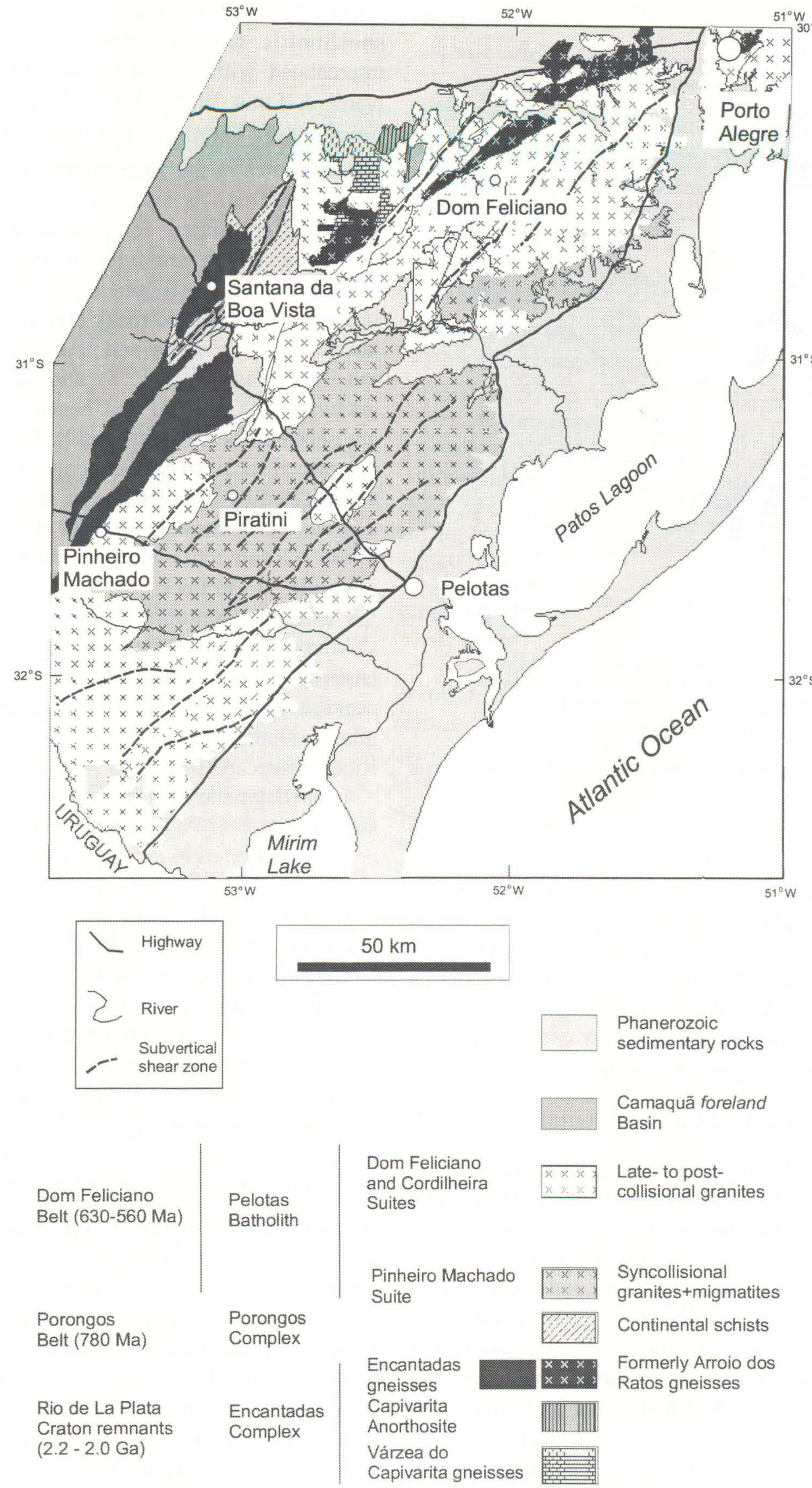

Figure 4. Geological map of eastern portion of Rio Grande do Sul shield (modified from Ramgrab & Wildner, 1988; Ramgrab *et al.*, 1997; Philipp, 1998).

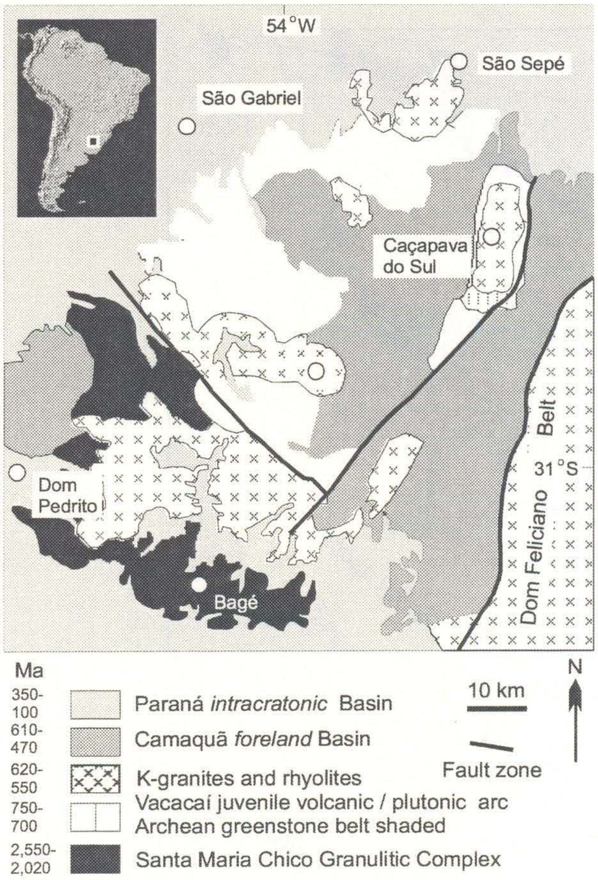

Figure 5. Geological map of western portion of Rio Grande do Sul shield (Hartmann *et al.*, 1999a).

Andesites

Calcalkaline andesites are abundant in the juvenile Vacacaí Group; the explosive index (pyroclastic / pyroclastic + lavas) is very high (>90%) in the Campestre Formation. The chemistry of the Vacacaí Group is depleted in incompatible elements (Fig. 7) and is the most K-depleted volcanism in the shield (Koppe & Hartmann 1990).

Foreland Basin Volcanism

A basic to acid volcanic suite is well displayed in the shield of Rio Grande do Sul and occurs as dyke swarms and remnant lava plateaus in the eastern portion, but is more voluminous and better investigated in the western region and these will be described in more detail. These large volumes of volcanic rocks are associated with thick sediment piles in the Camaquã Basin. Three major volcanic episodes have been identified in the basin, based on field, geochemical and isotopical data. We now describe the Hilário Formation, the Acampamento Velho Formation and the Rodeio Velho Formation.

Hilário Formation – The Hilário Formation contains shoshonitic trachybasalts and trachyandesites, intercalated with volcanic sediments (Lima 1994; Nardi & Lima 1985; Lima & Nardi 1985), which cover the Cambaí Complex tonalites and trondhjemites in the western part of the shield. The base of the unit is made up of trachybasalts, with more differentiated compositions higher in the sequence, which are intercalated with reworked pyroclastic fall tuffs and small volumes of flow deposits. The volcanic rocks plot in the trachybasalt, basaltic trachyandesite and trachyandesite fields of the TAS diagram (Fig. 8) and show K_20 values greater than (Na_20-2), and hence are trachybasalts and shoshonites (LeMaitre 1989). The volcanism is of continental subaerial type and only locally subaqueous, as indicated by the presence of epiclastic and lahaar deposits and by the high intensity of columnar jointing. These volcanic rocks and associated epiclastics make up a pile ~3 km thick.

Some plutonic rocks belong to the same shoshonitic association, such as a spessartitic lamprophyre dome, monzonitic to quartz-monzonitic necks, traquiandesite and rhyolite dykes, besides some granitic plutons such as the Lavras core granite, Santa Rita Granite and the Santo Afonso Granitic Suite.

Magmatic ages have been determined on the suite by zircon U-Pb SHRIMP at ~610-590 Ma (Leite *et al.*1998; Remus *et al.* 1997a). Low initial Sr ratios at ~0.704 (Nardi 1984; Lima 1985) indicate mantle-derived or juvenile crustal rocks as the source of the magmas. Other correlated bodies in western Rio Grande do Sul yield similar Sr_i, such as the Santo Antônio Monzogranite (Barros & Nardi 1994).

This is an outstanding example of a Neoproterozoic shoshonitic volcanic association, because it spans the chemical composition from basalts to rhyolites (Fig. 8) and because the geochemistry fulfills all criteria for a shoshonitic association (Morrison 1980; Lima & Nardi 1998).

Acampamento Velho Formation – The main volcanic rocks present are rhyolitic lavas and smaller amounts of trachytic and trachydacitic lavas; pyroclastic flow deposits are common as variably welded high temperature ignimbrites. Some breccias also occur with lapilli matrix. Some lag and fine tuff deposits are also present. Spherulites and micropoikilitic texture are seen in the devitrifyed rhyolites.

These acid volcanics tend to occur higher up in the stratigraphic sequence than the Hilário

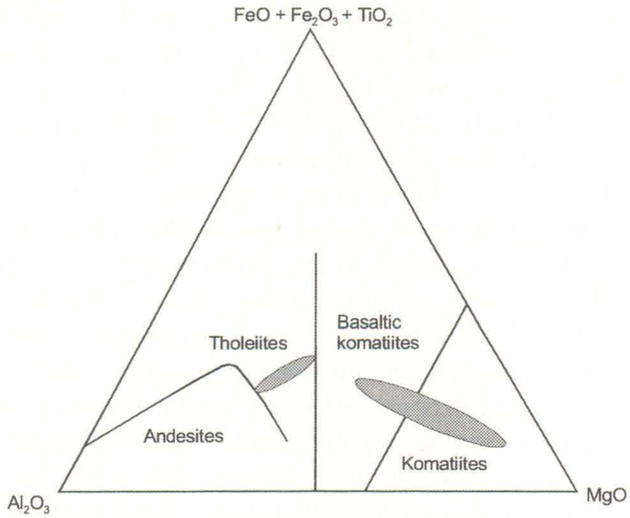

Figure 6. Jensen (1986) diagram indicating komatiitic and basaltic komatiitic composition of Cambaizinho and Passo Feio Sul talc-chlorite-tremolite schists; basalts are mostly tholeiites in these two regions as shown.

Formation (Porcher & Fernandes 1990; Wildner *et al.* 1999; Sommer 1994), as seen in the Cerro do Bugio, Cerro do Perau and Cerro Tupancy. In the Taquarembó Plateau, the acid lavas cover granulites of the Santa Maria Chico Complex and are covered by the Hilário Formation traquiandesites.

The age of the lavas is not well constrained, because they may either be associated with the alkaline Saibro Granite (~600-590 Ma – zircon U-Pb SHRIMP, Leite *et al.* 1998) or with the São Sepé Granite (~550 Ma – zircon U-Pb SHRIMP, Remus *et al.* 1997a). And also, there may be two such events of acid volcanism in the shield, each associated with a plutonic event of alkaline granitic magmatism.

These high silica rhyolites (Sommer 1994) are comenditic and may have formed by crystal fractionation of alkaline basic magmas and a small component of crustal assimilation in a post-tectonic environment (Nardi 1989; Gastal *et al.* 1992; Wildner *et al.* 1999).

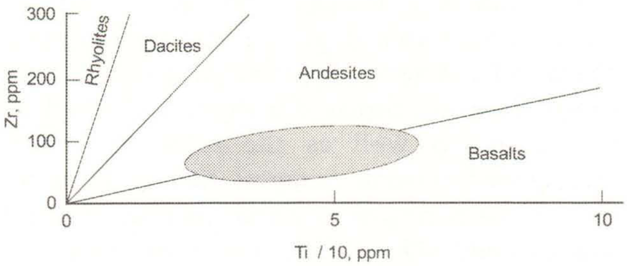

Figure 7. Ti X Zr diagram (Koppe & Hartmann, 1990) showing primitive chemistry of basalts and andesites from the Campestre Formation.

Rodeio Velho Formation – The Rodeio Velho basalts occur intercalated with arkoses deposited at the end of the molassic sedimentation of the Camaquã Basin at ~470 Ma (Hartmann *et al.* 1998). The lava flows are 0.5-2 m and up to 10 m thick, amydaloidal (40 vol.% of flow) and show tubes and chords with decimetric empty cores and locally aa structure, although the pahoehoe structure is dominant.

The lavas are intensely altered by hydrothermalism, making it difficult to evaluate the original chemistry. The intense silicification and carbonation leave some remnants of original olivine + clinopyroxene + plagioclase. Some intermediate compositions display large volumes of plagioclase, less than 4 vol.% clinopyroxene and no olivine. The magmatic affinity is probably tholeiitic with some alkaline component.

Granitic Rocks

Three major episodes of generation of granitic rocks occurred in the shield, and there seems to be a continuum of evolution of compositions through time. The Archean Santa Maria Chico trondhjemites are very low-K depleted magmas (Fig. 9), largely unaffected by the granulite facies metamorphism (Hartmann 1998); no large lithophile ion enrichment is observed in these rocks. The Encantadas Complex, on the other hand, contains tonalites and trondhjemites of undetermined but probably basaltic sources, and significantly more K-rich rocks such as syenogranites probably generated by melting of tonalites (Porcher 1992).

A wide spectrum of granitic rocks was formed during the Neoproterozoic, frequently with volumetrically minor mafic counterparts. These include a calcalkaline tonalite association – the Cambaí Complex, a high-K calcalkaline granitic suite, including the Caçapava, Viamão and Quitéria granites, a peraluminous granitic suite with crustal signature – the Cordilheira granites, and also the shoshonitic and alkaline granitoids related to the Hilário and Acampamento Velho Formations. Alkaline granites also occur in the eastern belt of the shield (Philipp *et al.* 1991). These granitoids from the whole shield seem to concentrate in two major orogenic events, namely the São Gabriel orogeny at ca. 750-700 Ma (Babinski *et al.* 1996; Leite *et al.* 1998) and Dom Feliciano orogeny at ca. 650-550 Ma (Babinski *et al.* 1997; Silva *et al.* 1999a).

This is an irreversible evolution of the lithosphere of Rio Grande do Sul from primitive mantle-derived magmas to more evolved crustal contaminated magmas. The relative position of the western and eastern portion of the shield may have modified by terrane accretion, but the general trend of lithospheric evolution is present. We now proceed to describe some of the Neoproterozoic associations.

Calcalkaline granitic rocks such as quartz diorites, tonalites, trondhjemites and granodiorites are abundant in the Cambaí Complex of Western Rio Grande do Sul. Their geochemical features are consistent with derivation by differentiation of medium to high potassium calcalkaline magmas (Silva F° 1984; Kraemer 1995; Kraemer *et al.* 1997). Compositionally similar syncollisional granitic rocks are also present in the Pinheiro Machado Suite, Pelotas Batholith (Bitencourt & Nardi 1993), although these are 100 Ma younger. The trace element content of the Cambaí Complex granitic rocks show similarity with collisional or continental arc calc-alkaline medium K-granites. In comparison, the Pinheiro Machado granitic rocks are slightly enriched in K, Ba, Rb, Nb and LREE in spite of similar differentiation degree. This geochemical feature is probably related to a thicker crust in a collisional setting for the Pinheiro Machado rocks as opposed to a thinner crust in a juvenile continental arc for the Cambaí Complex.

The Cambaí tonalites are followed by granodiorites and granites which are similar to high-K calcalkaline granitic rocks. The Sr initial ratios (Fig. 10) are close to 0.704, a value only slightly higher than the depleted mantle at the time (Soliani

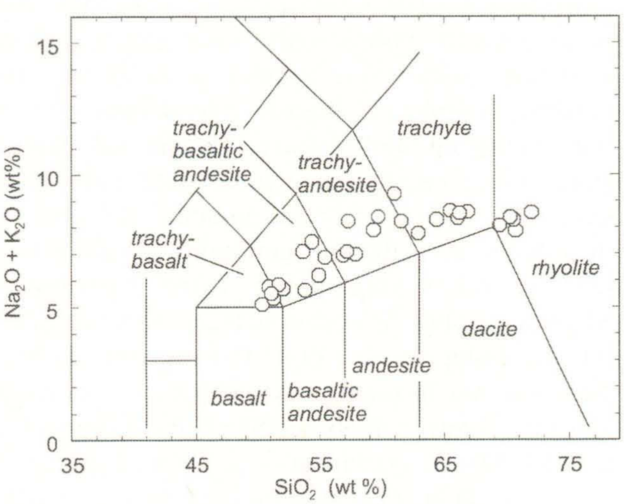

Figure 8. TAS (alkali silica) diagram of ~600 Ma-old shoshonitic-alkaline volcanism in Lavras do Sul region (Hilário Formation and Acampamento Velho Formation).

Jr. 1986). A compositionally similar magmatism occurs in the eastern portion in a transcurrent shear zone setting; Sr^i is high (~0.713) for these crustal melt 595 Ma old (zircon U-Pb conventional) rocks. The trace element composition of these granites is illustrated in figure 11 (e.g. Quitéria and Viamão Granites). A peraluminous granitic magmatism was associated with this event, probably generated by <10 kb melting of metatonalitic gneisses (Soares *et al.*1999). Trace element compositions of the two types of magmatism are consistent respectively with high-K calcalkaline rocks and crustal melting in a collisional setting. The intrusion of high-K calcalkaline granitic rocks was contemporaneous with basic magmas now seen as mafic microgranular enclaves. These enclaves are not present in the peraluminous granites, and indication of mantellic versus crustal origin of the magmas.

High-K calcalkaline granitic rocks and peraluminous leucogranites are also related to the late stages of transcurrent tectonics in the eastern region (Koester *et al.* 1995). Their compositions move gradually towards more alkaline compositions as the transcurrent tectonics evolves to an extensional regime (e.g., Philipp 1998), as evidenced by a diminishing intensity of deformation in the studied granitic bodies.

In the western region, a most important shoshonitic magmatism is associated with the beginning of the Camaquã Basin – e.g., Lavras Granite is intrusive into the basin lower sediments and lavas. This magmatism (Nardi & Lima 1985; Lima & Nardi 1998) has Sr_i near 0.704 and typical shoshonitic trace element composition (Figs. 8, 10, 11). Shoshonitic magmatism is produced by partial melting of the mantle wedge above subduction zones, previously hydrated and metasomatized by fluids related to an older subduction zone.

Metaluminous granitic rocks, with subordinate peralkaline terms, are widespread in both regions of the shield (Philipp *et al.* 1991; Gastal 1998; Nardi 1991; Vasquez 1998). In the west, they are associated with large volcanic plateaus (e.g., Taquarembó Plateau). Representative trace element compositions are displayed in figure 9. The high La/Nb ratios, as well as the relatively HREE fractionated patterns, suggest that most of this magmatism is related to partial melting of mantle sources modified by oceanic crust subduction, just as proposed for the calcalkaline and shoshonitic rocks. Crustal melting and assimilation may have contributed for the generation of these metaluminous granites, particularly for the magmas high in Sr^i and relatively low in HFS and REE. The 100 Ma time interval between the active subduction and the generation of these magmas is quite comparable to the geotectonic setting described in other regions (Wyllie 1994). The late to postcollisional recurrence of (generally) high-K calcalkaline magmatism long after the subduction ceased is probably related to the effect of deep shear zones promoting melting in metasomatised lithospheric wedges.

MINERALIZATIONS

Ore deposits in the Archean and Paleoproterozoic terrains have not been discovered thus far, although greenstone belts are known worldwide to contain significant deposits. High-grade terrains also contain major deposits in other regions – e.g., Cu in Curaçá (Bahia, Brazil) pyroxenites, Pb/Zn in Broken Hill, Australia. The Santa Maria Chico granulites contain gold prospects in young shear zones. But it is the Neoproterozoic/Cambrian that offers the better known metal deposits in the State.

Southernmost Brazil has two tectonic types of known major mineralized environments. One is the juvenile Vila Nova Terrane in the west and the other is the extensive Pelotas Batholith generated by collisional magmatism. The Cu, Au (Pb, Zn, Ag) province in the juvenile terrane has produced metals for many decades and still has a high potential for new discoveries based on new data and interpretations.

Two major deposit styles have been discovered in the juvenile terrane. One is the orogenic gold deposit of the Bossoroca Mine (Koppe 1990) in a shear zone in 750 Ma-old juvenile arc (Remus *et al.*, 1999b). The other is the magmatic mesothermal/epithermal Cu-Au system of deposits which formed at 600 Ma in a postectonic environment - the granite-hosted Bloco Butiá Au deposit in Lavras do Sul and the epithermal Camaquã Cu-Au Mine (Remus *et al.* 1997b). This epithermal model can be used for exploration in the other foreland basins of southern Brazil.

The 600 Ma crustal reworking of southern Brazil produced extensive batholiths and mineralizations of fluorite, Sn, Mo, and Pb. These constitute prospects in eastern Rio Grande do Sul, but are an indication that large deposits may occur. Fluids generated in the Brasiliano Cycle of 750-600 Ma were volumetrically large and crossed receptive older lithologies and structures in many places. Each tectonic episode can generate ore deposits.

The Bossoroca orogenic Au deposit

The Neoproterozoic Bossoroca juvenile volcanic arc of southernmost Brazil contains arc-related gold deposits (Pinto 1997; Remus *et al.* 1999b). The Bossoroca Mine deposit consists of veins and stockworks of quartz-gold ores with minor pyrite, chalcopyrite, galena and tellurides. Carbonate, chlorite, sericite and tourmaline are the main gangue minerals. The ore shoots are contained in calc-alkaline pyroclastic andesites and dacites, with minor basalts and epiclastic rocks, of the Campestre Formation.

SHRIMP U/Th/Pb investigations of zircon show that the island-arc sequence was formed ca.757 Ma ago in the early Brasiliano Cycle and metamorphosed in transitional greenschist/amphibolite facies at ca. 700 Ma. Nearby postectonic São Sepé Granite was intruded in the volcanic arc at ca. 550 Ma. Lead isotopes on galena from the gold ore, on feldspar and total rock from the associated volcanic pile, and also on feldspar and total rock from the São Sepé Granite (Mattos 1997). These isotopes indicate a clear 757 Ma old source of gold mineralization from the volcanic rocks, constituting an epizonal orogenic deposit (Groves *et al.* 1997); the gold was probaby deposited at ca. 700 Ma (Remus *et al.* 1999b).

The Lavras/Camaquã magmatic-epitermal Cu-Au deposits

A most important mineralizing system developed at ~580-590 Ma in the cooling stages of the Lavras Granite (Reischl, 1980), strongly altering the granite internally and also the andesitic country rocks. This hydrothermal alteration extended farther and up into the Camaquã Basin and deposited Cu (Au) in the Camaquã Mine and Pb, Zn in the Santa Maria Deposit. These we now describe.

The Volta Grande region contains Pre-Cambrian volcanic and pyroclastic (tuffs and breccias) rocks of the Hilário Formation which were intruded by the transitional granite of the Lavras Granitic Complex. This intrusive relationship generated an up to 500 m contact metamorphic ring with a metamorphic grade from lower hornblende hornfels to epidote-albite hornfels (Mexias 1990; Mexias *et al.* 1990). The granitic intrusion was the heat source for the generation and maintenance of a hydrothermal system similar, in terms of its characteristics and patterns of alteration products zonation, to Cu-porphyry deposits. Subsequently, late

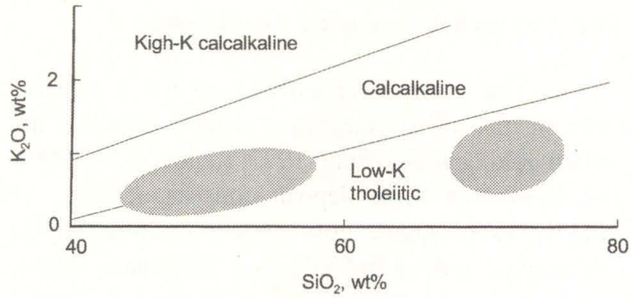

Figure 9. Low-K tholeiitic composition of mafic and trondhjemitic granulites from the Santa Maria Chico Complex (Hartmann, 1998).

magmatic fluids cross cut the host rock (including hornfelses) near the granite contact through interconnected fractures and deposited the higher temperature parageneses with the hydrothermal system - potassic alteration. Mostly under conductive heat transfer conditions, the foroction of epidote + clorite (+ actinolite near the granitic intrusion) took place within microfractures and stagnant pores as a result of the interaction between fluids and the host rock - propylitic alteration (Mexias *et al.*1993). The hydrothermal minerals formed during this alteration process were influenced by the original chemical composition of the rocks. After or coeval with the propylitic alteration, under similar to slightly higher temperature conditions (300 °C), higher activity H^+

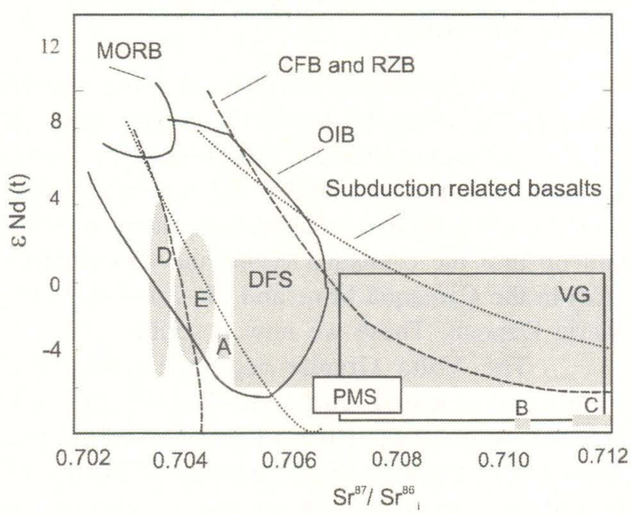

Figure 10. Isotopic constraints on crustal evolution of Lavras perthite granite (A), Encruzilhada granite (B), Cordilheira intrusive suite granite (C), Imbicuí orthometamorphic suite (D), Lavras do Sul shoshonitic association (E); DFS = Dom Feliciano suite; VG = Viamão granite; PMS = Pinheiro Machado suite. MORB = mid-ocean ridge basalt; CFB = continental flood basalt; RZB = ridge zone basalt; OIB = ocean island basalt (fields from Wilson, 1989). eNd and $^{87}Sr/^{86}Sr$ initial ratio values for Neoproterozoic magmatism are consistent with crustal-contaminated sources for most of them, as also suggested by trace-element evidence. Nevertheless, crustal contribution was small or else the crust involved was not enriched.

fluids destructively percolated through fractures and generated a white mica + chlorite + quartz + pyrite paragenesis. Either as a final product of the hydrothermal activity or as a result of another system (e.g. later fault reactivation), high fCO_2 and fO_2 fluid circulation took place through fractures and deposited calcite, corrensite, hematite and feldspar (adularia). This hydrothermal system remobilized and concentrated the Au and Cu. Pb and Zn ore deposits occur further to the east from the granite contact and were formed by hydrothermal processes ascribed to the volcanic event of the Hilário Formation of the same age as the granite.

The Bloco do Butiá area (Mexias *et al.* 1994;1995) is the main gold mineralized area and is located in the westernmost part of the perthite granite (Nardi 1984; Gastal & Lafon 1998). This granite is composed of perthitic alkali feldspar, quartz and amphibole and minor amount of titanite, apatite, zircon, ilmenite and magnetite. These rocks host mostly gold ores and are oversaturated alkaline magmas (Gastal & Lafon 1998). The ores fill mostly E-W and N70W, hundred meters long fractures and show few centimetres to tens of meters wide alteration halos. At these places the hydrothermal alteration (Mexias *et al.* 1994) is multi-episodic and has started with a propylitic phase (inactive flow), characterized by the pseudomorphic transformation of amphibole (iron-edenite) mainly into clorite + quartz + calcite. A later, phyllic alteration (active flow) took place and presented a destructive nature, even on the previously formed propylitic minerals. Regions which have suffered a profound residual chloritization (probably with a dense venular shape), precocious in this type of alteration, were also influenced by the phyllic alteration. The phyllic alteration has a paragenesis composed by white mica (phengite + illite) + quartz + sulphides (mostly pyrite which hosts the "invisible gold" - Mexias & Dani 1995). This paragenesis formed at ca. 450°C (Fig. 12). Finally, taking place as a final hydrothermal event, vein swarms cross cut the rocks affected by the previous alteration processes and are characterized by several generations of iron-rich clorite (chamosite) + calcite + quartz.

This porphyry copper type of deposit has the same age and overall tectonic control as the Camaquã and Santa Maria base metal deposits in the Camaquã Mine. The origin of this mineralisation has been related to volcanic rocks (Leinz *et al.* 1941; Ribeiro 1986), a deep magmatic body (Bettencourt 1972;1976) or derivation from

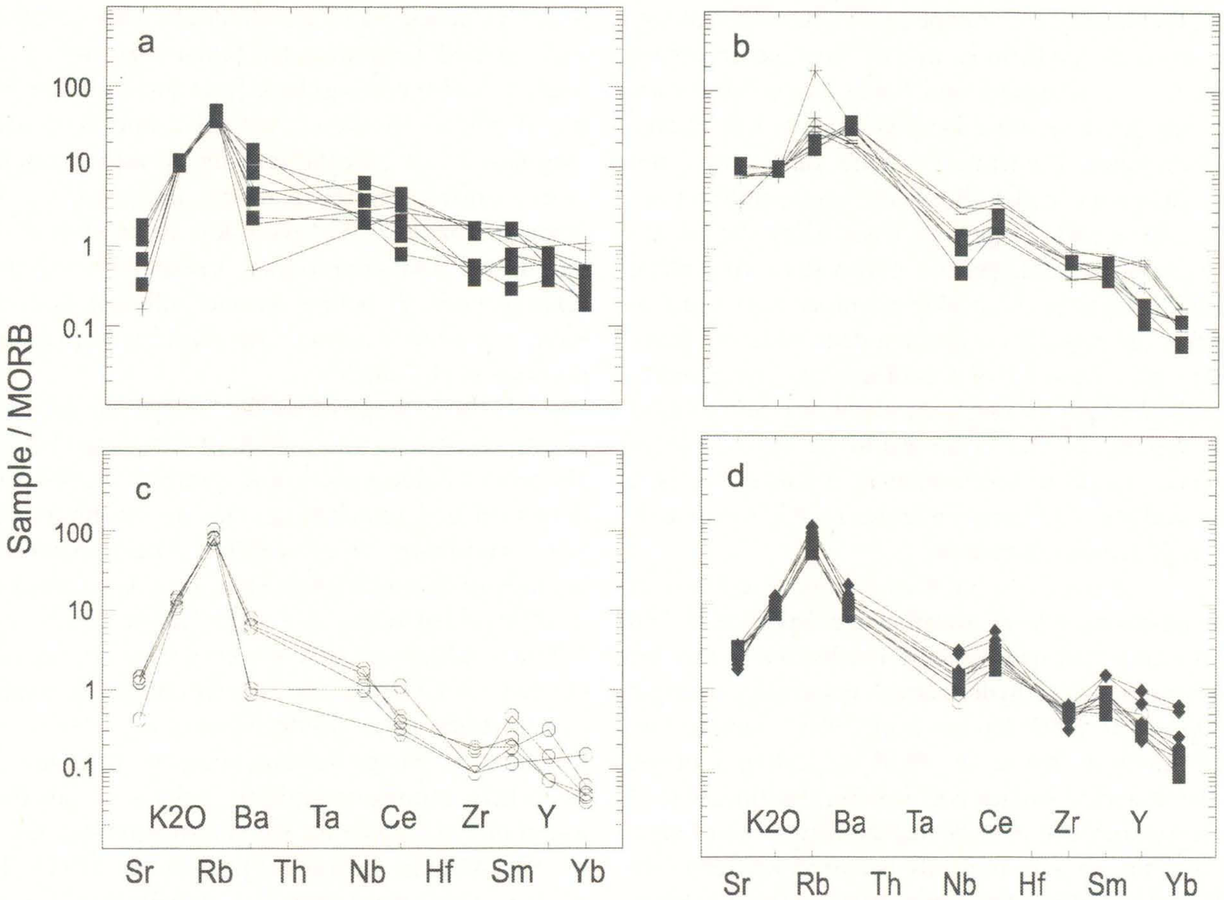

Figure 11. Incompatible element geochemical plot granitic rocks from the Rio Grande do Sul shield. a – Saibro Intrusive Suite granites (Nardi & Bonin, 1991); b – Lavras do Sul shoshonitic association granites (Nardi & Lima, 1985); c – Cordilheira Intrusive Suite granites (Koester, 1995); d – Viamão granites and Quitéria granite (Philipp *et al.*, 1998; Koester, 1995). Samples normalized to MORB (Pearce *et al.*, 1984).

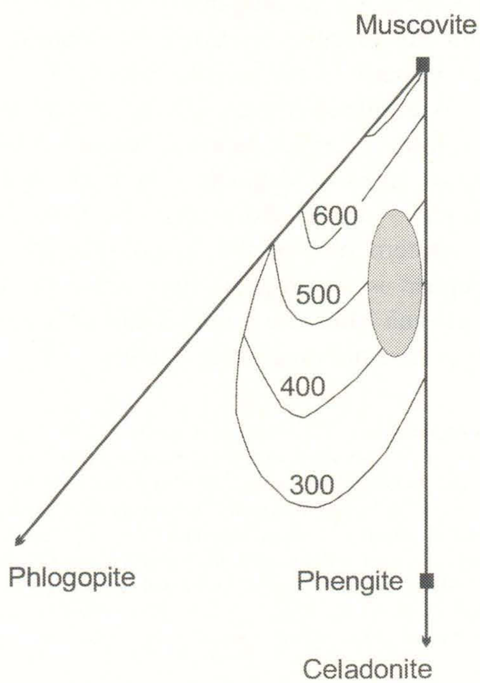

Figure 12. Phengite compositions indicating temperatures of crystallization around 450°C.

sedimentary clastic-diagenetic processes (Badi 1983; Ribeiro 1990). One group of genetic hypotheses considers the deposits diagenetic, based on observations in the stratiform control of part of mineralizations and also on the fine grain size of ores in these structures. The stratiform aspect of ore minerals is better seen in the Santa Maria Deposit, where galena and sphalerite are disseminated in the matrix of arenites and conglomerates. In the Camaquã Mines the major part of Cu and Fe ore sulphides are controled by NW-trending fractures while pyrite is the main sulphide disseminated in arenites and chalcocite in the conglomerates.

However, the stratiform control is not totally convincing for the origin of ores in Santa Maria Deposit, because in several areas in the mine the ore minerals cross cut the stratigraphy (Badi 1983). The major part of syngenetic/diagenetic base-metal sedimentary deposits around the world are hosted by low energy, marine-sedimentary sequences. Whereas, the sedimentary sequence hosting the Camaquã and

Santa Maria Mines are high energy, continental fan-delta, dominantly non-marine sediments. Additionally, the reduced conditions in the host sedimentary sequences of Camaquã and Santa Maria Mines are very restricted to some local lacustrine depositional environments (centimeter wide dark gray and greenish pelitic beds). Because these condition are critical for S and C supply of basin being the precursor of syngenetic/diagenetic pyrite (e.g. via sulfate reduction bacteria or abiological processes) and Cu-sulfides, the non-marine characteristic of Bom Jardim Group play against one sedimentary syngenetic-diagenetic origin for this mineralizations. Some sulfur contribution for the basin could be derived from sulphides found in volcanoclastic fragments of host rocks and possible from fumaroles related to volcanic events of Hilario Formation.

The overall evidences (strutural control of mineralisations, mineral zonation in a deposit scale and the previous and new isotopic results) show that the mineralizations are hydrothermal epigenetic in origin (Groves *et al.* 1997; Remus *et al.* 1998). Temperature determinations based on fluid inclusion, chlorite geothermometry studies and isotopic fractionating of sulfur isotopes also indicate that the deposition of main ore and the gangue minerals occurred between 210 and 300°C (Beckel 1990; Lima, 1985). Also, the values for $d^{34}S$ of sulphides around 0‰ are better explained by a magmatic-hydrothermal source (Bettencourt 1976; Remus *et al.* 1998).

The initial Pb isotope results for sulphides from the Camaquã-Santa Maria Mines seem to indicate that the metals were derived from a largely crustal source with very primitive Pb at the end of Brasiliano Cycle. Mineralisation is therefore inferred to be related to the magmatic event reflected by the end of Brasiliano magmatism possibly related to Lavras or Caçapava Granite plutonism, but Pb was derived largely from an old basement and the sedimentary rocks of the Bom Jardim Group when fluid ascended through the thick volcano-sedimentary package (Remus *et al.* 1998).

FINAL CONSIDERATIONS

The diversified and long-lived magmatism occurring in the shield of Rio Grande do Sul is dominated by granitic rocks and includes voluminous volcanism of tholeiitic, shoshonitic and alkaline affinity, in addition to a small volume of komatiitic rocks. Gabbroic rocks are minor but widespread and little studied. Granitic rocks register the irreversible evolution of the lithosphere from low-K magmas in the Archean to mixed tonalitic and K-granitic magmas in the Paleoproterozoic to minor tonalitic and dominantly K-granitic magmas in the Neoproterozoic. This evolution is present in the dated and analyzed rocks, irrespective of their relative position before terrane collision that may have occurred between the western and eastern portions of the shield.

The geology of the Rio Grande do Sul shield is comparable to the shield of Uruguay, because abundant Paleoproterozoic granitic rocks were deformed and remelted during the Neoproterozoic (e.g., Hartmann *et al.* 1999b). The Precambrian geology of Santa Catarina State has this bimodal age distribution of rocks as a main feature (Silva *et al.* 1999a), which is also observed on the eastern extension of Gondwana Supercontinent in western Africa (Leite *et al.* 1999; Silva *et al.* 1999b). The presence of Neoproterozoic juvenile terranes and reworked granitic-migmatitic belts such as those found in Rio Grande do Sul is also a marked feature of NE African geology (e.g., Stern 1994). The geology of all these regions is comparable, because most of the crust was accreted from the mantle in the Archean and mostly in the Paleoproterozoic and intensely reworked in the Neoproterozoic Brasiliano / Pan-African Cycle orogenies. The also share in common the juvenile accretion of Neoproterozoic terranes in parts of the mobile belts.

Widespread occurrences of metals indicate the possibility of major deposits, but as yet the only two major types of deposits – both currently non commercial – are related to the Vila Nova Terrane in the western part of the shield. The Bossoroca gold deposit is an orogenic type while the Lavras and Camaquã Mine are a continuum of a porphyry copper epithermal magmatic system.

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