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EXTENSÃO SUL DO SISTEMA OROGÊNICO TOCANTINS NO CONTEXTO GEODINÂMICO DA AGLUTINAÇÃO DO GONDWANA: EXERCÍCIO DE TECTÔNICA

Mario da Costa Campos Neto

Tese apresentada para o Concurso de Livre-Docência junto ao Departamento de Mineralogia e Geotectônica do Instituto de Geociências da Universidade de São Paulo. Área de Conhecimento: de Geologia Estrutural/Geotectônica.

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ÍNDICE

CAPÍTULO 1

BREVE APRESENTAÇÃO

Essa tese de Livre Docência resulta da sistematização científica empreendida nos anos de 1998 e de 1999. Alicerçada em trabalhos de campo sistemáticos, na análise estrutural e na petrologia metamórfica como ferramentas básicas, aliadas ao manuseio do acêrvo isotópico e geocronológico, ela possui na análise tectônica seu principal vetor de direção.

No entanto, pressionado pela Reitoria da Universidade de São Paulo através da Comissão Especial de Regimes de Trabalho (CERT) e pelas principais agências nacionais e estadual de fomento à pesquisa, deu-se prioridade à preparação de artigos endereçados à comunidade científica internacional, antecedendo a formulação integrada em uma tese. Assim, quatro trabalhos foram preparados, três para as revistas *Precambrian Research*, *Tectonics* e *Episodes* (ver referências bibliográficas) e um para o livro *Tectonic Evolution of South America*, a ser editado pelo 31° Congresso Geológico Internacional. Destes, os dois primeiros (preparados com a colaboração do Dr. Renaud Caby, Diretor de Pesquisas do CNRS, França) e o ultimo constituem o corpo desta tese. São eles:

Campos Neto, M.C. e Caby, R., 1999. Neoproterozoic high-pressure metamorphism and tectonic constraint from the nappe system south of the São Francisco Craton, southeast Brazil. *Precambrian Research*, **97**, 3-26.

Campos Neto, M.C. e Caby, R. (inédito). Terrane accretion and upward extrusion of high-pressure granulites in the Neoproterozoic nappes of southeast Brazil: Petrologic and estructural constraints. *Tectonics* (aceito para publicação).

Campos Neto, M.C. (inédito). Orogenic systems from SW-Gondwana: an approach to Brasiliano-Pan African cycle and orogenic collage in SE-Brazil. E.J. Milani e A. Thomaz Filho (edts.) Tectonic Evolution of South America, *International Union of Geological Science-31th International Geological Congress* (submetido).

O tempo, constrangido a prazos rígidos, não permitiu que esses trabalhos fossem reescritos em português e integrados no contexto da tese. Por este motivo ela está sendo apresentada em inglês. Cada trabalho corresponde a um capítulo, respeitada a sua integridade, do título aos agradecimentos. As referências bibliográficas foram unificadas e as figuras renumeradas de acordo com os capítulos.

Como são artigos que se complementam, a ordenação dos capítulos permite, sem quebras maiores no encadeamento do texto, uma visão geral, dos objetos (ou dados obtidos) aos processos e a integração destes na dinâmica global. Essa relação entre os artigos, aliada ao fato de dois deles ainda não terem sido publicados, garante o caráter inédito desta tese.

O Capítulo 2 trata do sistema de nappes que se empilham lateralmente à borda sul do cráton do São Francisco. Distingue nessas estruturas, padrões cinemáticos diferenciados e trajetórias metamórficas conflitantes. A enfase está nos alóctones inferiores, onde o metamorfismo de alta pressão, caracterizado pioneiramente por Trouw (1992), situa parte

do orógeno como resultante da extrusão forçada e de baixo ângulo, de um prisma de subducção continental, grosseiramente orientado para oeste.

A ênfase do Capítulo 3 está nas nappes superiores, de alta temperatura, colocadas em evidência, inicialmente, por Campos Neto et al. (1984). São terrenos identificados com um ambiente de raiz de arco magmático, cujo registro metamórfico e estrutural assemelha-se a um orógeno colisional himalaiano. O registro químico e isotópico apresentado, reforçado no trabalho de Janasi (1999), alia-se aos distintos ambientes tectônicos deduzidos pelas incompatibilidades e diferenças nas trajetórias metamórficas, permitindo um avanço no reconhecimento de terrenos, ou de ambientes tectônicos exóticos em relação a placa do São Francisco.

A evolução geodinâmica apresentada no Capítulo 4 discute o processo de aglutinação do sudeste do continente brasileiro dentro do contexto da colagem orogênica do sudoeste do Gondwana. Parte-se dos registros, na região, dos processos de quebra e dispersão de Rodínia, de interação de placas oceânicas e do diacronismo dos regimes tectônicos.

CAPÍTULO 2

NEOPROTEROZOIC HIGH-PRESSURE METAMORPHISM AND TECTONIC CONSTRAINT FROM NAPPE SYSTEM SOUTH OF THE SÃO FRANCISCO CRATON, SOUTHEAST BRAZIL

Abstract

The Neoproterozoic giant nappe system exposed south of the São Francisco craton underwent a minimum of 150 km of near-horizontal northeastward displacement. This nappe system comprises an uppermost unit derived from a plutonic magmatic arc terrane with high-pressure, high-temperature intermediate to mafic granulites at its base (Socorro-Guaxupé nappe), underlain in sequence by a high-pressure kyanite granulite nappe, an amphibolite facies metapelite nappe, and finally by a quartzite nappe which forms the lowest part of the pile and rests on a parautochthonous unit related to the passive margin of the craton .The kyanite granulites crystallised around 13 kbar, 750°C and have only at their top sillimanite related to T-increase overprinting (T=890°C), a consequence of downward heat advection from the overlying Socorro-Guaxupé granulites equilibrated at 900°C. Pressures of 13-14 kbar are documented in the underlying metapelite nappe with temperatures of 640-670°C, in which lenses of eclogite indicate Pmax of ca. 17.5 kbar. Phyllites of the parautochthonous unit are directly overlain by HP granulites in the north and record P≈ 7 kbar and T= 500°C. The distribution of metamorphic facies is reminiscent of inverted metamorphism with eclogites from subduction-related metamorphism and kyanite granulites from early extrusion of subducted continental crust. The metamorphic conditions of the parautochthon may represent a stage achieved during late metamorphic thinning of the nappe pile. The overall picture suggests that high-pressure units recrystallised in a subduction zone located to the WSW. The frontal thrusts of the nappe system show a late, north northeastward transported thin-skinned pattern.

Keywords: Brasilian/Pan-African; collision tectonics; nappe system; high-pressure metamorphism; kyanite granulite.

2-1. Introduction

Most granulites formed in the lower crust of collisional orogens generally underwent late-kinematic recrystallisation because they were eventually maintained during a long time at elevated temperatures close to hot mantle. Sillimanite kinzigites are normal end products of most metapelitic granulites formed within the lower crust of former mountain roots. The exhumation of the lower crust either results from regional extension and/or asthenospheric doming (i.e. Permian-Mesozoic exhumation of the Ivrea zone, Zinng et al., 1990).

In himalayan-type collisions that generally result from continuous plate convergence and continental subduction, the lower crust is exposed through piling-up of crystalline nappes displaced 100 km or more over less metamorphic allochthons, giving rise to metamorphic inversion (Le Fort et al, 1986; Burg et al., 1987). Mineral assemblages in high grade metamorphic rocks from such nappes may register a severe high-temperature decompression with low-pressure recrystallisation and anatexis that overprints most of the

earlier higher pressure mineral assemblages. In central Himalaya maximum pressures around 9 kbar have been calculated for most metapelites by Vannay and Hodges (1996), with values up to 12 kbar in Langtang (Macfarlane, 1995). Indeed, the occurrence of kyanite in the primary assemblage of metapelites associated with dry leucosomes towards the base of the main crystalline allochthon in central Nepal (Caby et al., 1983) leads to the assumption that much higher pressure rocks may be present at depths. Such is the case of northern Pakistan where high-pressure metapelites (650-700°C and 8-13 kbar) were exhumated under decreasing temperatures in the kyanite stability field (Pognante et al., 1993). Also lenses of medium-temperature eclogites survived enclosed in gneisses and metatexites (Pognante and Spencer, 1991; Tonarini et al., 1993; Le Fort et al, 1997). Liu and Zhong (1997) have described in eastern Himalaya relics of high-pressure granulites. In the Tso Morari dome at the North Himalayan Massif a high-pressure and low-temperature mafic and pelitic eclogites was recently described, implying in a continental subduction at the onset of the Indian-Eurasian collision (Guillot et al., 1997 and Sigoyer et al., 1997).

Slightly retrogressed mafic eclogites with preserved low to medium-temperature prograde minerals such as lawsonite have been reported elsewhere in granulites and anatectic metapelites (Biino, 1994), showing that early high-pressure metamorphic conditions may survive retrogression even at high temperatures. There are however very few examples of outcropping slightly or unretrogressed kyanite granulites (see Pin and Vielzeuf, 1983). The occurrences of kyanite granulites described are all associated with eclogites but kyanite is invariably overgrown by sillimanite as in the Iberian massif (Ibarguchi et al., 1990; Arenas, 1991; Abalos et al, 1996) or in the Bohemian massif (Carswell and O'Brien, 1993). In contrast, kyanite is the only Al-silicate present in rocks adjacent to all reported ultra high-pressure rocks in the world. This may suggest that subduction settings with low geothermal gradients (<12°C/ km) represent the only site where high-pressure granulites can form and be exhumed rapidly, thus escaping reequilibration in the sillimanite stability field.

We describe in this paper the tectonic setting and metamorphic evolution of kyanite kinzigites and associated rocks that form the base of himalayan-type nappes with associated reverse metamorphism in the Neoproterozoic Brasiliano belt, south of the São Francisco craton. We then discuss the tectonic implication of the reconstructed P/T paths of granulites and adjacents units and we propose a scenario for nappe stacking and exhumation according to the available U-Pb and Sm-Nd geochronological data.

2-2. Geological setting

The Archaean-Paleoproterozoic São Francisco Craton in SE Brazil (Fig. 2-1) is bounded in its western and southern margins by nappes involving Proterozoic rift and continental margin sequences (Brasília and Alto Rio Grande belts, Brito Neves et al, 1995; Paciullo et al., 1998). It comprises from top to bottom: a giant high-temperature granulite-migmatitic allochthon (the Socorro-Guaxupé nappe) that is part of the Apiai-Guaxupé terrane (Campos Neto and Figueiredo, 1995); an upper kyanite-granulite nappe with high-pressure metamorphism (Vasconcellos, et al. 1991; Trouw, 1992; Trouw and Castro, 1996; Campos Neto and Caby, 1997, Trouw et al., 1998); a lower metapelite nappe with medium-temperature, high-pressure metamorphism; a quartzite nappe with passive continental margin affinity (Ribeiro et al., 1995), and a parautochthonous unit overlying the southern edge of the São Francisco craton (Fig. 2-1). This Neoproterozoic nappe system exposed

south of the São Francisco craton is the extension of the Brasilia belt (Trouw et al., 1984a; Fuck et al., 1994; Valeriano et al, 1995 and 1998; Simões, 1995; Seer et al, 1998). The nappes that underlie the Socorro-Guaxupé nappe have been named the "Alto Rio Grande belt" and their lithostratigraphy, structure and metamorphism were first studied by Trouw et al. (1980, 1982, 1983, 1984b, 1986), Ribeiro and Heibron (1982), Campos Neto et al. (1990), Junho et al. (1992), and Ribeiro et al. (1995). The nappe system is bounded to the southeast by major syn to late-metamorphic shear zones that were active till 570 Ma (Machado et al., 1996).

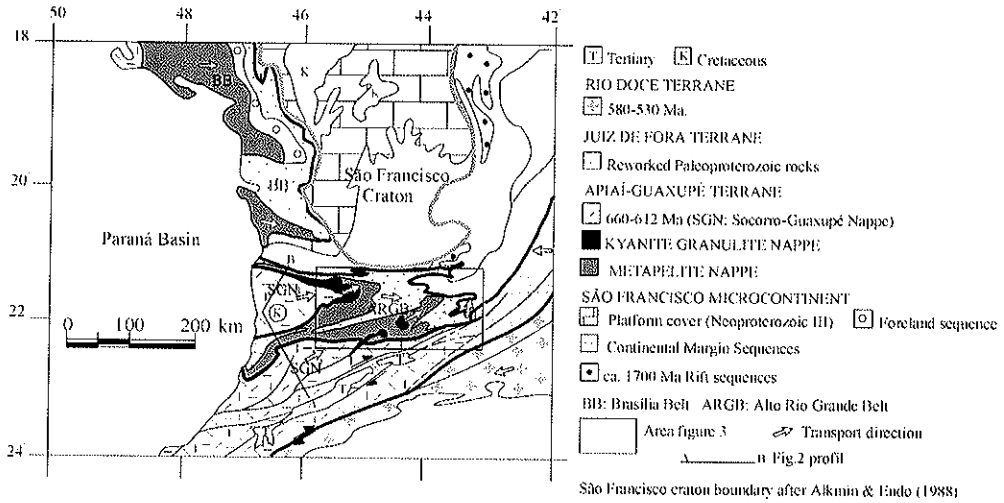

Figure2-1: Sketch tectonic map of Southeast Brazil.

2-2.1 The Socorro-Guaxupé nappe

The Socorro-Guaxupé nappe comprises a flat-lying to gently southwestward dipping sole of enderbitic granulites ca. 3 km thick. These granulites grade upward into grey to pink, biotite-hornblende diatexites ca 6 km thick interlayered at their top with pelitic to semi-pelitic migmatites and subordinate lenses of quartzite, calc-silicate gneiss, rare marbles and mafic metaintrusives. Peraluminous muscovite-bearing granites intrude the top of the allochthon (Fig. 2-2). The basal green-colored, medium-grained, garnet bearing banded granulites of enderbitic modal composition are metaluminous, low-K rocks of calc-alkaline affinity with lower amounts of large ion lithophile elements (Campos Neto et al., 1996) than the other granulitic plutonic rocks of the nappe unit (Fernandes et al., 1987; Iyer et al., 1996). The anhydrous enderbitic light-coloured leucosomes and the coarse-grained grey to pink hololeucocratic charnockite veins are interpreted as *in situ* dry melts. Decimetre-thick dark gabbro-noritic layers considered as syn-metamorphic intrusives are common. The Neoproterozoic age of granulitic metamorphism is constrained by a 629 ± 14 Ma Sm-Nd garnet-biotite-whole rock isochron age from a granulite sample from the Piranguinho quarry (Fig. 2-3, Teixeira, written communication, data from Centro de Pesquisas Geocronológicas, Universidade de São Paulo, Brazil). The protoliths of these enderbitic granulites give a Sm/Nd T_{dm} model age of 1290 Ma, with ε_{Nd} (0.640) = -1.2. These results are in agreement with the isotopic primitive composition of the Mara Rosa arc in the hinterland of the Brasilia belt, where the main metamorphism also took place around 630 Ma (Pimentel et al., 1997). The intrusive charnockites dated at 640 Ma by the U-Pb

zircon method (Basei et al, 1995) grade upward into biotite-hornblende granitoids, both rock types exhibiting porphyritic texture. The granitoids with a high-K calc-alkaline trend were emplaced as syn-metamorphic batholiths (630-625 Ma, Ebert et al., 1996; Töpfner, 1996) and are coeval with stratoid mangerites (Campos Neto et al., 1988; Janasi, 1997).

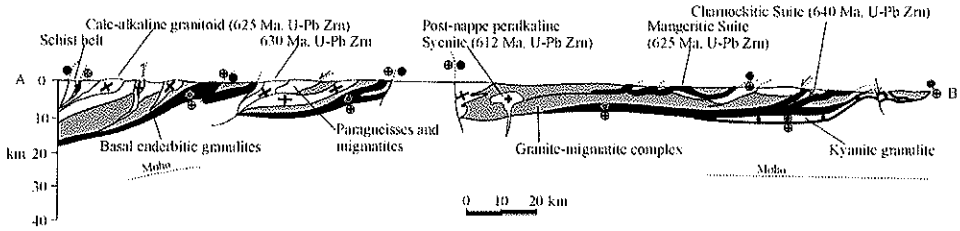

Figure 2-2: Schematic cross-section of Socorro-Guaxupé nappe.

The basal granulites are characterised by garnet-clinopyroxene-orthopyroxene-plagioclase-quartz assemblages in mafic rocks and garnet-sillimanite-cordierite-green spinel-biotite-plagioclase-quartz as reequilibrated assemblage in metapelites. Previous petrologic studies (Table 2-1) point to initial high-pressure, high-temperature metamorphism at P= 12.5 Kbar, T= 900^{o}C followed by partial reequilibration at P= 7.5 Kkar and T= 850^{o}C. Only high temperature-low pressure conditions prevail on the top of the nappe.

NAPPE POSITION	MAIN MINERAL ASSEMBLAGE	P (KBAR)	T (^{0}C)	REFERENCE
Top	Grt-Crd-Sil-Bt-Pl-Kfs	4.5	820	Vasconcellos et al, 1991
	Grt-Crd-Sil- Bt-Spl-Pl-Kfs	7.5	850	Oliveira & Ruberti, 1979
	Grt-Cpx-Pl-Qzt	8.5	850	Iyer et al, 1996
	Grt-Cpx-Hbl-Bt-Pl-Qzt	12.5	900	Del Lama et al, 1994
Base	Grt-Cpx-Opx- Pl-Qzt	12.0	890	Campos Neto & Caby (unpublished)

Table 2-1: Summary of thermobarometric data of Socorro-Guaxupé terrane. Mineral name abbreviations from Kretz (1983).

The whole Socorro-Guaxupé nappe maintained a near horizontal foliation, and the ENE trending lineations with E-directed shear sense indicators throughout the nappe argue for its eastward displacement (around 200 km, Fig.2-3). To the south, a major NE-trending dextral shear belt truncates the Socorro-Guaxupé nappe. Syn-metamorphic structures in the nappe are cut by undeformed circular high-K diorite to syenitic plutons emplaced at ca.10 km depth (Janasi et al, 1993) at 612 Ma (Töpfner, 1996) that belong to ultrapotassic suites. An alkaline intrusive suite adjacent to a graben filled with molassic and volcanic sequences (ca. 600 Ma, Siga Jr. et al, 1995) at the southwestern boundary of Apiaí-Guaxupé Terrane also reflect this last extensional regime.

2-3. The kyanite-granulite nappe

2-3.1 Lithology

This ca. 5 km thick high-pressure nappe comprises mainly coarse-grained kyanite-garnet granulites with lesser amounts of kyanite quartzites, impure quartzites, few calc-silicate rocks and garnet- rich quartzites. The typical granulites are derived from potassic,

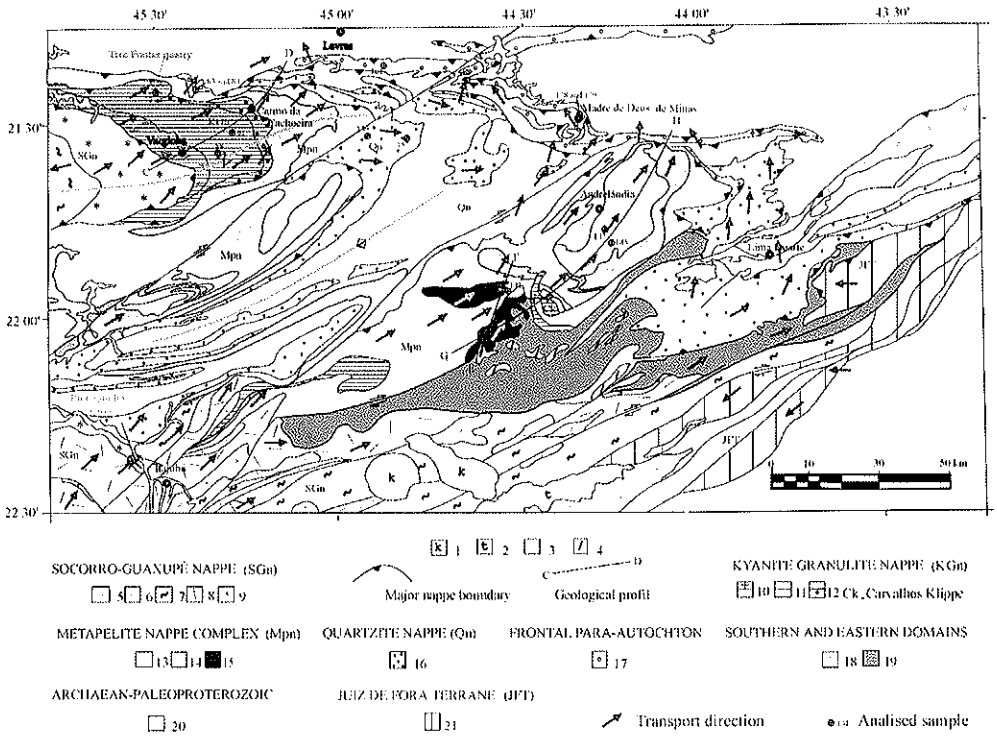

Figure 2-3: Geological map of nappe system South of São Francisco craton

1. Cretaceous, 2.Tertiary, 3. plutonic rocks (ca. 595-570 Ma), 4. tourmaline-bearing granites. Socorro-Guaxupé nappe: 5. high-K calc-alkaline granitoids (ca. 630 Ma), 6. schist belt, 7. paragneisses and migmatites, 8. granite-migmatite complex, 9. granulites. Kyanite-Granulite nappe (KGN): 10. sillimanite-kyanite migmatites, 11. kyanite granulite, 12. metabasic-quartzitic association. Metapelite nappe complex (Mpn): 13. metapelites, 14. metagreywackes, 15. kyanite-bearing migmatites. Quartzite nappe (Qn): 16. quartzitic-schist assemblage. Frontal Para-autochthonous units: 17. interbedded quartzites and phyllites. Southern and Eastern domains: 18. metavolcanosedimentary sequence, 19. migmatite terrain. Archaean-Paleoproterozoic: 20. orthogneisses, migmatites and metamafic-ultramafic sequence. Juiz de Fora terrane: 21. Paleoproterozoic reworked enderbites.

hyper-Al and Ca-poor pelites (Três Pontas type). This sequence devoid of significant retrogression grades upward into sillimanite-garnet granulites (Varginha-type) approaching the basal contact of the Socorro-Guaxupé nappe (Fig. 2-4). At Tres Pontas, these granulites form a moderately boudinaged sequence in which the compositional layering inherited from sedimentary bedding is outlined by the variable proportion of kyanite, garnet and minor micaceous layers. Layers a few centimetres thick with up to 80% of garnet, others a few millimetres thick with kyanite as the main mineral, grey quartzites, various amphibole and calc-silicate-bearing rocks, and rare mafic/ultramafic rocks are intercalated within the main kyanite-garnet granulite type. To the south two klippen made up of the same kyanite granulites are preserved, thus arguing for a minimum of 100 km of eastward displacement of the nappe (Fig. 2-1 and 2-3). One Sm/Nd whole-rock from a kyanite granulite of the Três Pontas and one from the Varginha types give T_{dm} model ages of 1.4 and 1.55 Ga respectively with ε_{Nd} (0.625) of -3.6 and -2.1 (Janasi verbal communication, data from Isotope Research Laboratory, Kansas University, USA). Such values seems to indicate that the source of the sediments had a mixed Proterozoic-Archaean age different from the

terrigenous cover of São Francisco craton, and had active continental margin characteristics (McLennan et al., 1990).

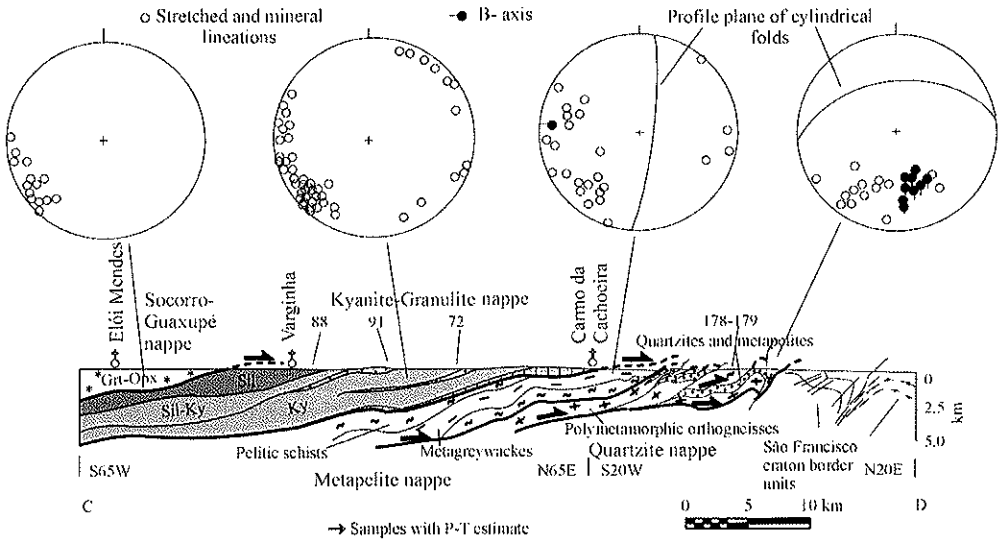

Figure 2-4: Cross-section of kyanite-granulite nappe and Carmo da Cachoeira nappe with equal-area stereographic lower hemisphere projection of mineral and stretching lineations.
91 – analysed sample for P-T.

2-3.2 Kinematics

The main structural pattern is similar to that of the Socorro-Guaxupé nappe and is characterized by a sub-horizontal foliation. ENE trending mineral and stretching lineations (kyanite, rutile, white mica, quartz ribbons, Fig. 2-4), whereas in the Carvalhos Klippen lineations are oriented E-W (Fig. 2-5). The most common structures are asymmetrical boudins (up to 5 m long) even in metapelites of similar rheology, and rare interfolial folds. The ENE direction of ductile flow is evidenced by asymmetric structures such as winged porphyroclasts, decimetric metabasic swells of pull-apart type and small isoclinal a-type folds. Mylonitic bands are associated with in-plane type winged porphyroclasts and tight small-scale folds with stretched limbs.

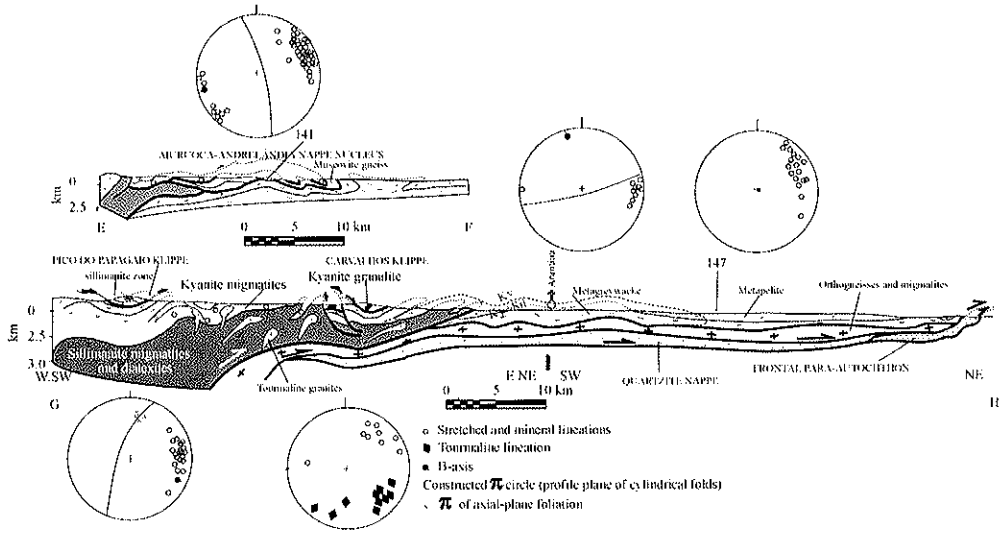

Figure 2-5: Cross-sections of Aiuruoca-Andrelândia nappe complex with equal-area stereographic lower hemisphere projection of mineral and stretching lineations.
141 – analysed sample for P-T.

2-3.3 Microstructures and mineral assemblages

The Três Pontas type kyanite-garnet granulites are light-gray to bluish, coarse-grained massive rocks with 0.5 cm mean grain size. Bands with porphyroblastic structure containing garnet, kyanite and rutile alternate with thinner bands of more massive granoblastic, calc-silicate-rich and mica-poor rocks that did not undergo through post mineral deformation and/or recrystallization.

An early prograde stage is preserved in pyrope-rich garnets that display cores with unrecrystallized microdomains containning relics of a folded cleavage defined by minute acicular rutile crystals. The syn-kinematic foliation is defined in most granulites by quartz ribbons, by the planar disposition of rare micas and platy kyanite prisms, the elongations of which defines the lineation in hand specimen. Most layers display porphyroblastic microstructures except for a few massive, garnet-rich rocks and calc-silicate rocks collected from boudin cores. Feldspar and kyanite augen up to 2 centimetres long and minute augen enclosed in coarse monocrystalline quartz up to 1-2 cm long register pervasive ductile flow at rather high pressures, since sillimanite is absent in most samples. Minute prismatic sillimanite (125μ) has only been observed along grain boundaries from a few samples. On the basis of the textural relationships, it is possible to distinguish an early stage of crystallisation reaching coarse grain size, followed by synkinematic granoblastic recrystallisation.

The first stage assemblage comprises quartz, mesoperthite, rare plagioclase, almandine-pyrope garnet, white mica, rutile, ankerite, graphite, monazite and rare primary biotite. Quartzo-feldspathic lenses formed by up to 80% of centimetre size mesoperthitic feldspar, quartz, and some kyanite, primary white mica and garnet, are regarded as metamorphic segregates representing recrystallized dry melts extracted from underlying aluminous granulites, and affected by further solid-state deformation. Garnet-free, kyanite-bearing granitic layers may represent a younger generation of stromatic leucosomes. Larger, better preserved garnets have pyrope-rich rings surrounding domains with fossilized early stages of growth that contain numerous inclusions of prismatic rutile, monazite, quartz and kyanite, the latter being more abundant towards the rims of the garnet. Rutile, monazite and quartz drops, as well as rare small grains of primary white mica are included in kyanite. White mica flakes are occasionally in contact with garnet rims, some being rarely included in garnet outer zones. Locally layers a few centimetres thick contain up to 30 % of white mica, associated with quartz, kyanite, garnet and rutile. Such a mineral assemblage is reminiscent of white-schists. Pseudomorphs after Na-pyroxene (albite+chlorite+carbonate) have been observed in one sample.

The second syn-kinematic stage assemblage comprises quartz, discontinuous almandine-rich garnet rims, biotite, kyanite, microcline, plagioclase, myrmekite, ilmenite, white mica and calcite. High-temperature plastic flow has deformed and partly destroyed the coarse grain minerals formed during the previous stage. Perthites are plastically deformed and mantled by minute sub-grains of recrystallised microcline, quartz, myrmekite and plagioclase. Primary white mica is bent and rimmed by brown biotite. Kyanite may be plastically microfolded or kinked, though it is mostly unaltered in mica-poor samples.

However in white mica-rich layers the kyanite is partly replaced (though in textural equilibrium) by aggregates of secondary muscovite or by a finer and randomly oriented to radiating aggregate of white mica. Secondary muscovite is the main mineral of some non foliated, feldspar and garnet-poor layers, in which all stages of replacement after kyanite can be observed, in equilibrium with plagioclase and calcite. Most of the brown biotite grew during this stage: in the fine-grained matrix; as large undulose flakes in the pressure shadows of garnet; or like a strain cap of quarter structures (Hanmer and Passchier, 1991). The biotite also occurs in fractures and deep embayments in garnet, in equilibrium with polygonal plagioclase, ilmenite and recrystalized kyanite, thus giving the appearance of primary biotite nucleation in garnet cores.

Medium-temperature synkinematic retrogression occurred in selected bands with protomylonitic fabrics in which garnet is flat and crushed. Total replacement of garnet by biotite occurs approaching cross cutting fissures filled with biotite. Kyanite from such bands is however only slightely retrogressed into white mica. Such features indicate that a fluid phase percolating in cracks promoted the synkinematic retrogression and caused rehydration of granulites. Lower temperature retrogression, though negligible in analysed samples, is evidenced in greenish samples by the nucleation of green biotite and chlorite, calcite and albite. Millimetre-thick veinlets filled with such minerals may be also present.

Mafic rocks form layers and boudins. They comprise both metabasites and more complex Fe-Mg-Ca calc-silicate rocks of metasedimentary origin. One ultramafic rock consists in ca. 40% of plastically deformed orthopyroxene prisms in equilibrium with clinopyroxene, set in a fine- grained mosaic of tremolite. Another metabasite lens (ca. 2 metres-thick) cut by leucocratic segregations comprises garnet, clinopyroxene clasts in a fine-grained biotitic matrix. Calc-silicate layers interbedded with grey Fe-Mg quartzite are amphibole-rich. Some plagioclase-free samples contain predominant brownish amphiboles and biotite, quartz, sphene and garnet with rutile inclusions. Other Mg-rich amphibolites contain clinopyroxene, plagioclase, quartz, phlogopite and scapolite. A garnet-amphibole-rich rock displays the unusual coexistence of kyanite+ankerite in a coarse grain assemblage of quartz, plagioclase and scapolite.

A sillimanite overprint is conspicuous in Varginha-type granulites that contain microcline, plagioclase, myrmekite, rutile and/or ilmenite as well as pyrope-rich garnet. Abundant syn-kinematic sillimanite has substituted most of the kyanite. Unaltered kyanite prisms may however survive in more resistant layers and in garnet cores. Recrystallisation of deformed kyanite into tiny prisms may also occur, in association with the blastesis of minute prismatic sillimanite along small shear bands and in equilibrium with newly formed prismatic rutile. The nucleation of prismatic sillimanite also progressed in the form of fine-grains or replacement of kyanite prisms. Rutile in these rocks is entirely replaced by ilmenite. Inclusions of prismatic sillimanite occur towards the rims of pyrope-rich garnet. A few feldspathic bands similar to those from the Tres Pontas granulites are also present.

2-3.4 Mineral chemistry and P/T estimation

Garnet cores from Três Pontas metapelites without biotite nucleation have the mean composition Alm50-Prp42-Grs7. Towards the rim garnet (Alm48-Prp45-Grs7) is in equilibrium with biotite, kyanite, mesoperthite and white mica. The discontinuous <500μ rim in equilibrium with biotite is almandine rich up to 62 mole %, with a corresponding pyrope decrease to 34 mole %. Grossular content is always about 5-7 mole %, and

	72b		72 H		88b		91b		141.2		141c		147.2	147c		145i		178a	
	C	R	C	R	C	R	C	R	C	R	C	R	C	C	R	C	R	C	R
SiO_2	38.00	37.76	37.62	37.24	39.91	39.99	38.64	37.62	38.00	38.13	37.34	37.31	36.92	37.99	37.65	37.59	37.57	36.31	36.18
TiO_2	0.07	0.03	0.08	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.01	0.00	0.05	0.00	0.14
Al_2O_3	21.40	21.37	22.23	22.48	22.04	22.27	22.62	22.21	22.41	22.39	22.16	22.12	21.53	21.32	21.61	21.16	20.90	21.21	21.65
Cr_2O_3	0.01	0.04	0.03	0.01	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.02	0.00
FeO^t	33.90	34.48	28.14	28.45	23.63	23.55	25.06	28.79	26.68	27.87	26.72	25.56	36.61	33.10	34.67	35.58	35.56	29.84	32.14
MnO	0.28	0.27	0.45	0.47	0.56	0.56	0.52	0.66	0.54	0.69	0.59	0.55	0.71	1.19	1.26	0.90	0.82	3.10	0.86
MgO	5.04	5.17	8.42	8.61	10.28	10.20	12.06	9.19	4.44	4.23	4.91	4.46	4.52	3.19	2.80	3.32	3.20	1.58	2.44
CaO	1.00	0.92	2.53	2.47	2.46	2.33	1.52	1.52	9.67	8.04	7.66	9.26	0.69	2.95	1.80	1.30	1.35	7.24	5.78
Na_2O	0.04	0.00	0.00	0.06	0.11	0.12	0.00	0.00	0.00	0.00	0.03	0.02	0.00	0.10	0.15	0.00	0.00	0.03	0.06
Total	99.74	100.0	99.48	99.79	99.04	99.08	100.7	99.99	101.9	101.4	100.7	99.28	101.2	99.97	99.99	99.86	99.45	99.33	99.25
Structural formulae normalised to 12 oxygen with ferric iron calculated																			
Si	3.02	3.00	2.92	2.88	3.06	3.06	2.91	2.90	2.920	2.95	2.93	2.93	2.92	3.04	3.02	3.02	3.04	2.93	2.91
Al^T	0.00	0.00	0.08	0.12	0.00	0.00	0.09	0.10	0.08	0.05	0.07	0.07	0.08	0.00	0.00	0.00	0.00	0.06	0.08
Al^{IV}	2.00	1.99	1.95	1.92	1.99	2.01	1.91	2.09	1.945	1.99	1.98	1.98	1.93	2.01	2.04	2.00	1.99	1.95	1.96
Fe^3	0.11	0.11	0.09	0.09	0.07	0.07	0.18	0.181	0.135	0.05	0.09	0.08	0.14	0.11	0.11	0.12	0.12	0.10	0.11
Fe^2	2.14	2.17	1.73	1.74	1.44	1.43	1.40	1.676	1.580	1.75	1.66	1.59	2.28	2.10	2.21	2.27	2.28	1.91	2.05
Mg	0.60	0.61	0.97	0.99	1.17	1.16	1.35	1.056	0.509	0.49	0.57	0.52	0.53	0.38	0.33	0.40	0.38	0.19	0.29
Mn	0.02	0.01	0.03	0.03	0.03	0.03	0.03	0.043	0.035	0.05	0.04	0.03	0.05	0.08	0.08	0.06	0.05	0.21	0.06
Ca	0.08	0.08	0.21	0.20	0.20	0.19	0.12	0.125	0.796	0.67	0.64	0.78	0.06	0.25	0.15	0.11	0.11	0.62	0.50
X_{Fe}	0.75	0.75	0.58	0.58	0.50	0.51	0.48	0.58	0.54	0.59	0.57	0.54	0.78	0.74	0.79	0.80	0.80	0.65	0.70
X_{Mg}	0.21	0.21	0.33	0.33	0.41	0.41	0.47	0.36	0.16	0.17	0.19	0.18	0.18	0.13	0.12	0.14	0.14	0.06	0.10
X_{Ca}	0.03	0.03	0.07	0.07	0.07	0.07	0.04	0.04	0.27	0.23	0.22	0.26	0.02	0.09	0.05	0.04	0.04	0.21	0.17
	GRANULITE FACIES ROCKS								ECLOGITE FACIES ROCKS				AMPHIBOLITE FACIES ROCKS						

Table 2-2: Selected analyses of garnets. C: core, R: rim. FeO^t: total Fe as FeO

	72b Mc 18	72h Mc 14	91b Mpth22	91b Pl30	88b Pl 23	141.2 Pl^2 37	Pl^1 30	141c Pl^2 4	Pl^3 6	147c Pl 31	145i Pl 18	178a Pl 11
SiO_2	64.14	64.22	62.12	61.80	60.89	64.01	65.14	64.06	59.46	60.90	63.99	62.60
Al_2O_3	18.70	18.83	22.16	24.14	24.25	23.69	22.34	23.07	25.87	24.47	22.27	24.17
FeO^T	0.00	0.00	0.03	0.04	0.09	0.20	0.07	0.04	0.02	0.05	0.01	0.00
MnO	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.00	0.01	0.00
BaO	0.42	0.42	-	-	0.00	-	0.00	0.00	0.08	0.00	0.05	0.00
CaO	0.00	0.00	3.50	5.25	6.08	4.16	3.08	4.30	7.65	5.72	3.31	5.10
Na_2O	0.46	1.89	7.15	8.57	7.99	9.41	9.12	8.48	6.82	8.35	9.30	8.09
K_2O	16.33	13.83	3.84	0.29	0.36	0.02	0.00	0.08	0.06	0.07	0.06	0.04
Total	100.05	99.19	98.80	100.09	100.37	101.5	99.76	100.03	99.96	99.56	98.94	100.00
Structural formulae normalised to 8 oxygen												
Si	2.97	2.97	2.81	2.74	2.70	2.79	2.86	2.82	2.65	2.71	2.84	2.76
Al	1.02	1.03	1.18	1.26	1.30	1.22	1.15	1.19	1.36	1.28	1.16	1.25
Ca	0.00	0.00	0.17	0.25	0.29	0.19	0.14	0.20	0.36	0.27	0.16	0.24
Na	0.04	0.17	0.63	0.74	0.68	0.79	0.77	0.72	0.59	0.72	0.80	0.69
K	0.96	0.82	0.22	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ab	4.1	17.2	62.0	73.0	64.0	80.0	84.3	77.7	61.5	72.3	83.3	74.0
An	0.0	0.0	17.0	25.0	29.0	20.0	15.7	21.8	38.1	27.3	16.4	25.8
Or	95.9	82.8	21.0	2.0	2.0	0.0	0.0	0.4	0.3	0.4	0.3	0.2
	Granulite facies rocks					Eclogite facies rocks				Amphibolite facies rocks		

Table 2-3: Selected analyses of feldspars. Mc: microcline; Mpth: mesoperthite; Pl: plagioclase; Pl^1: symplectite intergrowth with cpx; Pl^2: coronitic garnet ring; Pl^3: amphibole intergrowth.

	72B	147.2	147C	145i	179B	178A	159C	157	161C	161E	84C	84A	188A
	Ms 33	Prg137	Ms23	Ms23	Ms11	Ms21	Ms13	Ms4	Ms9	Phg43	Phg60	Phg26	Ms6
SiO_2	46.25	46.72	45.90	46.22	46.35	46.50	47.04	47.28	46.16	48.33	47.26	46.78	46.69
TiO_2	0.99	0.06	0.44	1.01	0.50	0.13	0.32	0.42	0.14	0.24	1.14	0.86	0.33
Al_2O_3	34.41	41.36	36.29	35.49	36.84	37.03	35.90	35.68	37.47	32.56	25.82	27.83	36.28
Cr_2O_3	0.02	0.00	0.00	0.04	0.11	0.07	0.02	0.00	0.07	0.00	0.00	0.00	0.00
FeO^t	1.15	0.97	0.84	1.47	0.96	0.73	1.43	1.10	0.24	1.13	7.88	6.78	1.17
MnO	0.00	0.01	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.05	0.02	0.00	0.06
MgO	0.74	0.00	0.62	0.61	0.57	0.60	0.86	0.88	0.19	0.74	1.81	1.43	0.66
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.04
Na_2O	0.26	7.68	1.14	1.12	1.91	1.49	0.76	0.92	1.81	1.44	0.13	0.17	0.88
K_2O	10.65	0.44	9.76	8.72	8.49	9.10	10.52	10.60	7.85	8.33	10.78	10.56	9.65
H_2O	4.47	4.77	4.51	4.51	4.57	4.57	4.58	4.58	4.53	4.45	4.31	4.33	4.55
Total	98.94	102.1	99.50	99.20	100.3	100.2	101.2	101.46	98.46	97.27	99.15	98.74	100.3
Structural formulae normalised to 12 oxygen													
Si	3.10	2.93	3.05	3.07	3.04	3.05	3.08	3.09	3.05	3.25	3.29	3.24	3.07
Al^{IV}	0.89	1.06	0.95	0.93	0.96	0.94	0.92	0.91	0.94	0.75	0.71	0.76	0.92
Al^{VI}	1.82	2.00	1.89	1.85	1.89	1.92	1.85	1.84	1.98	1.83	1.40	1.51	1.88
Ti	0.05	0.00	0.02	0.05	0.02	0.00	0.01	0.02	0.00	0.01	0.06	0.04	0.01
Fe^2	0.06	0.05	0.04	0.08	0.05	0.04	0.08	0.06	0.01	0.06	0.46	0.39	0.06
Mg	0.07	0.00	0.06	0.06	0.05	0.06	0.00	0.08	0.02	0.07	0.19	0.15	0.06
Na	0.03	0.94	0.14	0.14	0.24	0.19	0.10	0.12	0.23	0.19	0.02	0.02	0.11
K	0.91	0.04	0.82	0.74	0.71	0.76	0.88	0.88	0.66	0.72	0.96	0.93	0.81
X_{ms}	0.83	0.03	0.89	0.85	0.89	0.91	0.85	0.84	0.98	0.84	0.49	0.57	0.88
X_{Prg}	-	0.88	-	-	-	-	-	-	-	-	-	-	-
X_{cel}	0.13	0.0	0.11	0.11	0.10	0.11	0.15	0.15	0.04	0.15	0.26	0.22	0.11
	Gnl np	Metapelite nappe					Quartzite nappe		Frontal parauthochthonous unit				

Table 2-4: Select analyses of white mica. Ms: muscovite, Prg: paragonite, Phg: phengite. Gnl np: kyanite granulite nappe.

spessartine < 1 mole % (Table 2-2). Primary plagioclase is oligoclase as porphyroclasts with An 14 to 17 mole % (Table 2-3), and as strings in mesoperthite. Primary white mica (Table 2-4) has low Si content (3.10 p.f.u.) and low molar fraction of celadonite (Xcel=0.13). Secondary muscovite has similar low Si and celadonite content but is less titaniferous. Biotite inclusions from pyrope-rich rings have higher phlogopite (X_{Phl} up to 0.16) and TiO_2 (up to 4 wt%) than matrix biotite (Table 2-5). Garnet from the sillimanite-containnin Varginha-type granulites also has high pyrope content of around 40-mole % in equilibrium with phlogopite-rich, titaniferous biotite (up to 4 wt% TiO2) and plagioclase (ca. An28).

	72b Bt32	91b Bt31	72h Bt2	88b Bt11	147.2 Bt146	147c Bt*28	145i Bt7	178a Bt19
SiO_2	35.07	36.73	37.17	36.84	35.57	36.40	36.19	36.38
TiO_2	3.23	2.74	4.41	4.01	0.95	1.44	1.62	1.63
Al_2O_3	17.31	17.05	17.69	16.40	19.70	19.96	19.51	19.31
Cr_2O_3	0.00	-	0.00	0.09	-	0.01	0.05	0.07
FeO^t	24.10	10.54	13.60	12.62	19.57	17.71	19.42	17.71
MnO	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.00
MgO	6.45	14.78	13.26	15.00	9.60	10.59	10.40	11.95
BaO	0.10	-	0.11	0.10	-	0.18	0.06	0.00
Na_2O	0.02	0.05	0.05	0.09	0.63	0.25	0.18	0.23
K_2O	9.35	10.73	9.95	10.4	9.95	9.11	8.42	8.96
H_2O	3.85	3.96	4.07	4.04	3.95	4.01	4.00	4.03
Total	99.50	96.61	99.91	99.23	99.92	99.66	99.87	100.2
Structural formulae normalised to 12 oxygen								
Si	2.76	2.78	2.74	2.73	2.70	2.72	2.71	2.70
Al^{IV}	1.23	1.06	1.26	1.26	1.25	1.27	1.28	1.29
Al^{VI}	0.33	0.46	0.27	0.16	0.51	0.48	0.44	0.39
Ti	0.18	0.16	0.22	0.22	0.05	0.08	0.09	0.09
Fe^2	1.54	0.67	0.84	0.78	1.24	1.11	1.22	1.10
Mg	0.73	1.66	1.45	1.66	1.09	1.18	1.16	1.32
Na	0.00	0.01	0.00	0.01	0.09	0.03	0.02	0.03
K	0.91	1.04	0.93	0.95	0.96	0.87	0.80	0.85
X_{ann}	0.14	0.01	0.02	0.01	0.06	0.05	0.06	0.046
X_{phl}	0.01	0.16	0.11	0.16	0.04	0.06	0.06	0.08
	Granulite facies rocks				Amphibolite facies rocks			

Table 2-5: Selected analyses of biotites. Bt*: biotite included in garnet.

The restricted occurrence of rutile (Table 2-6) in both prograde and primary assemblages implies that initial and peak pressures were higher than the GRAIL net transfer reaction (Bohlen et al., 1983). Temperatures were estimated using Fe-Mg partitioning between coexisting garnet and biotite, or garnet and phengite in metapelitic rocks from KFMASH system. The available models for this thermometer (Ferry and Spear, 1978; Hodges and Spear, 1982, Green and Hellman, 1982, and Indares and Martignole, 1985) were applied and results are shown with its estimated errors in Table 2-7. The equilibrium temperatures between two pairs of primary biotite and pyrope-rich rims from the Três Pontas metapelites are between 690 and 780°C (Indares and Martignole, 1985) and are 730°C for primary muscovite and almandine-rich garnet rims

(Green and Hellman, 1982). Such values argue for initial minimum pressures around 12.0 kbar according to GRAIL in pyrope-rich garnets (Alm48-Prp47). Taking into account the coexistence of mesoperthite and primary plagioclase, aminimum pressure of about 13.0 kbar can be deduced from the GRIPS reaction using matrix ilmenite activty=0.93 (Bohlen and Liotta, 1986).The experimentaly calibrated garnet-biotite Fe-Mg exchange thermometer of Ferry and Spear (1978) and the revised model of Hodges and Spear (1982) do not take into account the presence of Al^{VI} and Ti in natural biotites as was done by Indares and Martignole (1985) for granulitic rocks. Thus the scattered and unrealistically high temperatures obtained for some granulites from Ferry and Spear and Hodges and Spear model`s (Table 2-7) is attributed to the presence of appreciable Ti in biotite (up to 4.4% of TiO_2, Table 2-5). For these samples the Indares and Martignole (1985) formulation was used instead, furnishing values of T=890°C for the sillimanite-bearing Varginha-type granulite, and T=780°C for the kyanite-bearing Três Pontas-type granulite, both with white mica.

	72B		147.2	178A	179B	157	159C	161E	
	Rt 35	Ilm 48	Ilm131	St11	St 8	St 1	St21	St 30	Ctd1
SiO_2	0.03	0.03	0.28	28.35	28.62	29.12	28.21	28.66	24.20
TiO_2	94.67	50.90	46.01	0.60	0.60	0.42	0.68	0.46	0.00
Al_2O_3	0.02	0.00	0.12	53.42	54.45	55.29	54.89	55.60	41.05
Cr_2O_3	0.05	0.02	0.04	0.13	0.05	0.00	0.25	0.00	0.00
FeO^T	3.66	44.78	47.18	13.48	13.11	13.19	14.26	10.37	21.63
MnO	0.02	0.6	0.07	0.05	0.10	0.13	0.44	0.18	0.30
MgO	0.03	0.10	0.43	1.86	1.15	0.90	1.21	1.25	4.05
CaO	0.01	0.00	-	0.04	0.04	0.00	0.00	0.00	0.03
Na_2O	0.00	0.00	-	0.08	0.03	0.00	0.00	0.00	0.01
K_2O	0.01	0.01	-	0.00	0.00	0.00	0.00	0.00	0.00
ZnO	-	-	-	0.00	0.00	0.20	0.18	1.88	-
Total	98.50	96.44	94.13	98.01	98.19	99.08	99.95	98.43	91.27
X_{Fe}	-	0.97	0.91	0.78	0.85	0.87	0.82	0.71	0.74
X_{Mg}	-	-	-	0.19	0.13	0.10	0.12	0.15	0.25
X_{Zn}	-	-	-	-	-	0.01	0.01	0.11	-
	Ky granulite nap.			Metapelite nappe		Quartzite nappe		Parautochthon	

Table 2-6: Selected analyses of chloritoid, staurolite, rutile and ilmenite. FeO^t: total Fe as FeO.

Sample	T_1 ±50°C	T_2 ±50°C	T_3 ±5°C	T_4 °C	T_5 ±40°C	P_1 ±0.5kbar	P_2 ±1.0kbar	P_3 ±0.8kbar
91B Alm r	621.9	640.0	614.3			11.3-10.9		
91B Alm r	672.5	692.0	643.3			12.0-12.5		
91B Py	719.0	730.0	691.5			13.0-12.5		
72H Py	874.7	903.0	781.2				12.3 min.	
72B Alm				733			12.2 min.	
88B Py	994.6	1022.	891.1			12.2		11.5
147C Alm r	582.0	615.0	618.7			12.1		
147C Alm r	574.0	606.0	608.8			11.9		
147C Alm c				665		13.0		
147C Alm c					500.0		7.0	
147.2 Alm r	567.0	598.0					9.2	
147.2 Alm c					541.3		8.6 - 8.9	
178A Grs c				571				7.3
178A Alm r	463.7		514.2					5.9
179B Alm r				682				
159C Alm r				627				

Table 2-7: Thermobarometry for the KFMASH system. Alm r: almandine rich rim; Alm c: almandine rich core; Grs c: grossular rich core; Prp: pyrope rich garnet; min.: minimum pressure; T_1: Ferry & Spear (1978), T_2: Hodges & Spear (1982); T_3: Indares & Martignole (1985), T_4: Green & Heliman (1982); T_5: Pownceby et al. (1991); P_1: Bohlen et al (1983); P_2: Bohlen & Liotta (1986); P_3: Newton & Haselton (1981).

The Fe-Mg exchange between the thinner and incomplete garnet outer rim (Alm61) and the low titanium phlogopite-rich biotite (TiO_2=1.5% and Phl21) is related to a retrograde equilibrium at up to T=640°C and P=11.3 kbar (Table 2-7).

The Varginha type granulite (sample 88) displays recrystallised mylonitic bands with a oligoclase, sillimanite, phlogopite-rich biotite (Xphl=0.16) and ilmenite assemblage, which deflect around pyrope-rich garnet porphyroblasts. Contacts between high-Ti biotite and garnet are straight and remains of kyanite and rutile are present in the non-mylonitic assemblage. The Indares and Martignole geothermometer gives temperature up to 890°C (Ferry and Spear and Hodges and Spear models yield temperatures above the mineral assemblage equilibrium). The pressure estimated by the GRIPS assemblage is in agreement with Newton and Haselton (1981) garnet-plagioclase-Al2SiO5-quartz geobarometer: 12.0 kbar and 11.5 kbar respectively (Table 2-7).

The approximate P/T (Fig. 2-6) path is based on assumed chemical equillibrium between minerals from the garnet inner-rim to almandine-rich outer-rim assemblages (sample 91B). The near-isobaric heating corresponds to a late metamorphic trajectory towards sillimanite replacement (Varginha-type granulite, sample 88).

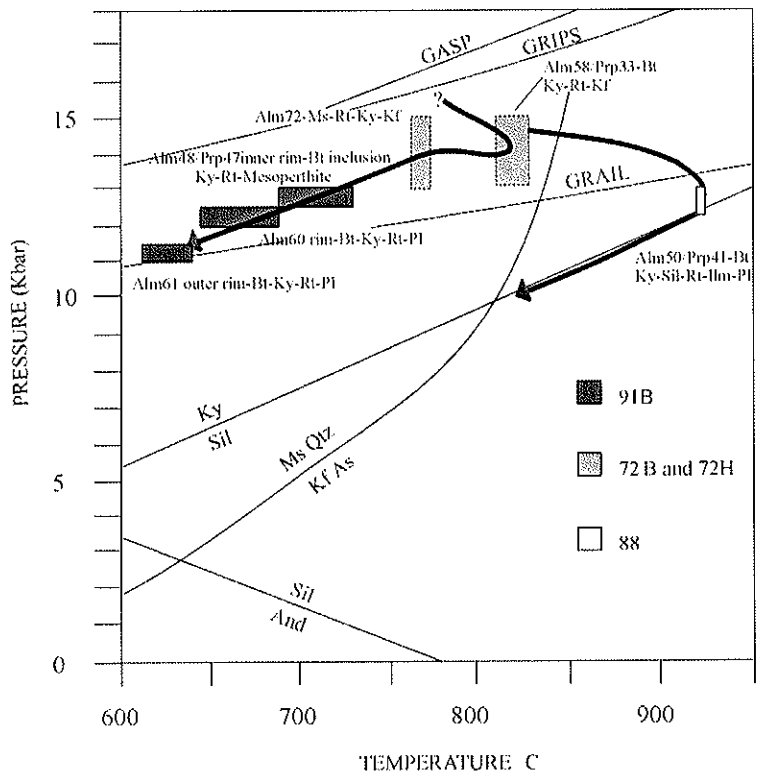

Figure 2-6: Kyanite-granulite P-T path. 91B: analysed thin section; GASP: Koziol & Newton (1988); GRIPS: Bohlen & Liotta (1986); GRAIL: Bohlen et al (1983); Ms+Qtz→Kf+As and Al_2SiO_5 triple point: Xu et al (1994).

2-4. The metapelite nappe complex

This nappe complex is chiefly made up of aluminous micaschists and garnetiferous paragneisses. It essentially comprises a layered sequence of aluminous mica-schists and

dark-gray, massive and medium-grained garnet-biotite-plagioclase gneiss/schists containing rutile and kyanite concentrated in syn-kinematic quartz veinlets. Coarse-grained kyanite blasts up to 5 cm, centimetric garnet and rutile in a matrix of white mica, quartz and late biotite are characteristic of most mica-schists. The garnet-biotite-plagioclase gneiss/schists interpreted as calc-alkaline volcanoclastics (Campos Neto et al, 1990) may represent metagraywackes. Lenses of garnet amphibolites derived from probable sills have retroeclogites (Trouw, 1992) in their cores, and retrogessed plagioclase-rich amphibolites at the borders. The retroeclogites have given a Sm-Nd garnet/whole rock age of 604 Ma (Trouw and Pankhurst, 1993).

The metapelite nappe complex forms two distinct near-horizontal sheets above the quartzite nappe (Fig. 2-3). The Carmo da Cachoeira nappe in the west (Fig. 2-4) is chiefly made up of metagraywackes and staurolite-free micaschists associated with thin beds of Mn-rich garnet-quartz rocks, calc-silicate gneiss and slices of meta-ultramafic/mafic rocks. This nappe went through a non-coaxial deformation as shown by the development of syn-metamorphic S/C foliation fabric with mica-fish and well-developed mineral and stretching lineations showing a northeastward flow direction. The lineations are scattered in SW low-plunging dispersion pattern (Fig. 2-4) controlled in part by later buckling of large synformal fold (Fig. 2-3). Allochthonous metapelites from the Madre de Deus region are also considered as part of this nappe, but they were overthrusted later by the quartzite nappe. The canoe-like Aiuruoca-Andrelândia nappe transported to the NE (Figs. 2-3 and 2-5) comprises an inner refolded root zone ca. 10-km thick and a stretched thinned front up to 2 km thick. Migmatites with garnet-kyanite bearing dry stromatic leucosomes, grading upwards into two-mica well-banded plagioclase-(kyanite)-garnet gneiss, are observed in the root zone and form a km-scale a-type recumbent fold towards the front of the nappe. They are detached over biotite diatexites and sillimanite-bearing stromatic migmatites that occur in the deeper part of the nappe and are cut by several muscovite-tourmaline bearing granite plutons that also form stocks in the upper part of the nappe. Small klippen of sillimanite-bearing schists with relict kyanite and with a sole of retrogressive, colder mylonites were emplaced on top of the kyanite schists in the southern part of the Aiuruoca-Andrelândia nappe (Fig. 2-5). Lineations throughout the nappe pile indicate ENE-directed displacement.

2-4.1 Petrology of eclogitic rocks and kyanite metapelites

Garnet clinopyroxenites collected from the core of mafic lenses are green coloured with medium-grained porphyroblastic texture. The garnet porphyroblasts ca. 4 mm in diameter are often surrounded by a thin plagioclase (An16 mole %) ring and by a 1 mm wide corona of brown amphibole (pargasite or hornblende). The ca. 3-mm poikiloblastic grains of clinopyroxene have blebs of quartz and plagioclase, contain both rutile and ilmenite mostly mantled by sphene, and are also surrounded by amphibole. Garnet is slightly zoned with Alm57-44, Prp19-22 and Grs22-31 mole % in the cores and Alm59-54, Prp17-18 and Grs23-26 mole % toward the rims. Rutile, apatite and prismatic blue Fe-pargasite, blue-green Mg-horblende and rare clinopyroxene are the more common inclusions. The largest ca. 1-mm clinopyroxene inclusions which cause semi-radial cracks in garnet have diopside or diopside-omphacite compositions at the contact with garnet and enclose relict lamellas of jadeite (Table 2-8). The matrix diopside re-equilibrated during the early stages of the decompression is devoid of significant Na-content and the intergrown plagioclase contain An16 mole %. The plagioclase enclosed in brown amphibole has up to

An38 mole %. Such a complex pattern may suggest the re-equilibration of former omphacitic pyroxene.

	72.V		141C			141.2		141.2		141C	
	Opx162	Cpx161	Cpx3Cpx 29		Jd 33	Omp 40	Cpx 48	Pg[1]12	Pg[2]35	Hbl[1] 24	Hbl[2] 42
SiO_2	56.60	53.39	53.01	52.51	62.89	55.52	52.48	38.35	43.97	46.18	45.02
TiO_2	0.00	0.00	0.00	0.05	0.00	0.00	0.05	0.00	0.38	0.83	1.04
Al_2O_3	0.09	0.07	1.38	1.48	23.54	8.64	3.35	21.34	13.47	10.09	11.86
Cr_2O_3	0.03	0.00	0.03	0.00	0.00	0.00	0.03	0.00	0.02	0.07	0.14
FeO^T	8.94	2.37	9.00	9.33	0.17	6.78	8.73	16.69	15.42	16.73	16.07
MnO	0.31	0.16	0.05	0.13	0.01	0.06	0.07	0.08	0.06	0.14	0.05
MgO	33.22	17.77	12.81	12.48	0.05	8.28	11.87	7.83	11.07	11.08	10.29
CaO	0.11	24.83	23.82	23.32	4.73	18.19	22.76	11.19	11.15	11.43	11.94
Na_2O	0.00	0.10	0.54	0.50	9.41	3.99	0.90	2.84	2.26	1.02	1.49
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.09	0.10
Total	99.33	98.72	100.64	99.89	100.8	101.4	100.3	98.33	97.93	97.59	97.86
Si	1.98	1.96	1.96	1.96	2.20	1.99	1.95	5.64	6.44	6.76	6.26
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.11
Al	0.004	0.003	0.06	0.06	0.97	0.36	0.15	3.69	2.32	1.74	2.05
Cr	0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Fe^{3+}	0.03	0.00	0.04	0.03	0.00	0.00	0.02	0.47	0.36	0.44	0.16
Fe^{2+}	0.235	0.046	0.23	0.25	0.01	0.20	0.25	1.58	1.52	1.60	1.82
Mn	0.009	0.005	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.00
Mg	1.74	0.97	0.71	0.69	0.01	0.44	0.66	1.72	2.42	2.42	2.26
Ca	0.004	0.98	0.94	0.93	0.18	0.70	0.91	1.76	1.75	1.79	1.88
Na	0.00	0.01	0.04	0.03	0.64	0.28	0.06	0.81	0.64	0.29	0.02
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.02

Table 2-8 Selected analyes of pyroxenes and amphiboles. Structural formulae of Px normalised to 6 oxygen; structural formulae of Amp: average normalised to 15 cations excluding K, Na and Ca. FeO^t: total Fe as FeO. [1]: amphibole included in garnet; [2]: coronitic amphibole. Opx: orthopyroxene, Cpx: clinopyroxene, Jd: jadeite; Omp: omphacite, Pg: pargasite, Hbl: hornblende.

Metapelitic schists from the upper part of the nappe are staurolite free, Ky-Rt-Grt-Ms-Pl-Qtz assemblages. From this zone downwards staurolite becomes stable and ilmenite is found instead of rutile. Kyanite is the only Al-silicate of high-Al metapelites. Synkinematic muscovite generally mantles garnet, staurolite and kyanite. It has a high X_{Ms}/X_{Cel} ratio (ca. 8.0) although the Si-content remains low and constant (3.05 p.f.u.). Biotite overgrows and/or partially replaces the muscovite. Garnet may contain composite inclusions of kyanite, rutile, ilmenite, paragonite (X_{Prg}=0.9) and staurolite (Tables 2-4 and 2-6) in a strain sensitive fabric. Muscovite and biotite also occur as inclusions towards clear garnet rims. Garnet is almandine rich with higher grossular content in the core (Fig. 2-7A). Plagioclase (An16-27) is a late phase in equilibrium with muscovite, biotite and ilmenite.

Metapelites from the Madre de Deus de Minas region (Fig. 2-3) contain abundant staurolite and ilmenite as well as kyanite. Staurolite seems to precede kyanite according to Ribeiro and Heilbron (1982) and Heilbron (1985) who have mapped NE-oriented isograds oblique to nappe contours. Fe-staurolite (Table 2-6) and kyanite up to 1-cm size show straight boundaries with optical continuity. The staurolite often displays several fabric-sensitive inclusions of ilmenite and quartz. The garnet, also porphyroblastic, with ilmenite, white mica, albite and quartz inclusions, is zoned (Fig. 2-7 B). Chlorite also may be abundant and is associated with sulfides.

2-4.2. P-T estimates

The garnet-clinopyroxenite seems to record a pre-eclogite stage as evidenced by the bluish pargasite and Mg-hornblende inclusions in garnet. The garnet-amphibole

thermometer of Graham and Powell (1984) yields 569°C for the garnet (Alm45-Prp22-Grs31)-hornblende pair and 660°C for the garnet (Alm59-Prp13-Grs26)-pargasite pairs.

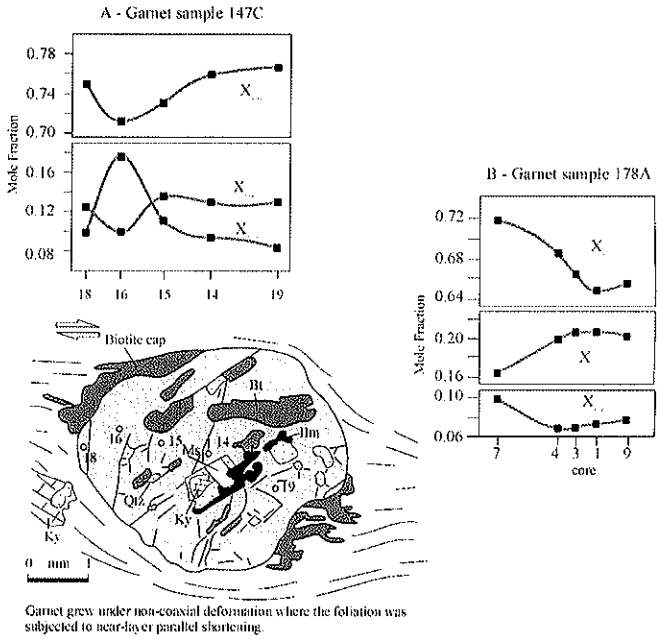

Figure 2-7: Garnet compositional profiles. A: sample 147C with garnet sketch; Bt=biotite, Ms=muscovite, Ilm=ilmenite, Ky=kyanite, dotted=quartz. B: sample 178A.

Although the igneous Al-in hornblende geobarometer (Hammarstrom and Zen, 1986 and Hollister et al., 1987) gives ca. 11.5 kbar the pressure from pargasite bound 14 kbar. The pressure peak recorded by the unzoned jadeite lamella in Cpx included in garnet (X_{Jd} up to 0.76) reaches 17.5 kbar (Meyre et al., 1997) for a T fixed at 660°C. The garnet core (Alm58-Prp17-Grs23) and omphacite inclusion (X_{Jd}=0.3) furnishes ca. T= 716°C (based on Powell, 1985) and P=15 kbar (Meyre et al., 1997) also for the eclogite stage. The Fe-Mg exchange between coexisting garnet (core compositions of Alm57-Prp18-Grs23 from thin section 141.2 and Alm45-Prp22-Grs31 from thin section 141.C) and diopside (respectively either as inclusion or as matrix assemblage with high-Na oligoclase simplectitic texture) is the first record of eclogite retrogression at a mean T= 650±33°C and P=13.7±1.9 kbar (Eckert et al, 1991). The garnet outer-rim, plagioclase ring and outer amphibole assemblage in a well-developed coronitic texture is the final record of retrograde stage. Garnet-amphibole thermometry (Graham and Powell, 1985) gives a mean temperature of about 632±35°C compatible, within the errors, with the temperature by amphibole-plagioclase thermometry (Blundy and Holland, 1990), T=650±75°C (Table 2-9). The pressure is up to 11.6 kbar (Khon and Spear, 1990).

The eclogitic rocks may have passed through a prograde metamorphic stage with strong isothermal loading followed by heating and decompression in a clockwise P-T loop. Their retrogression history included a near-isobaric cooling stage (Fig. 2-8).

P-T estimation for the metapelites in the Aiuruoca-Andrelândia nappe have been attempted on the kyanite-staurolite gneiss/schist. Garnet (Alm71-Grs18) cores Fe/(Fe+Mg) mol = 0.83 indicate a temperature of about 580°C (Spear and Cheney, 1989), and the temperature

approach decrease to 540°C applying the Fe-Mn partitioning between coexisting garnet and ilmenite (Ilm activity=0.92) as inclusion (Pownceby et al., 1991) in spite of the low Mn content of garnet (Alm79-Grs1-Sps1), both in agreement with the presence of staurolite and paragonite inclusions. The garnet core assemblage (also kyanite and rutile inclusions) gives a pressure up to 8.9 kbar based on GRAIL barometry (Table 2-7). The assumed equilibrium

Sample	T_1 °C	T_2 ±75°C	T_3 ±5°C	T_4 °C	P_1 ±0.5 kbar	P_2 ±1.9 kbar	P_3 kbar
141.2 corona	668	671.3			11.1		
141.2 corona	597	654.4			10.9-11.6		
141.2 Di incl			667.3	646		13.5±1.9	
141.2 Di incl			640.4	618		13.0±1.9	
141.2 Di incl			704.5	684		14.2±1.9	
141.2 Omp incl			736.5	716			15.0
141.2 Jd incl							17.5 at 660°C
141.2 Prg incl	653-675						
141.C corona		620.0					
141.C Di/Grt core			661.6	641		14.2±1.9	
141.C Di/Grt rim			696.8	677		12.9±1.9	
141.C Hbl incl	569						

Table 2-9: Thermobarometry for eclogitic rocks. Di incl: diopside inclusion; Omp incl: omphacite inclusion; Jd incl: jadeite inclusion; Pg incl: pargasite inclusion; Di/Grs-Prp: diopside and grossular-pyrope rich garnet pair; Hbl incl: hornblende inclusion; T1:Graham & Powell (1984); T_2: Blundy & Holland (1990); T_3: Ellis & Green (1979); T_4: Powell (1985); P_1: Kohn & Spear (1990); P_2: Eckert et al (1991): P_3: Meyre et al. (1997).

between near rim almandine-rich garnet, matrix muscovite and plagioclase would occur at T≈665°C (Green and Hellman, 1982) and P≈13.0 kbar using the GRAIL barometer, and the GRIPS reaction. The almandine-rich rim and biotite mantle both in contact with plagioclase imply T≈610°C and P≈12.0 kbar, respectively using Indares and Martignole (1985), Bohlen et al (1983) and Bohlen and Liotta (1986). A higher-pressure stage in these metapelites, consistent with the eclogitic assemblage recorded in mafic lenses, is inferred from the occurrence of chlorite+albite+carbonate pseudomorphs possibly after Na-Ca pyroxene. These data suggest a clockwise P-T loop and are in agreement with the high-pressure amphibolite facies decompression path of eclogitic mafic lenses (Fig. 2-8).

In the kyanite-staurolite schists near Madre de Deus the asymmetrical portions of Alm-poor, Gros-rich garnets having straight contacts with muscovite furnish a temperature of 580°C (Green and Hellman, 1982). The incomplete clean Alm-rich garnet rim in textural equilibrium with synkinematic and late biotite gives T ca. 517°C by Indares and Martignole (1985) thermometer. The garnet-kyanite-plagioclase-quartz barometer (Newton and Haselton, 1981, modified by Koziol and Newton, 1988) applied to Alm-poor garnet-muscovite pairs with low-Ca oligoclase porphyroclasts furnish 7.3 kbar, while the Alm-rich garnet-biotite pairs accompanying polygonal oligoclase crystals indicate P≈5.9 kbar (Table 2-7). Although no information is deduced about the peak pressure, the metapelites seems to show the same metamorphic path of the eclogites (Fig. 2-8).

2-5. The quartzite nappe complex

The quartzite nappe complex is a lower allochthon cropping out as a window surrounded by the metapelitic nappe. White and green-mica quartzites, with locally

preseved detrital grains grade upward and westward into well bedded to laminated quartzites interlayered with graphitic metapelites (ca.100 m thick). A cratonic area is the

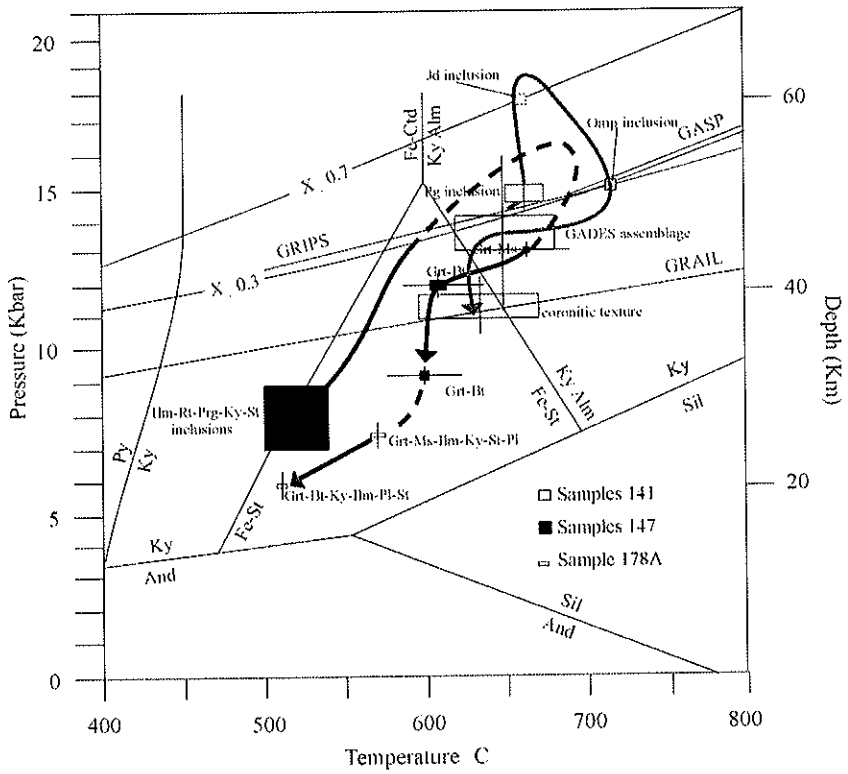

Figure 2-8: Aiuruoca-Andrelândia nappe P-T path. $X_{Jd}0.7$ based on the reaction Ab=Jd+Qtz: Meyre et al. (1997); GASP: Koziol & Newton (1988); GRIPS: Bholen & Liotta (1986); GRAIL: Bholen et al (1983); staurolite field: Powell et Holland (1990); Al_2SiO_5 triple point: Xu et al (1994); 141C and 141.2: analysed thin sections.

assumed source of these metasediments, which were deposited in a shelf/ramp environment after 1.87 Ga (minimum U-Pb age of detrital zircons, Söllner and Trouw, *in* Ribeiro et al., 1995). The syn-metamorphic foliation is axial-plane of kilometric, a-type recumbent and E-SE verging folds (Trouw et al., 1980; 1983). S/C-type structures and associated strong E-SE mineral and stretching lineations (Fig. 2-3) were formed during eastwards syn-metamorphic transport (Trouw et al., 1982). The quartzite nappe also includes a large volume of polymetamorphic orthogneisses ascribed to the basement of the quartzites. The basement consists of migmatites and meta-ultramafic slices, but the quartzitic sequence is allochthonous above the orthogneisses, except for a few remnants of possibly undetached cover. In the quartzite nappe, in the Lima Duarte region 50-km southeast of Andrelândia, only sillimanite is found in quartzites and metapelites.

Metapelite samples (157-159) ca. 30-km southeast of Lavras have a staurolite-ilmenite-garnet-muscovite-quartz assemblage with abundant tourmaline. The garnet is compositionally zoned (Alm70-81 Prp15-11 Sps14-6 from core to rim), the staurolite is Fe-rich (mean X_{Fe} = 0.85), the muscovite has low Si and Cel contents (mean Si = 3.06 p.f.u., X_{Cel} = 0.13) and ilmenite has a high Fe activity (0.94). Almandine-rich garnet and stable muscovite pairs furnish a temperature of 620 to 636 °C (Green and Hellman, 1982 calculated for P= 6.5 kbar, Table 2-7-sample 159).

2-6. The parautochthonous unit

This frontal unit crops out in a narrow belt between Paleoproterozoic rocks of the São Francisco craton and the nappes. It was affected by the lowest temperature metamorphism and has a thin-skinned structural behaviour. It comprises a shelf-type series made up of interbedded quartzites and gray phyllites. The main metamorphic cleavage defined by chloritoid and white micas is deformed by tight, near isoclinal and N-verging folds generally with wavelengths up to some tens of metre, with an associated axial-planar crenulation cleavage developed in metapelites. Most stretching lineations observed in quartzites are related to these folds. Southeast of Lavras the crenulation cleavage progressively flattens downward approaching a rarely outcropping low-angle mylonitic sole thrust. Hundreds of metre scale duplex structures with flat-ramps and antiformal stacks have also been observed.

Al-Fe-Mg metapelites contain abundant Fe-chloritoid and variable amounts of Mg and Fe-chlorite, phengite, Zn-rich staurolite (Table 2-6), kyanite, rutile, and ilmenite. Xenomorphic kyanite shows an asymmetrical chloritoid-muscovite fringe. Kyanite and chloritoid show apparent gradational boundaries. Staurolite (X_{Fe} = 0.71, X_{Zn} =0.11) occurs as idioblastic and twinned crystals with abundant dark dusty inclusions is free of appendages, and displays inclusion-free overgrowths. In these rocks the Si content of phengite reaches 3.25 p.f.u. and the X_{Cel} reaches 0.28 (sample 161E, Table 2-4), resulting in a pressure around 7 kbar for temperature around 500°C (Oberhänsli et al., 1995) that may control the appearance of Zn staurolite in the absence of garnet and biotite. Maximum Si content up to 3.3 has been measured in white mica from samples east of Três Pontas quarry (Table 2-4).

2-7. Discussion

The nappe system exposed south of the São Francisco craton shows a coherent metamorphic pattern with T-max decreasing downward beneath the Socorro-Guaxupé nappe, and is therefore similar to that reported from the Central Himalayas (Caby et al., 1983; Le Fort et al., 1986; Burg et al., 1987; Macfarlane, 1995; Vannay and Hodges, 1996; Hodges et al., 1996). The Guaxupé basal granulites record T-max around 900°C at 630 Ma, coeval with the emplacement of noritic magmas. These high temperatures were reached regionally at P-max around 12 kbar, and coincided with the emplacement of charnockitic/mangeritic magmas extracted from underlying granulites. Geochemical data suggest that the Socorro-Guaxupé granulites derive mainly from igneous protoliths in the mafic roots of a Neoproterozoic arc assemblage. The strong decompression down to 4.5 kbar observed at the top of the Socorro-Guaxupé nappe relates to tectonic unroofing through southeast-directed normal shearing.

The kyanite granulites nappe ca. 6 km-thick under the Socorro-Guaxupé nappe displays the same foliation and ENE-verging kinematics records P-max around 13 kbar and T around 750°C increasing upward to 890°C (Varginha-type granulites), thus similar to that of overlying Guaxupé granulites. Rare ultramafic cumulates were emplaced in the kyanite granulites. Lower temperatures of about 650°C were attained in the lower high-pressure nappe (P=12-14 kbar) related to the decompression stage of eclogitic basic rocks at 17.5 kbar (T=660°C). T decreases to ca. 600°C and P to 7 kbar downward in the quartzite nappe and only reaches 500°C at ca. 7 kbar in the parautochthons. Since the kyanite granulites are

separated from the parautochthons by only a few hundreds of metres (15 km north of Varginha), a major post metamorphic displacement of the granulites may have taken place in agreement with a temperature gap of about 250°C. This late contact is responsible for the truncation of the quartzite nappe southwest of Lavras. The maximum thickness of the metapelitic nappe (ca. 11 km) occurs south of Adrelândia where klippen of kyanite granulites are preserved on top of this nappe showing that the still-hot granulites were displaced more than 100 km towards the ENE. ENE to NE-directed syn-metamorphic transport is well constrained in both the Varginha and the Andrelândia regions. The metapelite nappe records fast exhumation from eclogitic to amphibolite facies conditions and its re-equilibration at T=660°C and P=13 kbar could be interpreted as representing the maximum nappe stacking before thinning. The lack of evidence for high-pressures in the lower parts of the nappe system, together with E-directed and N-directed transport directions in the quartzite nappe and in the Madre de Deus region, respectively, suggest that the emplacement of the high-pressure overlying nappes is a late event that occurred after significant thinning of the allochthons.

Apparently high thermal conductivity may be inferred from eclogitic metamorphic assemblages from the metapelite nappe. Such a value is typical for subduction-related metamorphism (Ernst, 1988) suggesting an open oceanic domain to the west. This is supported by the occurrence of a mafic-ultramafic sequence with podiform chromite (Petunia complex) exposed below the Socorro-Guaxupé nappe 130-km WNW of Varginha. These rocks were considered as a fragment of Neoproterozoic oceanic crust by Choudhuri et al. (1995) although not supported by available geocronological data. The Neoproterozoic ca. 800 Ma Maratá Sequence with podiform chromite has been described in the Brasilia Belt (Fuck et al, 1994).

The metamorphic conditions from both the kyanite granulite nappe and the metapelite nappe could represent the early exhumation process of subducted continental crust material.

The lack of evidence for Neoproterozoic high-pressure conditions in the basement rocks of the southern part of the São Francisco craton (rare minute brown biotite and white micas) implies that the nappes had been significantly thinned when they overrode this area of the craton margin. In contrast, rocks of the eastern domain around Lima Duarte underwent a high temperature imprint with formation of sillimanite.

The Socorro-Guaxupé nappe shows a rather different temperature evolution with T-max as high as 900°C possibly connected with heat advection by noritic magmas corresponding to a high heat flow and steep paleothermal gradients. The near-isothermal decompression recorded on the top of Socorro-Guaxupé nappe necessarily requires regional heating during extension that may have been connected with mantle upwelling, as suggested by the occurrence of lenses of ultramafics interleaved with granulites in the middle part of the nappe.

2-8. Conclusions

The high-pressure nappe system at the southern border of the São Francisco Craton represents part of the history of Neoproterozoic Gondwana assembly between the São Francisco microcontinent and a western plate that included magmatic arc assemblages. The roots of this magmatic arc are represented by the Socorro-Guaxupé granulites whereas the upper part could be represented by the 860 Ma old Mara Rosa arc of oceanic affinities

(Pimentel et al., 1997), with possible relics of oceanic lithosphere. The P-T conditions deduced from mineral assemblages of both the high-pressure granulite and the metapelite nappes strongly suggests that these have been exhumed eastward from a west-dipping subduction complex deduced from eclogitic rocks. Early ENE-directed syn-metamorphic transport around 630 Ma stacked the HP-HT thick-skinned arc terrane (Socorro-Guaxupé nappe) over metapelitic units (kyanite-granulites and metapelitic nappe) that were subjected to nearly synchronous high-pressure metamorphic conditions. These metapelitic units are not considered as belonging to the cover of the São Francisco craton in the light of ε_{Nd} (0.630) between -2 and -3,5 and T(dm) 1.4 and 1.55. The whole high-pressure pile may have been exhumed from the subduction prism through the return-flow mechanism proposed by Chemenda et al. (1995). Metamorphic facies thus record an inverted metamorphism. Sillimanite overprint visible only on top of the kyanite granulites records a T increase due to downward heat advection from the overlying hotter Socorro-Guaxupé granulites during its eastward displacement. The excellent preservation of kyanite granulites that form a 4.5-km sheet devoid of overprinting in the sillimanite stability field is exceptional. This pile was subsequently thrust onto the lower portion of the nappe system that according to lithologic considerations and age of the source may derive from the São Francisco passive continental paleo-margin (quartzite nappe and parautochthons).

The late dextral movement along the strike-slip shear zones in the south may have controlled final displacements of the nappes, both parallel and radial to the craton boundary.

Acknowledgements

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CAPÍTULO 3

TERRANE ACRETION AND UPWARD EXTRUSION OF HIGH-PRESSURE NEOPROTEROZOIC NAPPES OF THE SOUTHEAST BRAZIL: PETROLOGIC AND STRUCTURAL CONSTRAINTS

Abstract

The high-grade crystalline nappes exposed southeast of the São Francisco craton comprise two distinct units of mainly granulite-facies rocks that represent a composite section of Neoproterozoic deep continental crust: the Socorro-Guaxupé nappe above, derived from an arc terrane, and the Três Pontas-Varginha nappe below. Metamorphism in the Três Pontas-Varginha nappe is characterized by the exceptional preservation of kyanite granulites (700-750° C, 15 kbar), and experienced limited retrogression. Maximum temperatures around 900-950° C were reached towards the base of the overlying Socorro-Guaxupé nappe, during the intrusion of charnockitic-mangeritic magmas. Lower pressure metamorphism, accompanied by anatexis, prevailed at shallower crustal levels. Our petrological results document an inverted thermal structure with isobaric heating of the top of the high-pressure granulite nappe. Both granulite nappes were transported more than 200 km eastward above lower nappes involving reworked basement and passive margin units, both metamorphosed to high pressure but lower temperature conditions. Significant thinning and cooling of the two granulite nappes may have occurred before their emplacement onto the lower nappes. The proposed geodynamic scenario considers that continental subduction took place westward underneath Neoproterozoic oceanic lithosphere. The two granulite units crystallised at ca 45 km depths under distinct paleogeotherms within this subduction zone around 630 Ma. The kyanite granulites were rapidely exhumed through the mechanism of low-angle "forced" extrusion, whereas syn-collisional collapse affected the soft, anatectic middle crust of the overlying arc terrane. The final emplacement of the thinned nappe pile onto the cold São Francisco craton and its platform cover, with at most, anchizonal to greenschist-facies metamorphism, occurred around 600 Ma .

3-1. Introduction

Recent advances in deciphering the geometry, kinematics and orogenic development of deeper crustal levels of major Proterozoic collisional orogens have revealed increasing similarities with Phanerozoic orogens such as the Himalaya, but observed at much deeper crustal levels. Crystalline nappes with associated reverse metamorphism, displaced at low angle onto less metamorphosed units, have been documented in several segments of Mesoproterozoic belts (*Rivers et al.,* 1989) and Neoproterozoic orogens of the Gondwana (*Caby,* 1989; *Castaing et al.,* 1993; *Caby,* 1994; *Attoh,* 1998). The occurrence of preserved high-pressure granulites and eclogites in continental margin units gives the opportunity to better constrain the P/T regimes from subducted continental crust. As pointed out by *Myashiro* (1973), paired metamorphic belts involving low-pressure rocks adjacent to high-pressure terrains imply rather contrasted paleogeotherms that may allow delineation with former suture zones. Perturbed paleogeotherms <15°C/km, reconstructed from continental units, are in agreement with subduction underneath cold oceanic lithosphere (*Peacock,*

1992), whereas those >45° C/km require the major role of mantle upwelling at shallow depths to account for the genesis of low-pressure granulites (*Spear,* 1993).

In this respect, the giant crystalline nappes thrust eastward onto the southern edge of the São Francisco craton (SFC) in SE Brazil include both high-temperature, medium to low-pressure units, and high-pressure (HP) terrains with the uncommon occurrence of unretrogressed felsic kyanite granulites (*Campos Neto & Caby,* in press). In this paper, we present new detailed metamorphic studies on the HP-granulites that allow to reconstruct two contrasting, nearly synchronous P-T paths. We document the syn-collisional collapse of the western hot allochthon intruded by a huge volume of charnockitic *sl* plutons and we propose a mechanism of low-angle extrusion for the exhumation of the deeper, HP-granulite nappe displaced 200 km eastwards onto lower temperature nappes derived from a passive margin. Then we present a new geodynamic and kinematic scenario for the evolution of SE Brazil that requires a west-dipping subduction setting.

3-2. Geological setting

Southeast and central Brazil records two major episodes of continent assembly on the western and southern edges of the SFC (Fig. 3-1) during Neoproterozoic-Cambrian times (*Campos Neto & Figueiredo,* 1995; *Pimentel et al.,* 1996; *Paciullo et al.*, 1998; *Heilbron et al.* 1998). The crustal roots of a magmatic arc accreted on the southeastern edge of SFC between 590-570 Ma (*Söllner et al.,* 1987, 1989 and 1991) essentially form the younger Rio Doce terrane. Steep foliations with overall subhorizontal stretching lineations, forming the 60 km wide axial zone, represent the frontal feature of this transpressive system (the Ribeira belt). West of the Archean-Paleoproterozoic SFC, the Brasilia belt (*Fuck et al.*, 1994) comprises the external zones parautochthons and lower allochthons with greenschist-facies metamorphism derived from the rift-type to passive continental margin metasedimentary sequences that were deposited on the SFC margin. HP-metagreywackes and metapelites forming the middle nappes (*Valeriano et al.*, 1995; *Seer et al.* 1998; *Valeriano et al.*, 1998; *Simões,* 1995), were transported eastward more than 100 km onto the anchizonal carbonates and glaciogenic rocks (Bambui Group). The internal tectonic units comprise a juvenile island arc terrane 900-750 Ma old (*Pimentel et al.*, 1991; *Pimentel & Fuck*, 1992; *Pimentel et al,* 1997). Regional metamorphism at 630 Ma (*Pimentel et al,* 1997) was related to ocean closure and continental collision. Post-kinematic granites were emplaced in Late Cambrian time (*Pimentel et al,* 1996).

The nappe system south of the SFC represents deeper crustal equivalents to the Brasilia belt (*Trouw et al.*, 1984). It comprises a flat-lying package of east-verging nappes with HP-metamorphism including retroeclogites (*Trouw,* 1992; *Campos Neto & Caby,* in press) overlying the allochthonous-parautochthonous units related to passive continental margin (*Ribeiro et al.*, 1995). No occurrences of metaluminous granites have been reported from these nappes. In contrast with the Brasilia nappe edifice, the upper allochthon (the Socorro-Guaxupé nappe - SGN) comprises mainly mafic granulites and a syn-kinematic suite of intrusions of charnockitic affinity. These high-grade units have been interpreted as the root of a magmatic arc formed along an active continental paleo-margin of a western plate (*Campos Neto & Figueiredo,* 1995) possibly connected with the Rio de la Plata/Parana craton. Major strike-slip shear zones connected with the Ribeira belt bound the SGN to the southeast. High-K post-kinematic granites and syenites were intruded in the SGN during the 612-590 Ma time span (*Töpfner,* 1996; *Pimentel et al.,* 1996). Lithostratigraphy, structure

and metamorphism of the units that underlie the SGN were summarised by *Trouw et al.* (1983 and 1986), *Campos Neto et al.* (1990), *Ribeiro et al.* (1995) and *Paciullo* (1997).

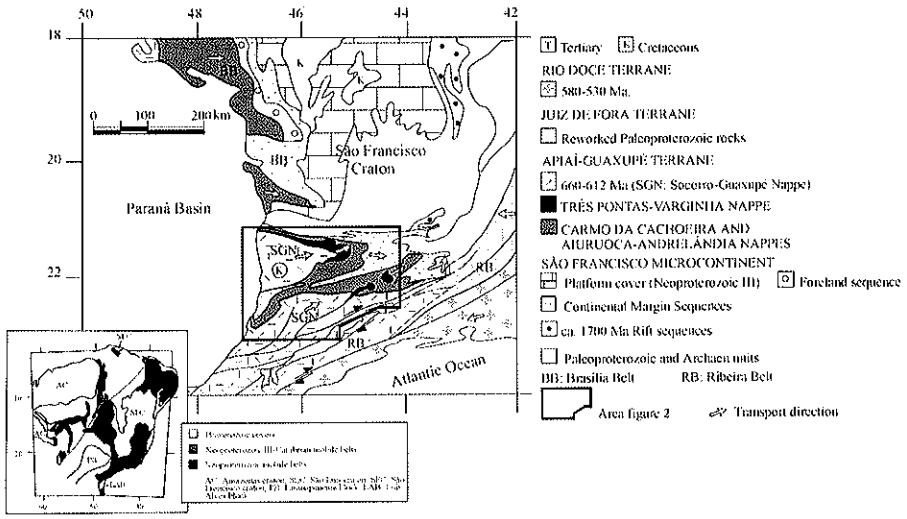

Figure 3-1. Regional tectonic map of part of southern Brazil.

3-3. Tectonic Units

3-3. 1. The Socorro-Guaxupé nappe – SGN

The SGN is a giant allochthon showing a right way up crustal section of hot and partially-melted, layered crust. Its basal sole thrust cuts across various terrains of the lower nappes, both the passive margin units and the reworked basement with Archean age protoliths. It comprises a Basal Granulitic Unit (ca. 3 km thick) that grades upward into grey to pink, metaluminous migmatites (Middle Diatexitic Unit, ca. 6 km thick) indenting at their top with pelitic to semi-pelitic migmatites (Upper Migmatite Unit). Normal faulting and dextral strike-slip shear zones control a major metamorphic jump between these migmatites and the green-schist facies unit in the southwest (Fig. 3-2).

3-3. 1. 1. The Basal Granulitic Unit

Green-coloured, banded Grt±Opx (symbols after Kretz, 1983) granulites of enderbitic modal composition are the main rock types of the Basal Granulite Unit, interleaved with decimetre-thick layers of gabbro-noritic gneiss considered as synmetamorphic intrusives. The well-developed stromatic structures are present as anhydrous hololeucocratic leucosomes (light-coloured enderbites and coarse-grained grey to pink charnockites). Concordant veins (0.10 to 1.0 m thick) of Grt-bearing mangerite also occur. The top of this unit is marked by the gradual transition into amphibolite facies, where the predominate rock types are Hbl and Bt-Hbl-bearing tonalite to granodiorite gneisses containing many decametre-thick metabasic lenses and white stromatic bands of leucotonalitic to trondhjemitic composition. Field and petrographic relations show that these amphibolite facies rocks are not the products of granulite retrogression (*Fernandes et al.*, 1987). Based on major and trace elements, *Campos Neto et al.* (1996) have established

that the enderbitic granulites may derive mainly from magmatic arc igneous protoliths. A few lenses of well-banded Grt-Bt-Spl-mesoperthite (Mph)-Pl gneisses of pelitic composition are interlayered with the mafic granulites. These aluminous rocks also show major element chemical relationships compatible with sedimentary protoliths deposited along an active margin. However, their restitic character in part, may disguise the primary chemical trend. The enderbitic granulites from the Piranguinho quarry (Fig. 3-2) show a preliminary Sm/Nd T(dm) age around 1290 Ma with ε_{Nd} (0.640)= -1.2 (Table 3-1) that constrains the Meso-Neoproterozoic age of the assumed magmatic arc. The Grt-Bt whole rock Sm-Nd date of 630 Ma (Table 3-1) constrains the age of granulite facies metamorphism.

3-3. 1. 2. The Middle Diatexitic Unit

Anatectic granitic-gneisses characterize the Middle Diatexitic Unit. Here, discontinuous stromatic migmatites are enclosed by widespread grey to pinkish nebulites and deformed porphyritic granitoids. Stromatic migmatites predominate as a dark-grey Hbl-Bt (Cpx) gneissic mesosome of dioritic-tonalitic composition. Light-grey hololeucocratic Bt-leucosomes (cm to m thick veins) of throndhjemitc composition alternate with Fe-Mg melanosomes. Pervasive grey to pinkish nebulites are leucocratic and coarse grained Bt (Hbl)-bearing granites showing transitional contacts with irregular and batholithic size bodies of deformed porphyritic granites. These contain enclaves of dioritic-monzodioritic gneisses and xenoliths of Grt-Di-Scp calc-silicate rocks. Lenses of Sil-Crd metapelites (=kinzigites), ca. 100 m thick and 3 km long occur among these granitic rocks.

3-3.1.3. The Upper Migmatitic Unit

This upper unit mainly consists of a migmatized metasedimentary sequence in which degree of anatexis decreases upward (southwestward). Grt-±Sil-Bt banded gneisses, mostly with light-grey, Bt-Grt-bearing leucosomes grade upward into peraluminous mica schist locally interleaved with Ms-bearing leucosomes. Subordinate Sil-Ms feldspathic quartzites and Qtz-rich gneisses, calc-silicate gneisses, rare marbles, Hbl gneisses and mafic metaintrusives are intercalated. Zircons from a high-grade metapelite have yielded a U/Pb upper intercept age in the range 1.9-2.1 Ga (*Ebert et al.,* 1996), a date that we interpret as the mean age of the inherited zircons incorporated in the sediment.

3-3.1 4. The syn-kinemtic plutonic intrusives

Various intrusives occur throughout the nappe pile. They are strongly stretched and linear, ca. 2 km thick bodies of charnockites concentrated towards the base of the allochthon. Higher in the pile occur large and well-oriented bodies of Hbl-Bt bearing granitoids. The porphyritic-porphyroclastic charnockitic rocks comprise a high-K calc-alkaline suite with a modal trend towards norite to enderbite-opdalite-charnockite compositions. Mc and subordinated Pl are the main megacrysts and Opx-Bt-Hbl are the mafic minerals. Pyroxene-bearing pegmatites occur in crosscutting veins. The mangeritic-granitic suite (625 Ma, Table 3-1) has a tabular shape and occurs within the migmatites of the Middle Diatexitic Unit. It comprise green-coloured, medium to coarse grained gneisses

from hypersthene (Hy)-bearing mangerite and charnockite, interleaved with pink, laminated and coarse-grained hornblende granite and hololeucocratic granite. These rocks have a mean chemical composition relatively high in Al, Fe, Na and K, low Ca, Sr and Mg# and characteristically higher Zr content, up to 1300 ppm (*Campos Neto et al.*, 1988; *Janasi,* 1997).

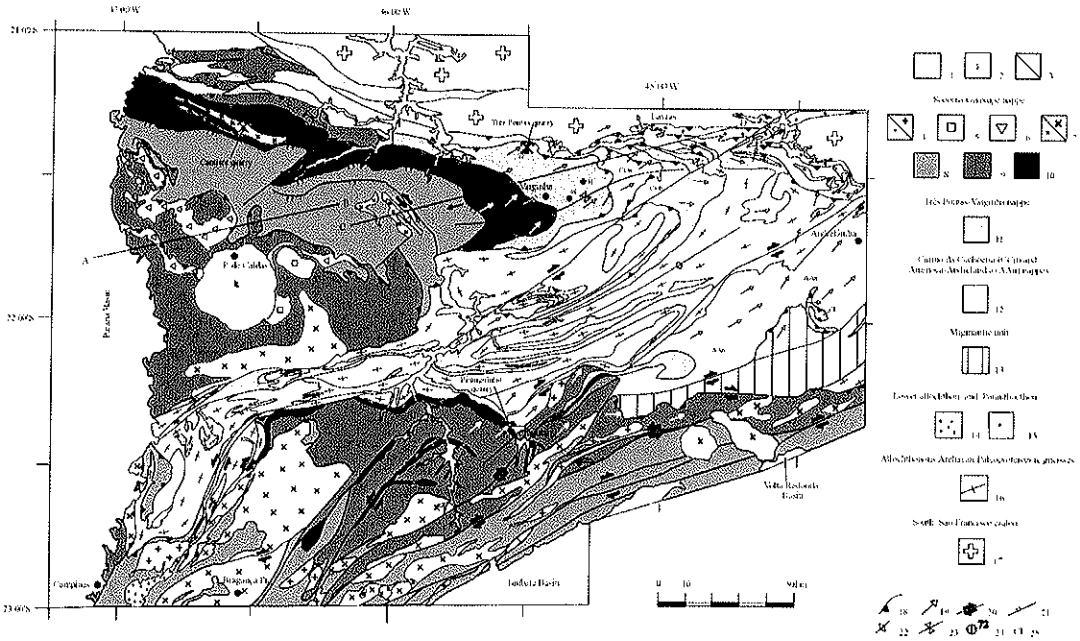

Figure 2. Geological map of the nappe system south of the São Francisco craton.
1. Phanerozoic basins; 2. Cretaceous alkaline plutons; 3. Small pull-apart basins. Socorro-Guaxupé nappe: 4. (small crosses) K-granites (ca.580 Ma) and (crosses) shear zone related granites (ca. 600-580 Ma); 5. Syenitic plutons (612 Ma); 6. Mangeritic-Granitic suite (625 Ma); 7. (x) K calc-alkaline porphyritic granitoids (ca.630 Ma) and (small x) Charnockitic suites; 8. Upper Migmatitic unit; 9. Middle Diatexitic unit; 10. Basal Granulitic unit. Três Pontas-Varginha nappe: 11. Ky-Grt granulites grading upward to Sil-bearing diatexites. Carmo da Cachoeira (CCn) and Aiuruoca-Andrelândia (AAn) nappes: 12. Metapelites and metagreywackes. Migmatitic unit: 13. Migmatites. Lower allochthon and parauthocthon: Quartzite-schist assemblage of the Quartzitic nappe 14 and the Parautochthon 15. Allochthonous Archaean-Paleoproterozoic gneisses: 16. Grey-gneisses and migmatites. South São Francisco Craton: 17. Grey-gneisses and mafic-ultramafic series. 18. Major thrusts; 19. Displacement vectors; 20. Strike-slip shear-zone; 21. Major ductile normal fault; 22. Antiform; 23 Synform; 24. Analysed sample; 25. Carvalhos klippe.

The granites forming the upper batholiths (dated around 630 Ma, Table 3-1) follow modally and chemically an expanded high-K calc-alkaline trend. Porphyritic Hbl-Bt-Qtz monzonites and monzogranites with abundant mafic enclaves and less abundant small bodies of gabbro prevail (*Campos Neto et al.*, 1984; *Wernick et al.*, 1984; *Janasi & Hulbrich*, 1991; *Haddad,* 1995). Monzodiorites, tonalites and granodiorites occur subordinately. Their isotopic signature (Sm-Nd and Rb-Sr) strongly suggests they formed above a subduction zone (*Janasi et al.*, 1997). The metaluminous pink to grey anatetic granites crop out in the Middle Diatexitic Units as pervasive large masses with poorly defined boundaries. Plutons of Ms-granites (625 Ma, Table 3-1) and light-grey Grt-Bt agmatitic granites prevail in the Upper Migmatitic Unit. The youngest plutons (612 Ma, Table 3-1) are undeformed ellipsoidal syenitic massifs, with local ring-like structure composed of unsaturated syenite (*Janasi et al.,* 1993; *Janasi & Vlach*, 1997).

3-3.2. The Três Pontas-Varginha nappe - TPVN

The TPVN (ca. 5 km thick) comprises mainly coarse-grained and granoblastic Ky-Grt granulites, lesser Ky-quartzites, impure quartzites, few calc-silicates and manganesiferous beds (gondites). From its base, where decametre lenses of metabasic rocks and quartzite occur, granulites form a moderately boudinaged sequence (Três Pontas-type) in which the compositional layering inherited from sedimentary bedding is outlined by the variable proportion of Ky, Grt and minor micaceous layers (Figs. 3-6). Layers a few centimetres thick with up to 80% of Grt, others a few millimeters thick with Ky as the chief mineral, grey quartzites and various amphibole-calc-silicates are intercalated in common kyanite granulites. Rare lenses of mafic/ultramafic rocks among which orthopyroxenite may represent synmetamorphic intrusives. Ductilely deformed kyanite-mesoperthite bearing leucosomes and younger kyanite-bearing granitoid veins are parallel to compositional layering. This sequence devoid of significant retrogression grades upward into Sil-Grt (Ky) granulites (Varginha-type) approaching the basal contact of the SGN. Bt-Grt-Sil anatectites also occur at the highest level.

Unit	Method	Age (Ma)	Ref.
Piranguinho basal Grt-granulite	Sm-Nd T_{dm} model age	1290 ε_{Nd} (0.640)=-1.2	1
	Sm-Nd Grt-Bt-whole rock	629±14	1
Cantière Charnockitic suite	U-Pb zircon evaporation	667±17	2
	U-Pb zircon	643±12	3
S. J. Rio Pardo Mangeritic suite	U-Pb zircon evaporation	630±16	2
	U-Pb zircon	625±7	3
Sil-Grt migmatite	U-Pb zircon (lower int.)	650	4
Socorro Porfiritic Granitoid	U-Pb zircon	629±3	5
Bragança Paulista Porfiroclastic Granitoid	U-Pb zircon	655 ±2	4
Tico-Tico Peraluminous Granite	U-Pb zircon	625±18	5
Pedra Branca peralkaline Syenite	U-Pb zircon	612±2.5	5
Shear zone-related Serra do Lopo Granite	U-Pb zircon	595±12	4

Table 1. Recent U-Pb and Sm-Nd geochronological data from Socorro-Guaxupé nappe 1. Teixeira (personal communication); 2. Kröner (written communication); 3. Basei et al. (1995); Ebert et al. (1996); 5. Topfner (1996).

The Três Pontas-type granulites are mainly derived from Al-rich and Ca-poor pelites (low Na_2O/K_2O ratio<1.0). Layers with a high content of Ca, Mg and Ti may represent impure carbonates. Other common intercalations are derived from relatively medium-Ca and high-Mg greywackes (high Na_2O/K_2O ratio 1.1). The Varginha type granulites show a variable Na_2O/K_2O ratio (both pelites and greywackes) and low Ti. Geochemical investigations in progress suggest that these rocks may derive from calc-alkaline, or high-Ca chemical sources possibly resulting from reworked magmatic arc rocks, whereas those with high-Al, low-Ca character may derive from Al-rich clays. One Sm/Nd whole-rock date from a granulite of Três Pontas and one from the Varginha type (both with chemical affinity of an active margin provenance) give T_{dm} model ages at 1.4 and 1.55 Ga respectively with eNd (0.625) of -3.6 and -2.1 (*Janasi,* unpublished result). Such values argue for a derivation of the sediments from a distinct Meso-Neoproterozoic terrane and show a broad incompatibility with a unique source from the Archean/Paleoproterozoic rocks of SFC. These data further constrain the foreign origin of both the Socorro-Guaxupé and the Três Pontas-Varginha granulites, that we therefore regard as two distinct terranes.

3-4. Nappe geometry, kinematics and metamorphic evolution

The sinuous tectonic front of the Brasilia nappes progressively overlaps to the south the southern edge of the SFC (Fig. 3-1). The flat geometry of the nappes in the south is that of spoon-like structures displaced eastward. These are separated by lateral ramps that were commonly reactivated as strike-slip faults after the main displacements. This argues for a greater tectonic transport from the west to the east (200 km), and this accounts for deeper crustal levels progressively exposed in the western nappes

Sample	T_1 ±50°C	T_2 ±50°C	T_3 (°C)	T_4 (°C)	T_5 (°C)	T_6 (°C)	T_7 (°C)	T_8 ±75°C	T_9 (°C)
81.B Opx-Cpx						848	869		
81.B Ca↑ Grt			810-833	792-817	777-786				756
81.B Fe↑ Grt			775-797	755-778	765-775				720
81.B Amp-Pl								755-756	
34.A Grt-Opx					861				
34.A matrix	890	919							
34.A matrix	954	982							
34.A rim	730	760			721				

Table 3-2. Thermometry of the granulites from the hanging wall of the main thrust. T1: Ferry & Spear (1978); T2: Hodges & Spear (1982); T3: Ellis & Green (1979); T4: Powell (1984); T5: Harley (1984); T6: Wells (1977); T7: Sen & Jones (1989); T8: Blundy & Holland (1990); T9: Grahan & Powell (1984).

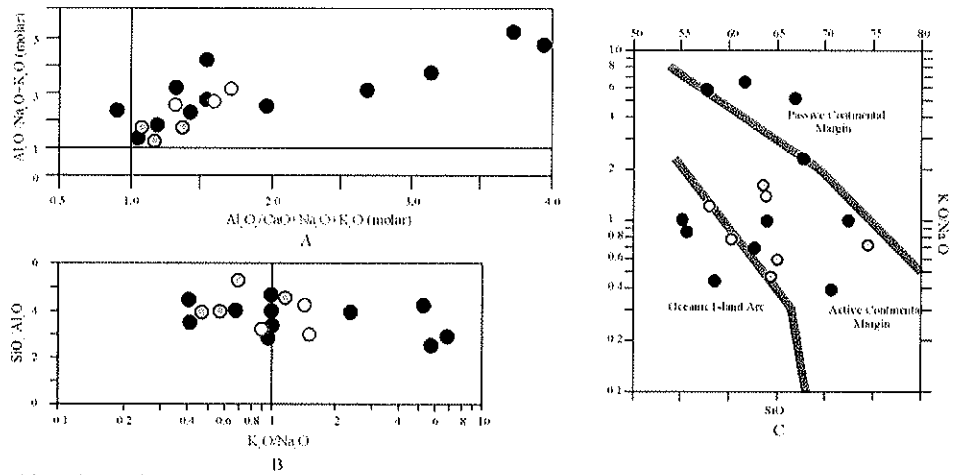

Figure 3-3. Chemical diagrams for rocks with metasedimentary affinities: 3.A- A/CNK (Shand Al-saturation index versus A/NK, Debon & Le Fort, 1983), 3.B- SiO2/Al2O3 versus K2O/Na2O (active margin field from McLennan et al., 1990), 3.C- K2O/Na2O versus SiO2 (Roser & Korsch, 1986). Open circles: Varginha-type granulites and black circles: Três Pontas-type granulites of Três Pontas-Varginha nappe; grey circles: granulites from Basal Granulitic unit of Socorro-Guaxupé nappe.

3-4.1. The Socorro-Guaxupé nappe (SGN)

Two major lobes bounded westward by the Phanerozoic Paraná Basin form the Socorro-Guaxupé nappe. Narrow and curved slices of reworked basement rocks and metasediments that are connected with the lower, less metamorphic nappes, the bulk representing an antiformal structure (Fig. 3-2) separate these two lobes. The northern lobe (ancient "Guaxupé Massif" of Almeida et al., 1981), is a ca. 10 km thick nappe with flat-lying to gently southwestward dipping foliation. The southern lobe also comprises large domains with recumbent foliation that was only refolded close to younger, late-metamorphic NE-oriented strike-slip shear zones. The main metamorphic foliation that maintains a recumbent attitude throughout the major part of the nappe is thus the earliest tectonic feature related to progressive non-coaxial deformation having taken place during the east-

northeast displacement of the nappes. Petrostructural and kinematic observations in the northern lobe (Fig. 3-2) allow to recognise distinct tectonometamorphic features that may have formed in three stages.

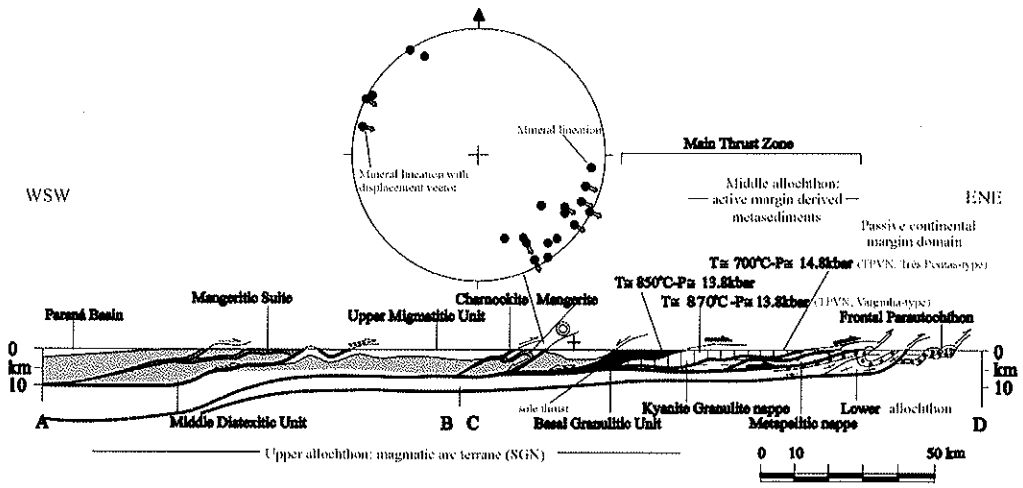

Figure 3-4. Cross-section of the northern nappe system (location in Fig. 2).

3-4.1.1. Basal sole thrust

The base of SGN (ca. 3 km thick) essentially consist of mafic granulites displaying a strong plano-linear fabric (mainly low plunging W-SW mineral and stretching lineations) and bearing several top-northeast shear sense indicators (Figs. 3-6 C and D). Isoclinal and sheath folds record the main movement of the nappe during wanishing granulite-facies conditions (630 Ma). In the southern lobe, the shear zone of the hanging wall of the main thrust reaches 1 km of thickness, with linear tectonites showing the same northeast-directed direction of transport.

Microstructures and mineral assemblages. Mafic granulites exposed south of Varginha City, close to the base of the northern lobe of SGN, contain centimetre size pyroxene-rich black layers. Metric bands of leucocratic granulite with Grt-poor, Qtz- norite composition and decimetre size lenses of mesocratic norite predominate among the main enderbitic composition. At the southern segment NW of Itajuba City, irregular, small (cm size) lenses of white Grt-trondhjemite leucosome also occur. The main enderbitic granulites exhibit a porphyroclastic structure defined by up to 1 cm in size stretched poikilitic phases with primary lobate boundaries: Opx, Grt, Pl and Qtz ribbons. These relict phases document HP granulite-facies conditions. They are surrounded by a recrystallized matrix essentially composed of Qtz, andesine and minor Bt with triple point microstructure resulting from late-kinematic annealing. The green amphibole can occur in textural equilibrium with both pyroxenes (hypersthene and a pleochroic pale greenish brown salite (up to 24% FeO), but normally it grew in the matrix and hardly replaces the pyroxenes displaying local equilibrium with outermost garnet-rims. Subordinate brown biotite (Bt-2) is Ti and Al^{VI}-rich (ca. Phl11-Ann2.5, Al^{VI}=0.215 p.f.u.). It is concentrated in shear bands (C'). Inclusions in garnet are represented by Ilm, Pl and Bt1 of different composition than that of the matrix (Phl-rich and relatively low Al^{VI}=0.18 p.f.u.). The Grt (Alm49-Prp26-Grs22)

occasionally occurring as a ring around earlier Pl shows increased $Fe^2/(Fe^2+MgO)$ ratio towards rims: (Alm52-Prp28-Grs18) when adjacent to Opx, and Alm58-Prp30-Grs7 garnet-rim when adjacent to Bt. The $Fe^2/(Fe^2+MgO)$ ratio may decrease in small garnet grains from the matrix (Alm55-Prp35-Grs5).

3-4.1.2. Syn-metamorphic normal shearing and Late-metamorphic NE-directed thrusting

NW-SE oriented mineral and stretching lineations, associated with many asymmetrical kinematic indicators consistent with top to the west, normal movements, occur towards the top of the basal granulites (Fig. 3-4). A major detachment, locally accommodated by a NW-oriented, oblique sinistral strike-slip faulting marks the contact between the Upper Migmatitic Unit and the Basal Granulitic Unit (Fig. 3-2). SE-plunging syn-metamorphic mineral and stretching lineations have been mapped widely in the Middle Diatexitic Unit (*Campos Neto et al.* 1985; *Ebert et al.*, 1996). These features which record top to the SW movements may result from the syn-metamorphic unroofing of the granulites and the collapse of the hot anatectic rocks, in which heat advection occurred through the large volume of charnockite-mangeritic magmas emplaced at mid-crustal levels.

Sample	T (°C)	P_1 - gads (±1.9 Kbar)	T (°C)	P_2 - gapes (±1.5 Kbar)	T (°C)	P_3 (±0.5 Kbar)
81.B Grs-rich	850	13.8±1.9				
81.B Grs-rich	820	13.3±1.9				
81.B Grs-rich			775	11.5±1.5		
81.B inner rim	780	11.9±1.9				
81.B rim					720	9.3-9.0
34.A matrix			860	11.5±1.5		
34.A matrix			920	11.7±1.5		
34.A inclus.			755	10.6±1.5		
34.A rim			720	10.5±1.5		
34.A rim			760	10.9±1.5		

Table 3. Barometry of the granulites from the hanging wall of the main thrust. P1 and P2: Eckert et al. (1991); P3: Kohn & Spear (1990).

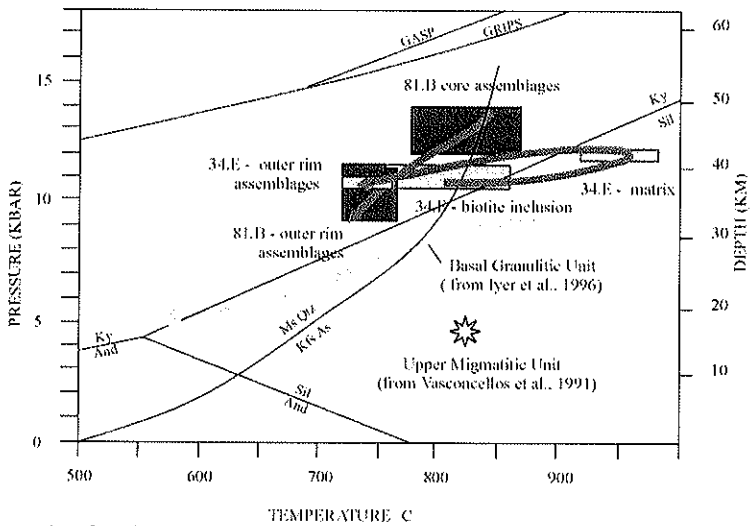

Figure 3-5. P-T trajectories for the granulites from the hanging wall of the main thrust - Basal Granulitic unit of the Socorro-Guaxupe nappe.

Large exposures of the Middle Diatexitic Unit representing the roof anatectic metasediments are controlled by thrusts. Reverse faults are well evidenced by the basal truncation of 625-630 Ma old granitic and mangeritic plutons. A pure-shear component of this thrust-shearing was responsible for the folding (up to 3.5 km of wavelenght) of the main foliation as a near-recumbent and asymmetrical, NE-verging fold system developed under amphibolite facies conditions (Bt and/or Hbl locallly in axial planes).

3-4.1.3. P/T estimation for SGN

Previous P/T estimates have revealed that the SGN and the TPVN have suffered two contrasting P/T evolutions. Values of T=820^{o}C and P=4.5 kbar (Crd-Sil-Grt-Bt) have been obtained on metapelites from the Upper Migmatite Unit (*Vasconcellos, et al.*, 1991). Similar mineral assemblages occurring near the contact with the Basal Granulitic Unit record P-T conditions of 800^{o}C and 7.5 kbar (recalculated data from *Oliveira & Ruberti*, 1979). HP/HT granulitic conditions were obtained on basal granulites from the SGN by *Iyer et al.*, (1996) and *Del Lama et al.*, (1994).

At the northern segment of the SGN, the Grt-Bt1 assemblage shows consistent T=755^{o}C, still higher than the Grt-rim/Opx thermometry (T=721^{o}C). The Opx-Cpx pairs from mafic granulites indicate T around 870^{o}C and T between 820^{o}C and 775^{o}C for garnet-pyroxene pairs and are interpreted as peak temperatures. A temperature of 720^{o}C is obtained from amphibole-garnet rim pairs (see Table 3-2 for the available thermometers). For the higher temperatures, the pressure varies from 14.0 to 11.5 kbar (GADS and GAPES barometers, Eckert et al., 1991) and 9.0 kbar for the lower temperatures (Grt-Amp-Pl-Qtz barometer, Kohn & Spear, 1990; Table 3-3). In the Socorro lobe, the temperatures obtained from Grt-Bt (*Hodges & Spear*, 1982) are scattered and some of them give unrealistically high values (up to 980^{o}C), perhaps due to non-ideal mixing (Fe-Mg-Ca-Mn) in garnet and/or to the too high Ti and Al^{VI} content of biotites (*Neogi et al.*, 1998). T-max of 920^{o}C can be assumed, whereas the Grt-Opx pairs furnish T=860^{o}C. These paleotemperatures are interpreted as indicating an isobaric heating scenario (P=11.7 to 10.5 kbar, Fig. 3-5) consistent with dry melting and with the emplacement of anhydrous charnockitic/mangeritic magmas.

3-4.2. The Três Pontas-Varginha nappe (TPVN)

This flat -lying nappe emerges from below the Guaxupé mafic granulites. It crops out for at least 170 km parallel to its displacement direction and is characterised by a recumbent primary foliation (Fig. 3-6). Two klippen made up of the same lithology of unretrogressed Ky-granulites are preserved above slightly anatectic metasediments (Fig. 3-2). Regular W-SW plunging mineral and stretching lineations, mostly defined by the shape fabric of Ky, Rt, Ms and Qtz-ribbons, are widespread. They result from homogeneous E-directed transport during HP-granulite facies conditions. Grt-Ky leucosomes formed in the pressure shadows of boudins of more rigid, less deformed and anhydrous granulites document renewed, syn-granulitic deformation. This thicker nappe (ca. 5 km) represents

the footwall of the main thrust zone. The E-NE direction of displacement is evidenced by asymmetry of boudins of winged, decimetric metabasic swells of pull-apart type and S-C composite shear fabrics. Renewed eastward tectonic transport related to exhumation toward amphibolite facies conditions keep the foliation on metric thight-inclined to recumbent, NE-verging a-type folds and sheath-folds coeval to mylonitic-forming ductile shear bands.

3-4.2.1. Microstructures of kyanite granulites

The Três Pontas type Rt-Ky-Grt granulites are light-gray to bluish, coarse-grained massive rocks with 0.5 cm mean grain size. A recumbent syn-kinematic foliation is defined in most granulites by the ribbon quartz fabric and the planar disposition of rare micas. Aligned Ky prisms define the lineation. In mica-poor layers, mesoperthite is concentrated in the pressure shadows of garnet and also in leucosomes. Horizons with feldspar and kyanite augen up to 2 centimetres long and minute ones enclosed in coarse monocrystalline quartz up to 1-2 cm long suggest pervasive ductile flow at rather high temperatures and pressures. Minute prismatic Sil (100m) growing along grain boundaries has been observed only in two samples around Varginha city. Only a few granoblastic calcsilicate, psammitic rocks and rare kyanite granulites are free of post mineral deformation.

3-4.2.2. Successive mineral assemblages and P/T estimates of kyanite and sillimanite granulites

Trouw (1992), *Trouw & Castro* (1996) and *Vasconcellos et al.* (1991) have described the high-pressure conditions of these rocks. *Campos Neto & Caby* (in press) report conditions of T=730^{o}C and P=13 kbar from the Três Pontas-type Ky-granulites, and an isobaric heating (up to T=890^{o}C) toward its top in the Varginha-type granulites.

The new results summarized below - which will be presented in another paper- are based upon microprobe analyses of a larger number of metapelie samples from different localities, which show distinct mineral chemistry. Coupled with textural arguments, these data allow to recognize in a few rocks both microdomains with a prograde evolution, and other rocks which registered at varying dregree part of the retrograde evolution related to exhumation. Several stages can thus be recognized in the metamorphic evolution of kyanite and sillimanite granulites, allowing us to reconstruct provisional P/T paths (Fig. 3-9). The available thermometers and barometers for each analysed sample from KFMASH (Table 3-4) and CMFASH (Table 3-5) systems of Três Pontas-type, and KFMASH system (Table 3-6) from Varginha-type granulites, always in presence of quartz, are indicated. Wherein the Ilm activty (0.93 to 0.95) is always used (even if it lacks in Grt rings) by GRAIL and GRIPS barometers, such values argue for initial minimum pressures.

An early prograde metamorphic stage has been fossilised in garnets from massive samples from the Três Pontas quarry. Cores ($Fe^2/(Fe^2+Mg)$)=0.86 display unrecrystallized micro domains revealedd by relics of a vestigial cleavage defined by minute acicular Rt and a dense halo of both quartz and fluid inclusions. Composite inclusions (150 m) of Prl-Sd-Rt and Qtz-Ilm-Ky-Bt (Bt with low-Ti and Phl8-Ann2) have been found in one sample. If primary, such mineral assemblages would argue for fossilised low temperatures. The only occurrence of rutile implies that pressure was higher than the GRAIL reaction.

Sample	Mineral assemblage	T_1 (±50 °C)	T_2 (±50°C)	T_3 (±5°C)	T_4 (°C)	P_1 GRIPS (±1.0kbar)	P_2 GASP (kbar	P_3 GRAIL (±0.5 kbar)
72.3 core	Alm82-Ann	459	468					7.5
72.3 inner rim	Alm80 Ms78-An0				700		14.8	
72.3 inner rim	Alm82 Ms73-An0				688	14.9	14.6	
72.3 outer rim	Alm81 Ann8-An2	574	600				10.9	
72.H	Prp40 Phl11-Mc	875	903	781				
72.B outer rim	Alm76 Ann14 Ms83-An0.6	1082	1355	1203	770			
72.Z leucosome	Alm82- Ms72-An19				782	13.5		
72.Z melanosome	Alm85-Ann 11-An19	741	747	684		10.6		
91.B inner rim	Prp47-Phl27 An17	719	730	691		13.0		
91.B outer rim	Alm60-phl 19-An24	672	692	643		12.0		
91.B outer rim	Alm61-Phl 21-An24	622	640	614		11.3		

Table 3-4. KFMASH P-T conditions of Très Pontas-type granulites. Mineral assemblage in mole % of the main end-members. T1: Ferry & Spear (1978); T2: Hodges & Spear (1982); T3: Indares & Martignole (1985); T4: Green & Hellman (1982); P1: Bohlen & Liotta (1986); P2: Newton & Haselton (1982) modified by Koziol & Newton (1988); P3: Bohlen et al. (1983).

Sample	Mineral assemblage	T_1 (±75°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_5 (±50°C)	P_1 (±0.5 Kbar)	P_2 gads (±1.9 Kbar)	P_3 (±0.5 Kbar)
72.5 near core	Alm45Grs 39-Di-An34			641	623			12.6±1.9	
72.5 inner rim	Alm45Prp 30-Di-An34			680	660			12.7±1.9	
72.5 inner rim	Alm47Prp 28-Di-An34			637	615			11.7±1.9	
72.5 outer rim	Alm46Prp 31-Pa-An35	735	690				10.8		
72.U core	Alm47Prp 27-Pa-An34	754	723				12.1		
72.U inner rim	Alm50Grs 26-Pa-An37	763	638.6				11.9		
72.U inner rim	Alm50Prp 23-Pa-An37	750	636.1				11.8		
72.U outer rim	Alm61-Phl 12-An31					668			9.2
72.U outer rim	Alm64-Phl 14-An31					681			9.0

Table 3-5. CMFASH P-T conditions of Très Pontas-type granulites. Mineral assemblage in mole % of the main end-members. T1: Blundy & Holland (1990); T2: Grahan & Powell (1984); T3: Ellis & Green (1979); T4: Powell (1985); T5: Hodges & Spear (1982); P1: Kohn & Spear (1990); P2: Eckert et al. (1991); P3: Bohlen et al. (1983). Pressures are calculated from Blundy & Holland, Powell and Hodges & Spear's thermometers.

The high-pressure granulite facies assemblage is fairly preserved in massive lithologies from the core of boudins in the Três Pontas quarry. Only a few layers comprises the anhydrous mineral assemblage Qtz, Msp, Alm-Prp, Ky, Rt, Graph, Mnz. Rare Bi, Ms and Pl, Fe sulphides and Ank seem to be also primary in other samples. Quartzo-feldspathic lenses formed by up to 80% of one cm in size mesoperthitic feldspar and quartz (few Ky, primary Ms and Grt) are regarded as early synmetamorphic leucosomes extracted from adjacent aluminous granulites and affected by further solid-state high-temperature shear.

Larger, best preserved garnets from garnetiferous layers (up to 2,5 cm) display Mg enrichment in rings (Alm50-Prp38-Grs9) that surround domains with the fossilized prograde stage. They also contain numerous inclusions of prismatic Rt, Mnz, Qtz and Ky, the latter mineral being more abundant towards the rims. Kyanite prisms up to 2 cm long contain Rt, Mnz and Qtz inclusions, as well as rare small grains of possibly primary white-mica. Muscovite flakes are occasionally in contact with garnet rims in some samples, some being rarely included in garnet outer zones. A few layers some centimeters thick contain up to 30 % of Ms associated with Qtz, Ky, Grt and Rt. Possible pseudomorphs after Na-Cpx (albite+carbonate+Fe-rich alteration followed by kaolinite and Na-illite) have been observed in one sample.

This first granulitic stage is related to mineral equilibrium between the homogeneous Prp-enriched composition of larger garnet rings, Pl strings from mesoperthite, Pl porphyroclast, Ky and Rt, Ms and rare Ti-rich Bt. Conditions of T max around 700^{o}C and P about 15 kbar have been calculated for samples from the Três Pontas quarry (Fig. 3-9).

The second syn-kinematic mineral assemblage. Plastic flow has deformed and partly destroyed the coarse grain minerals formed during the previous stage, except in the core of a few boudins. Mesoperthite clasts are plastically deformed and manteled by minute sub-grains of recrystallized Mc, Qtz, Pl and myrmekite. Early white mica is bent or completely recrystallized as polygonal arcs and rimmed by elongated Ms and Ky. Large (up to 7 mm) Ms flakes from polygonal arcs may include lobate Ky and show Ms-Qtz lamellae with symplectitic boundaries. Kyanite can be plastically microfolded or kinked, though it is mostly unaltered in mica-poor samples, and Rut is replaced by Ilm. Secondary Ms is the chief mineral of some non foliated, feldspar and garnet-poor layers, in which all stages of its replacement after kyanite (no margarite) can be observed, in equilibrium with plagioclase and calcite. Most of the brown biotite grew during this stage at the expenses of Grt. Alm-rich garnet rims may result of Fe-Mg exchange between both minerals at high temperatures. The biotite also occurs in fractures and deep embayments within garnet, in equilibrium with polygonal Pl, Ilm and recrystalized Ky, thus giving the false appearance of primary biotite inclusions in garnet cores. P/T conditions for this stage are estiamted from Fe-Mg exchange between Bt and thin Grt outermost rims with higher $Fe^{2}/(Fe^{2}+Mg)$ ratio. The conditions for this stage for the Três Pontas granulites are estimated at T=690^{o}C-600^{o}C, and P around 11 kbar. A distinct P/T path with progressive T increase to 760 ± 20°C and P around 10.5 to 13.5 kbar is recorded in other samples with minute intergranular fibrolite, collected at higher crustal levels 15 km northeast of Varginha.

Sillimanite overprint in the Varginha area is present in all samples collected towards the upper part of the allochthon, about 2.5 km above the main thrust boundary at several localities around the Varginha city. These sillimanite granulites with distinct evolution contain Msp, Mc, Pl, myrmekite, Rt and/or Ilm as well as Prp-rich garnet but no muscovite. Unaltered Ky prisms may however survive in resistant layers and are mainly preserved in Grt cores. Recrystalization of deformed Ky prisms along small shear bands into tiny prisms may also occur, in association with the blastesis of minute prismatic Sil neoblasts in equilibrium with newly formed prismatic Rt. Plurimillimetre in scale pismatic Sil is included towards the rims of Prp-rich garnet. In other rocks, the nucleation of prismatic Sil also progressed in the form of a fine-grain, progressive replacement of Ky prisms displaying dactylitic fringes, whereas Rt of such rock is entirely replaced by Ilm.

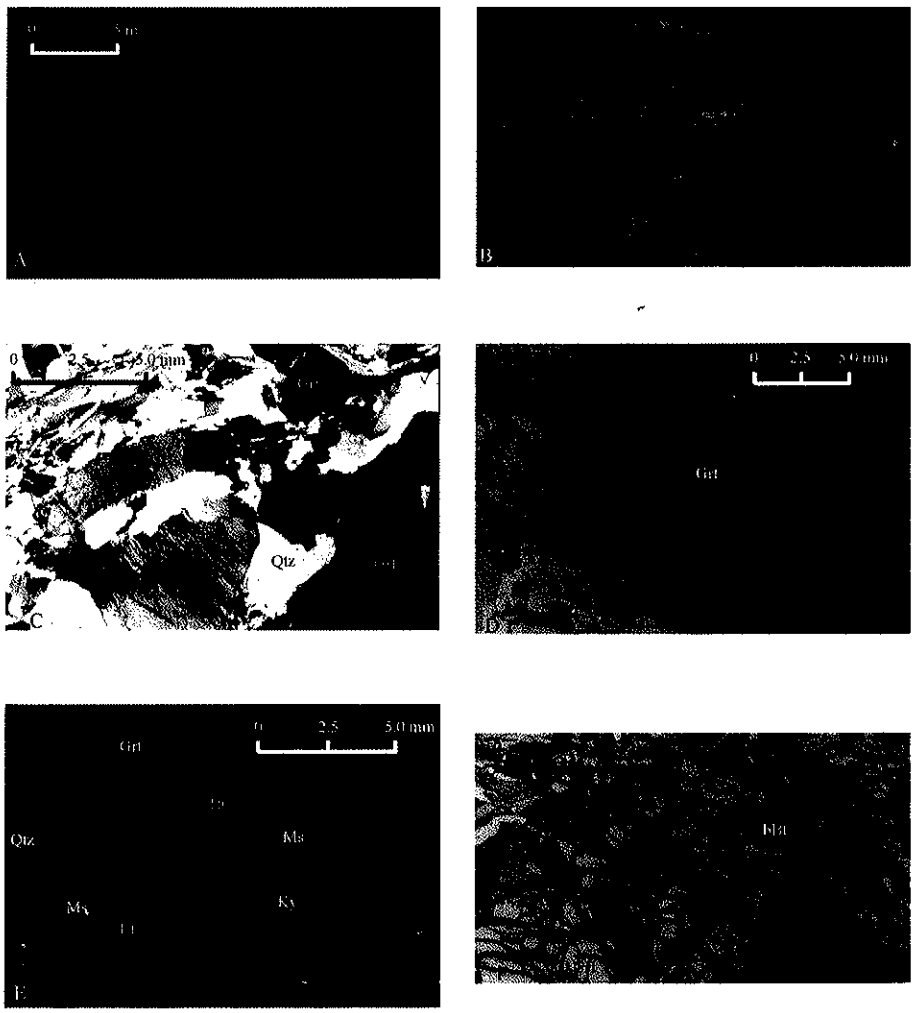

Figure 3-6. Plate of photos

A. Três Pontas quarry cliff. Well-banded granulites with massif boudinated layer. B. Kyanite-garnet granulite of Três Pontas-type. C. Garnet-mesoperthite-kyanite-quartz assemblage surrounded by biotite, quartz and samall garnets. Sample nesg 93 A2. D. Garnet porphyroblast with internal foliation drew by minute rutile inclusions. Note the discontinuous and clean garnet orim. E. Kyanite porphyroblast (rutile and monazite inclusions) showing corroded seriate boundary with surrounding muscovites; garnet-biotite and quartz. Sample nesg 72.3. F. Crushed garnet partially replaced by green-biotite after brown biotite.

Prismatic Sil is in textural equilibrium with garnet (Prp up to 45), Ky, Bt (Phl 15 to 17), oligoclase, Mc, Rt and Ilm. The temperatures furnished by Grt-Bt pairs from three samples give 830 and 950^{o}C at pressures around 12 kbar, the last figure being likely overestimated.

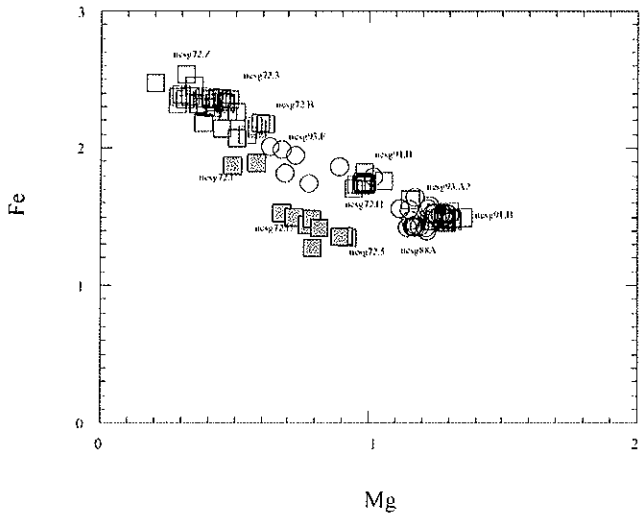

Figure 3-7. Fe2 X Mg diagrams for garnets from Três Pontas-Varginha nappe.

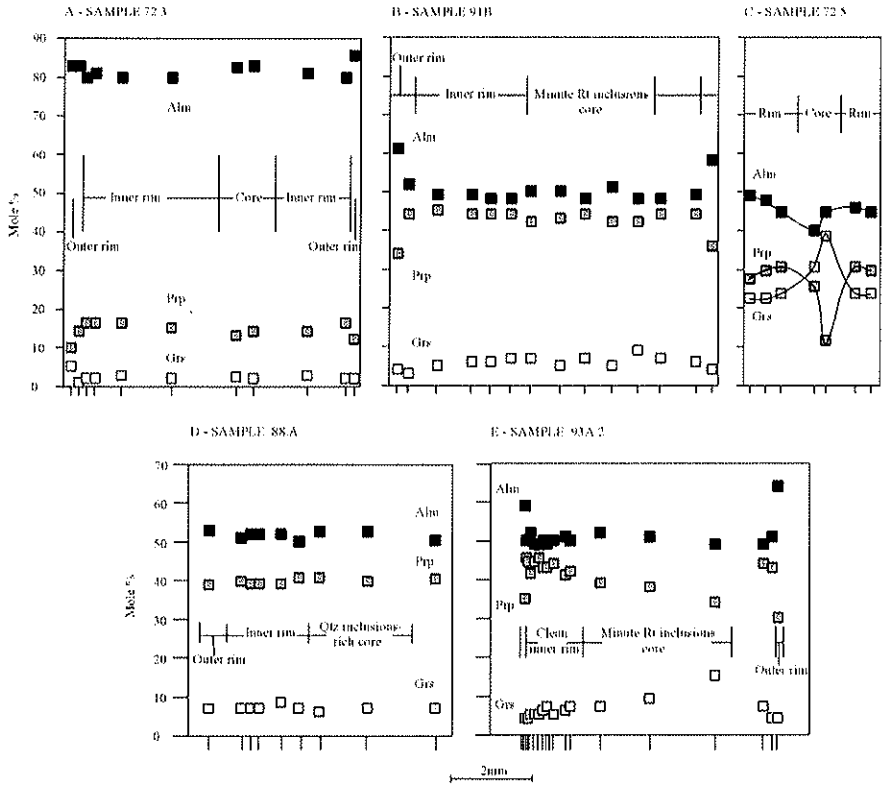

Figure 3-8. Core to rim garnet compositional profiles from Très Pontas and Varginha types granulites.

Some HT mylonites are characterised by sigmoid Qtz monocrystalline ribbons with undulose extinction, S-shaped and elongated clasts of garnet possibly resulting from its plastic deformation and showing different stages of replacement by abundant biotite (Phl 23) in textural equilibrium with sillimanite. This mineral occurs as minute acicular and spherolitic framework, as well as prismatic grains rimmed by Bt-Qtz symplectite in a quartz-oligoclase fine-grained seriate-interlobate matrix. Both relict Rt and Ilm also occur. Mineral equilibria from these mylonitic bands suggest a near-isothermal decompression toward T=765^{o}C and P=9 kbar. Another sample with crushed garnet (Alm60) in several sharp fragments intensively rimmed and replaced by brown-Bt crowded by abundant Sil inclusions and oligoclase neoblasts give T= 795^{o}C and P=7.9 kbar.

Syn-kinematic retrogression of granulites is well expressed in selected bands with protomylonitic fabrics 15 km northeast of Varginha. In such rocks, garnet was flattened and crushed. Its partial to total replacement by biotite occurs approaching cross-cutting fissures strongly enriched in Bt. Kyanite from such biotitized rocks is however partly retrogressed into Ms. Such features indicate that a fluid phase percolating in cracks assisted the synkinematic retrogression and caused the rehydration of granulites. Lower temperature retrogression, though negligible in all our analysed samples, is evidenced by green, Ti-free Bt and Chl, Cal and Ab. Such late lower temperature fabrics were assisted by low temperature fluid infiltration along fissures.

Sample	Mineral assemblage	T_1 (±50°C)	T_2 (±50°C)	T_3 (±5 °C)	T_4 (°C)	P_1 grips ±1kbar	P_2 grail ±0.5kbar	P_3 gasp
88.A outer rim	Alm53-Phl 15-An29	933	950	830.6				12.2
93.A2 inner rim	Prp40-Phl 17- An23	850	869			13.8		11.5
93.A2 inner rim	Prp44-Phl 22-An 22	800	822			11.9		11.5
93.A2 mylonite	Prp42-Phl 23-An24	748	764					8.8
93.A2 mylonite	Prp45-Phl 24-An23	756	771					9.2
93.A2 outer rim	Alm64-Phl 19.5-An23	564	580					6.4
93.A2 outer rim	Alm59-Phl 29-An23	516	533					6.5
93.F prograde	Alm59-Ms 71-An37				730	13.0		
93.F inner rim	Alm62-Phl 8-An37	800	839			12.4		9.9
93.F outer rim	Alm68-Phl 8-An28	774	795					7.9
93.F outer rim	Alm68-Phl 10-An28	611	639				7.8	6.8
93.F outer rim	Alm66-Phl 11-An28	666	697					7.6

Table 3-6. KFMASH P-T conditions of Varginha-type granulite. Mineral assemblage in mole % of the main end-members. T1: Ferry & Spear (1978); T2: Hodges & Spear (1982); T3: Indares & Martignole (1985); T4: Green & Hellman (1982); P1: Bohlen & Liotta (1986); P2: Bohlen et al. (1983); P3: Newton & Haselton (1982) modified by Koziol & Newton (1988).

3-4.3. The southern shear-belt

The southern part of the SGN was involved in the NE-trending southern shear-belt (or Ribeira Belt, Fig. 3-1), formed during a younger event (the Rio Doce orogeny). Several E-NE trending granitic plutons were emplaced into transpressional bends or segments of shear

zones according to *Ebert et al.*, (1996). The zircon ages of these shear-zone related plutons are bracketed between 595 and 580 Ma (Ebert et al, 1996; Machado et al, 1996; Töpfner, 1996), whereas monazites cluster between 580 and 563 Ma, suggesting a long-lived event closely related to shear zone activity. A sinistral movement during high temperature deformation has been documented (*Garcia & Campos Neto*, 1998), in agreement with the opening of molassic pull apart basins. In contrast, lower temperature renewed displacements along the major shear zones are clearly dextral. Cataclasites and pseudotachylites also account for possibly younger, Phanerozoic reactivations in the core of the shear zones. High-temperature dextral movements also predominate in the Ribeira belt (*Vauchez et al.*, 1994). The shortening propagation of the transpressional system toward the north was accommodated by small NW-directed brittle-ductile thrusts and by a continuous set of gently W-SW-plunging normal buckle folds with small amplitude/wavelength ratio and cylindrical geometry. These folds grade to upright tight folds close to the shear zones.

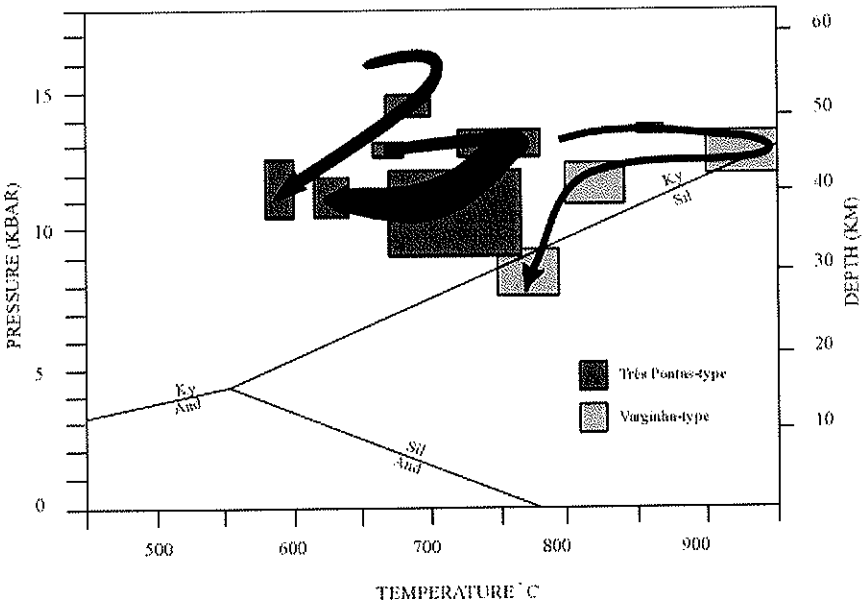

Figure 3-9. P-T trajectories for the granulites from the Três Pontas-Varginha nappe.

3-5. Age constraints on high-grade metamorphism and nappe emplacement

Imprecise U/Pb, zircon ages around 650-700 Ma (lower intercept) have been interpreted as related to the Neoproterozoic HT metamorphism by *Ebert et al.* (1996). The lower intercept age of 655 Ma obtained on a migmatite has also been interpreted by the same authors as dating the thermal peak. U-Pb zircon ages of 660 Ma (by evaporation process) and 640 Ma were also obtained (Table 3-1). In the southern lobe of SGN, upper intercept ages of 625 Ma and bracketed between 624 and 630 Ma were obtained on a peraluminous granite and on calc-alkaline granites, respectively (Töpfner, 1996). The Grt-Bt-whole rock Sm-Nd alignment at 630 Ma (Table 3-1) further constrains the age of granulite facies metamorphism in the deeper parts of the SGN. A post-kinematic peralkaline syenite emplaced at about 3 km depths (*Janasi et al.*, 1993) has given a nearly concordant age of 612 Ma (Töpfner, 1996) that gives a younger limit for the HT/HP metamorphism in the Socorro- Guaxupé terrane.

3-6. Summary of data and discussion

Lithology and preliminary geochemical and isotopic constraints from high-grade units of the nappe system exposed at the southwestern edge of the São Francisco craton suggest that three major geodynamic environments were juxtaposed during collisional processes: 1- a long-lived Late Mesoproterozoic to Neoproterozoic immature to mature magmatic arc terrane, represented by the HT upper allochthon (SGN); 2- a metasedimentary assemblage with geochemical affinities suggestive of its derivation from an active margin environment, possibly representing an accretionary prism: it forms the HP middle allochthon (HP kyanite-granulites of TPVN and the Carmo da Cachoeira and Aiuruoca-Andrelandia nappes, Fig. 3-2); and 3- the metasedimentary passive continental margin assemblage related to the SFC, exposed in the lower nappes and the frontal parautochthons (*Campos Neto & Caby, in press*).

The main thrust evidenced in the high-grade nappe system separates the magmatic arc terrane (SGN) from undelying HP Ky-granulites (TPVN). The hanging wall of the main thrust comprises a ca. 3 km thick syn-granulite shear zone (the Basal Granulitic unit of SGN) that records T-max around 950° C and P= 12 kbar dated at 630 Ma, roughly coeval in time with the emplacement of noritic magmas. Metasediments possibly derived from a Mesoproterozoic active continental margin define the footwall of this main thrust zone; they form the 5 km thick slab of mainly Ky-granulites (TPVN). A maximum temperature of 750 °C was attained at an estimated pressure of 15 kbar in the Três Pontas granulites. Progressive near-isobaric temperature increase up to 900°C, P=12 kbar occurred towards its top in the Varginha-type granulites. The TPVN is everywhere delimited at its base by a metamorphic gap evidenced by much lower temperatures downwards. These are below 600° C in the lower nappes (*Campos Neto & Caby, in press*). The resulting metamorphic pattern with inverted metamorphism is thus comparable to that reported from several collisional orogens formed after significant subduction of continental crust such as the Greater Himalayan zone (*Le Fort et al.*, 1986; *Burg et al.*, 1987; *Hubbard,* 1989; *Vannay & Hodges*, 1996; *Matte et al.*, 1997) and the Paleozoic orogens such as the Uralides and Variscides (*Matte*, 1998). Our results suggest an inverted metamorphic field gradient involving a perturbed paleogeotherm of about 13°C/km for the Ky-granulites to an upper steady state paleogeotherm ca. 20°C/km towards the base of the arc terrane. This thermal pattern may be related to diachronic equilibration at different temperatures but constant pressures throughout the metamorphic prism, as evidenced in the Indian Greater Himalayan zone by *Vannay & Grasemann* (1998). This thermal inversion model ("hot iron" type) also requires the rapid emplacement of the upper hot allochthon onto the TPVN, arguing for a similar age of metamorphic peak slightely before or around 630 Ma.

A SW-dipping detachment controlled by SE-transported sinistral, oblique strike-slip fault, bounds the top of the main thrust shear zone of the upper allochthon. Movement along this HT ductile normal fault was coeval with widespread anatexis and with the emplacement of mangeritic magmas extracted from surrounding granulites around 630-625 Ma. This hinterland-driven detachment may result from internal extension by dynamic compensation in response to the possible broad topographic gradient developed by the collisional extrusion, as reported from the Nepalese Himalayas (*Hodges et al.*, 1996). Such

apparent "extensional" regime compares well with the ductile normal fault formed on top of the hot, migmatitic Tibetan slab in the central Higher Himalaya, where it has been interpreted as syn-collisional collapse above the partialy melted crust at the time of collection of Himalayan leucogranites (*Caby et al.*, 1983; *Burg et al.*, 1987; *Burchfiel et al.*, 1992; *Chemenda et al.*, 1995; *Vannay & Hodges*, 1996).

Though nearly contemporaneous, the HT/LP metamorphism (T=820^{o}C and P=4.5 kbar) at shallow levels of the SGN arguing for a compressed paleogeotherm of about 50^{o}C/km is incompatible with the first syn-kinematic metamorphic stage recorded in the Ky-granulites. This metamorphic relationship argues for initial different tectonic environments for the two granulite nappes, and we therefore regard them as representing two juxtaposed terranes. Paleothermal constraints thus suggest that the closure of an ocean through a W-dipping subduction zone may have occurred in late Neoproterozoic time. Possible ophiolitic complexes (the Petunia complex, *Choudhuri et al.*, (1995) and the Maraba sequence (*Fuck et al.*, 1994), both comprising serpentinites with podiform chromite typical of oceanic mantle, provide strong further evidences for such an open ocean, west of the SFC. The position of the Ky-granulite slab that records much higher pressures than both the overlying and underlying units suggests that it was emplaced as an horizontally extruding slice through the mechanism of upward extrusions (*Chemenda et al.*, 1995; *Chemenda et al.*, 1996). Continental subduction may be responsible for the low-angle exhumation of HP units, as proposed for the Himalayas (*Matte et al.*, 1997) and for several domains of Paleozoic orogens (*Matte*, 1998). The Varginha-type granulites with final equilibration in the sillimanite field record a near-isothermal decompression metamorphic path around 8.5 kbar, whereas the basal Três Pontas-type granulites mainly record decompression in the Ky-field. The major foreland nappe stacking seems to be related to this younger stage of horizontal eastward displacement evidenced by retrogressive mylonites. The outward propagation of the nappe pile subjected to significant thinning was accompagned by T-decrease at each thrusted rock-package (T=600^{o}C in the lower allochton and T= 500^{o}C in the frontal parautochthon, *Campos Neto & Caby*, submitted). Since the TPVN practically overrides the parautochthons in its northern part, a major late-metamorphic out-of-sequence thrust is responsible for the final emplacement of the whole nappe pile, as it is the case for the Brasilia nappes in the north, where they overlie the anchimetamorphic Bambui Carbonates of the foreland. (Simões, 1995).

The preservation of an inverted metamorphic field gradient in rock units all equilibrated in the Ky-field requires rapid exhumation of the granulite nappes and simultaneous strong erosion and/or tectonic denudation or syn-displacement thinning. Thus the main thrust system could not represent a long-lived extrusion process of part of the lower crust, in which case the kyanite granulites would all have been thoroughly overprinted in the sillimanite stability field and affected by anatexis. The apparent episodic alternation of compressive and extentional structures may suggest progressive pulses of large-scale shortening and extrusion, as reported from the Nepalese Himalayas (*Hodges et al.*, 1996), but further isotopic and petrological data are required to evaluate such a possibility. Our data allow us to propose a short-lived tectonic scenario beginning around or shortly before 630 Ma and achieved by around 625 Ma, since the whole post-orogenic lithospheric extension took place prior to 610 Ma, as shown by U/Pb zircon ages of the cross-cutting syenites emplaced around 3 kbar. Thus, part of the lower crust was upwards exhumed from

a west-dipping subduction prism and driven horizontally above the southern edge of the SFC during the maximum time span of 20 Ma, resulting in a mean cooling rate of about 15-20°C/Ma. The superposed tectonic history after ca. 580 Ma is due to northwestward propagation of the transpressive Ribeira shear belt. K/Ar ages on amphibole of 610 Ma and micas that cluster around 550 Ma (*Teixeira & Cordani,* 1979) suggest a slow cooling rate in the south of SGN related to a long-lived thermal anomaly.

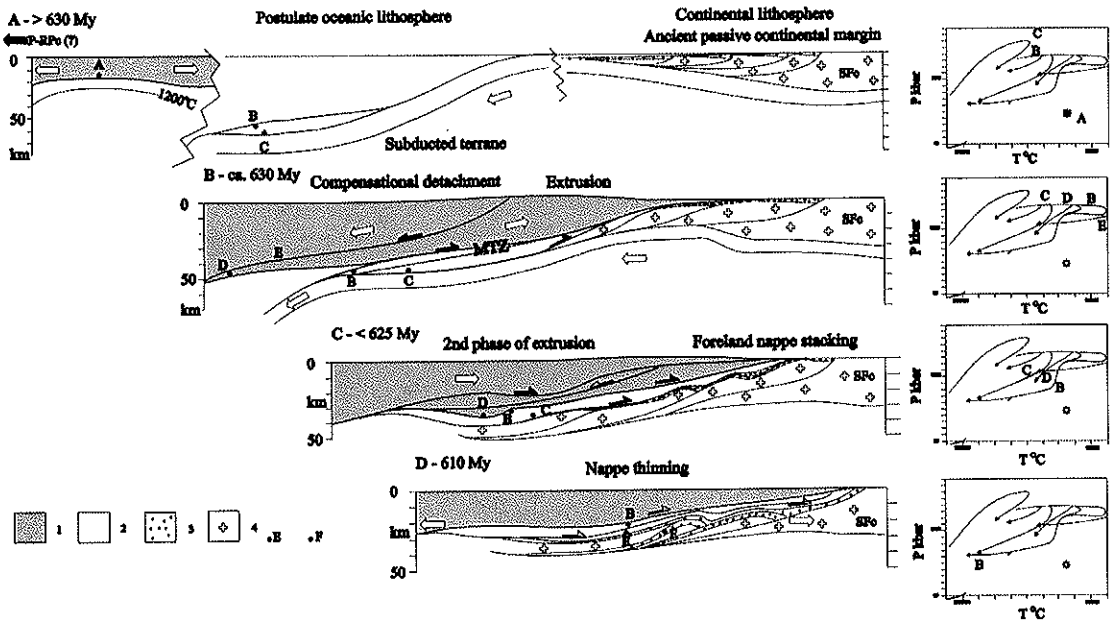

Figure 3-10. Suggested geodynamic model of Neoproterozoic collision SW of São Francisco craton.
1. Magmatic-arc terrane (Socorro-Guaxupe nappe); 2. Mantle beneath arc; 3. Subducted slab (Três Pontas-Varginha nappe and Carmo da Cachoeira, Aiuruoca-Andrelânia nappes); 4. Passive continental margim deposits; 5. Ancient gneisses; SFc: Sao Francisco craton; Pb: Parana block; .B: Thermobarometric conditions.

3-7. Conclusion

The granulite nappes exposed SE of the São Francisco craton derive from two distinct terranes assembled to form a composite section of deep continental crust: the Socorro-Guaxupé nappe above and the Três Pontas-Varginha nappe below. Metamorphism in the lower TPVN is unique by the preservation of High-Pressure Kyanite-granulites (750° C, 15 kbar). The pressure/temperature estimates presented here suggest that these HP granulites crystallized under a perturbed paleogeothermal gradient of about 13° C/km related to a west-dipping subduction zone underneath postulated oceanic lithosphere. Such paleogeotherm is indeed incompatible with metamorphic conditions in the overlying SGN that represents the possible roots of a continental arc and in which the different metamorphic facies at its top relate to a perturbed paleogeothermal gradient of about 50° C/km. Within the lower part of this upper nappe, maximum temperatures around 900-950° C were reached regionally during the intrusion of charnockitic-mangeritic magmas at 630-625 Ma.

The proposed subduction/collision scenario (Fig. 3-10) envisages the west dipping subduction of continental derived units underneath oceanic lithosphere. After complete resorbtion of the oceanic domain, collision with a magmatic arc related to the Rio de la

Plata craton produced the main crustal thickening. Exhumation of the deeply subducted units occurred then through the mechanism of low-angle, E-directed extrusions. At least 200 km of eastward displacement of the nappes took place along the southern margin of the SFC, an even greater displacement being likely if the HP-metapelite Airuoca/Andrelândia lower temperature nappes (Fig. 3-2) with eclogites are also taken into account. These new results suggest the Himalayan size and character of the Neoproterozoic nappe system of southeastern Brazil.

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CAPÍTULO 4

OROGENIC SYSTEMS FROM SW-GONDWANA: AN APPROACH TO BRASILIANO-PAN AFRICAN CYCLE AND OROGENIC COLLAGE IN SE-BRAZIL

Abstract

The Goianides Ocean was the product of the Tonian taphrogeny acting in the western portion of the São Francisco plate that resulted in the Rodinia Supercontinent break-up. Within this context the intraoceanic juvenile arc-crust accretion (0.90-0.85 Ga) triggered the orogenic collage toward the Gondwana Supercontinent. More evolved subduction-controlled magmatic arcs were generated driving the kinematics of plate convergence up to Rio de la Plata, São Francisco, continent overriding-type collision at 0.63 Ga. The Tocantins orogenic system (product of that Goianides Ocean closure) have involved deep reworking of old continental crust, high-pressure east-direct overthrusting with crustal thickening and indentation processes, having as modern analogues the India-Asia collision. At 0.6 Ga mostly of the orogens were exhumated.

Opposite to that, the Adamastor Ocean resulted from the Cryogenian taphrogeny and global Rodinia break-up. This ocean was populated by several microplates, which had diachronically collided against the just-assembled São Francisco-Rio de la Plata plate in a Cordilleran-style tectonics. These processes are related to the building of the Mantiqueira branching system of orogens, that displays early intra-oceanic juvenile accretionary components and yields average ages for the orogenic events between 0.61 and 0.54 Ga, up to the final oceanic lithosphere consumption at 0.52 Ga.

4-1. Introduction

The geological evolution toward the agglutination of the Gondwana supercontinent started immediately after the Grenvillian orogenies that built the predecessor Rodinia supercontinent. Since the beginning of the Neoproterozoic break-up and drift controlled by taphrogeny has driven plate kinematics toward orogenic interactions. These processes reache the Lower Ordovician and operated for at least 500 Ma, following all the steps of J.T. Wilson's tectonic cycle. An interesting characteristic of these orogenies is the diachronism of events, many of them coeval with taphrogenic processes elsewhere. Many orogenies were controlled by different kinds of plate interaction occurring diachronically at different places. These plurality of processes that converged to the closure of a wide oceanic space populated by small continental fragments (terranes or microplates) may be described by means of orogenic systems or branching systems of orogens, rather than the general and geometry-related mobile belt model. The collection of orogenic systems leading to supercontinent amalgamation represents the "orogenic collage" (Sengor, 1990).

The advance of geochronological knowledge in the SE-Brazil in the last decade, mostly due to U-Pb and Sm-Nd robustly constrained data, helped identify the concurrent metamorphic and plutonic events. The isotopic work revealed major lithospherical mantle accretionary processes and also the contrasting lithospheric signatures between terranes have shown powerful tectonic tools.

Two major orogenic systems could be described in Southeast Brazil. The Tocantins orogenic system was the former and it was related to the closure processes of a Tonian ocean located west of the São Francisco plate, the Goianides Ocean. It comprises several orogens, which have been collectively described as Brasília belt (Fuck et al., 1993) and Alto Rio Grande belt (Hasui, 1982). The global break-up of Rodinia, rifting apart its descendants, took place in the Middle Cryogenian. It accounts for the separation of East-Gondwana from Laurentia (Park, 1994) and the generation of the Adamastor Ocean (Hartnady et al., 1985), facing the Congo, Kalahari and São Francisco plates. The main plate convergence processes controlled several collisions and terrane dockage leading to the southeastward growing of the Brazilian continental crust. These processes were collectively related to the Mantiqueira orogenic system. It comprises the northern Ribeira belt (Almeida et al., 1973) and the southern Dom Feliciano belt (Fragoso-Cesar, 1980). The proposed Tocantins and Mantiqueira orogenic systems were taken from Almeida et al.'s (1981) structural provinces.

The evolution of different types of rifts and related passive continental margins and the role played by their final geometry within a plate kinematics scenario may be explained using Lister et al.'s (1986) model.

4-2. Major continental plates framework

The main geotectonic provinces, with special regard to the Precambrian of the South American Platform (the cratonic area for the Andean orogenic episodes) are shown in Fig. 4-1. These provinces are related to the huge continental lithospheric plates (Brito Neves and Cordani, 1991, Brito Neves et al., 1999), that were rifted apart during the break-up of Rodinia at the beginning of the Neoproterozoic (Dalziel, 1997, Weil et al., 1998). The further amalgamation of these old shields to form the Gondwana supercontinent is recorded by successive collision and plate indentation processes during the global Brasiliano-Pan African orogenies.

The Amazonas plate records roughly NW-trending belts, which are successively younger southwestward and added to an Archaean northeastern province (Tassinari et al., 1996). They comprise Paleoproterozoic belts from the Transamazonian cycle (ca. 2.2-1.8 Ga), which are followed by Statherian magmatic arc, and by the southern Mesoproterozoic collision of the Pampia terrane. A wide settlement of the Grenville province exceed the Neoproterozoic limits of the Amazonas plate, if one takes into account the further rifting apart of the Arequipa-Antofalla terrane and the Eastern Laurentia plate (Ramos and Vujovich, 1995, Bettencourt et al., 1996, Balburg and Hervé, 1997).

The Rio de la Plata plate is almost recovered by the Palaeozoic Paraná basin. Its southeastern edge, chiefly its outcropping domain, comprises a cratonic granite-greenstone province, ca. 2.0 Ga old, crosscut by undeformed mafic dyke swarm of ca. 1.8 Ga. A reworked gneiss-granulitic border is admitted. The Rio Apa granite-gneisses seem to belong to this plate, emerging from the Phanerozoic Paraná basin as a small Paleoproterozoic block. The old rocks of the Rio de la Plata plate first recognised by deep drilling (Cordani et al., 1984) were revealed, as a whole, by geophysical research, such as gravimetry (Mantovani and Shukowsky, 1996), and thermal constraining for P and S-wave velocity perturbations (VanDecar et al., 1995).The paleomagnetic data at the end of the Paleoproterozoic postulate a Laurentia conection of this major continental plate segment (Agrella Filho and Pacca, 1999).

The horse head-shaped São Francisco plate, which represents the northeastern extension of the Congo plate, has been defined since Almeida (1977) and Alkimim et al. (1993).

The remnants of oceanic plate segments between these blocks are still to be recognized.

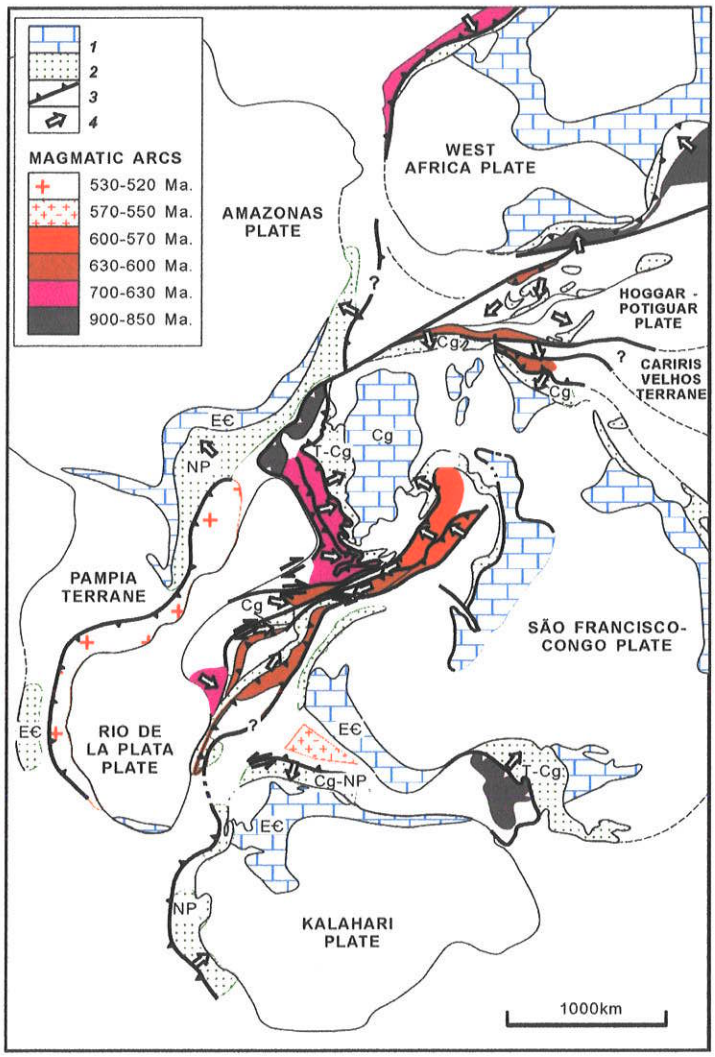

Figure 4-1: Western Gondwana continental plates and magmatic arcs
1. Platform covers, 2. Passive continental margin deposits or thinner continental crust, 3. Subduction zones with sense of dip, 4. Structural vergence.

4-2.1. Statherian taphrogeny: attempts to break-up of the São Francisco plate

Major and widespread upper Rhyacian (ca. 2.1Ga) orogenic collage accompanied by juvenile accretion and rework of the oldest Archaen crust (Teixeira et al., 1998) consolidated the proto-São Francisco plate. After these dramatic plate convergence processes localised zones of intense intraplate extension were collectively integrated in a broad taphrogeny. Failed rifts were responsible for the developement of the major NS-elongated Espinhaço basin and the western Araí basin (Fig. 4-2). Rhyolitic rocks occur at

the basal depositional sequences of both basins coeval with off-basin, small tin-bearing granites. These continental, anorogenic volcanic and plutonic suites yield a Statherian age (1.77-1.60 Ga, Brito Neves et al., 1979, Turpin et al., 1988, Machado et al., 1989, Pimentel et al., 1991). The sedimentary sequence (ca. 1,200m thick) of siliciclastic continent-dominated rocks (conglomerates, coarse-grained quartzite and siltstones) constitute the depositional systems of the pre-rift and rift stages. The upper units of the Espinhaço Supergroup represent a seaward connection (wave-ripple quartzite interlayer with shale and few carbonates) covering unconformably the adjacent non-stretched Archaean basement. They were related to a crust downwarping stage of the thermal-flexural type which controlled the change in subsidence regimes without breaking-up the São Francisco plate interior (Dominguez, 1993, Martins-Neto, 1998).

Tabular bodies (up to 110 m thick) of a sub-alkaline to alkaline suite of (Fe-hastingsite and Fe-salite) magnetite-bearing granite, related to anorogenic, extensional tectonic regime occur at the south edge of the São Francisco plate (Taguar granite), yielding an Ectasian age (Rb-Sr isochron of 1.4 Ga, $Sr^{87}/Sr^{86}_{(0)}$=0.719, Vasconcellos, 1988). Thus magmatic records of another extensional tectonics during the Ectasian followed the Statherian taphrogeny. However no evidence of an orogen had been registered since the end of the Rhyacian System until the Neoproterozoic in the São Francisco plate.

4-3. Fragments of the Rodinia history

4-3.1. Central Goiás terrane

The western edge of the São Francisco plate is bound by a N.NE-trending belt comprising an Archaean-Proterozoic continental remnant of an older plate against which the Neoproterozoic Mara Rosa island arc docked (see later). This fragment comprises Paleoproterozoic basic-ultrabasic complexes and Paleoproterozoic and Mesoproterozoic vulcanosedimentary sequences (Fig. 4-2).

The Archaean fragment comprises a typical granite-greenstone belt terrain. The metasediments are carbonaceous schist and metarhythmites from turbidite depositional environment. The metavolcanics consist of lower komatiite flows and upper intercalated mafic and felsic flows. The metaplutonic rocks are mainly tonalites and granodiorites (Rivalenti et al., 1989, Jost et al., 1996). Dome-and-keel is the structural framework and the interference geometry was produced by successive episodes of plutonism between 2.85 to 2.70 Ga (Queiroz et al., 1999) coeval with the komatiite lava flows (Arndt et al., 1989). The metamorphic recrystallisation quickly followed magmatism (2.7 Ga) and it was reprinted by the Rhyacian orogeny (2.14 Ga, Queiroz et al., 1999).

Over a narrow mylonitic granite-gneissic belt layered and stratiform mafic-ultramafic complexes (Barro Alto, Niquelândia and Cana Brava) occur discontinuously for 300-km (Danni et al., 1982). Gabbros, melagabbronorites, peridotites, pyroxenites, anorthosites and late diorites are the main rock types of these complexes. They show petrologic gradation from a less differentiated base (pyroxene and olivine cumulates) toward plagioclase cumulates in a more differentiated top. Interlayers of high-degree metamorphic metasediments can be found as well as xenoliths in the mafic rocks. The available data suggest an anorogenic extensional environment for these intrusions (Girardi, et al., 1986, Ferreira Filho et al., 1992) that was rifted apart from an uncertain continental plate. Well constrained U-Pb (SHRIMP) from Niquelândia (Correia et al., 1996) and a Sm-

Nd isochron from Cana-Brava (Fugi, 1989) pointed the emplacement of these complexes at the Rhyacian/Orosirian boundary (2.0 Ga). The quartz-dioritic intrusion at the basal layer of Barro Alto complex yields U-Pb zircon age of 1.7 Ga (Suita et al., 1996).

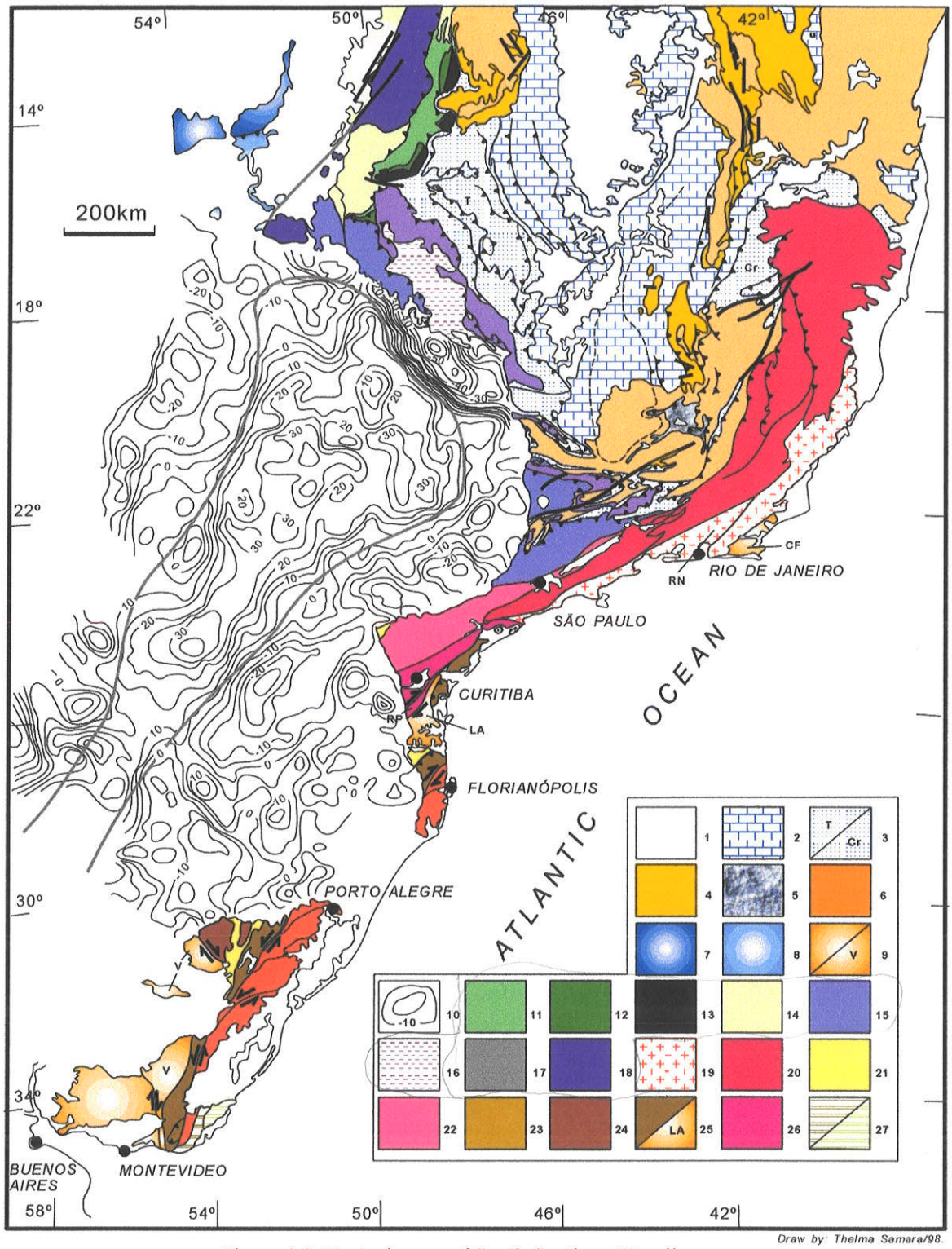

Figure 4-2: Tectonic map of South-Southeast Brazil

1. Phanerozoic covers. **São Francisco plate**: 2. Cryogenian/Neoproterozoic III platform cover of the cratonic domain (Bambuí Group and correlates), 3. Tonian(T)/Cryogenian(Cr) passive continental margin sequences with remnants of oceanic crust (western Paranoá, Canastra and Carrancas Groups, and eastern Macaúbas Group, Salinas and Ribeirão da Fôlha Formations), 4. Statherian rift-related sequences (eastern Espinhaço Supergroup, western Araí Group and southern São João del Rei Group). Archaean/Paleoproterozoic: 5. Minas and Rio das Velhas Groups, 6. Granite-gneiss basement. **Amazonas plate**: Neoproterozoic III/Cambrian: 7. Platform cover of cratonic domain, 8. Varengian rift-drift sequences. **Rio de la Plata plate**: 9. Paleoproterozoic granite-gneissic cratonic area and granulite-gneiss reworked Valentines terrain (V), 10. Gravimetric record of the basement of the Paraná basin. The gravimetric higher is related to the Rio de la Plata cratonic area. **Central Goiás terrane**: 11. Metasedimentary sequence, 12. Ectasian metavolcanosedimentary sequence displaying rift-to-drift assemblages (Juscelândia, Indaianópolis and Palmeirópolis sequences, including the southernmost Statherian? calc-alkaline related Mossâmedes metavolcanosedimentary sequence), 13. Rhyacian/Orosirian stratiform mafic-ultramafic complexes (Barro Alto, Niquelândia and Cana Brava), 14. Archaean/Paleoproterozoic granite-greenstone belt terrain. **Tocantins orogenic system**: 15. Cryogenian/Neoproterozoic III magmatic arc (Socorro-Guaxupé terrane, including Iporá-Jaupaci area), 16. Cryogenian back-arc related metasedimentary sequence with oceanic crust remnants, 17. Anápolis-Andrelândia terrane (volcano-plutonic arc and related metasedimentary sequence of Araxá Group, Aiuruóca-Andrelândia and Três Pontas-Varginha nappes), 18. Mara Rosa terrane (juvenile island arc crust). **Mantiqueira orogenic system**: 19. Neoproterozoic III/Cambrian Serra do Mar terrane (microplate with Rio Negro – RN, ca. 0.63-0.61 Ga, and Rio Doce – RD, ca. 0.58-0.56 Ga magmatic arcs), 20. Juiz de Fora terrane (Paleoproterozoic crust and Neoproterozoic arc-related metasediments of Embú and Paraíba do Sul complexes) as a microplate setting for (ca. 0.595-580 Ga) Galiléia Magmatic Arc, 21. Foreland basin (ca. 0.60-0.56 Ga Itajaí, Camaquã and Arroyo del Soldado Groups), 22. Apiaí terrane (Ectasian? Passive continental margin as a basement of a ca. 0.61 Ga plutonic magmatic arc (Cunhaporanga, Três Córregos and Agudos Grandes batholiths), 23. Pelotas terrane (ca. 0.62-0.61 Ga plutonic magmatic arc), 24. São Gabriel terrane (upper Cryogenian island arc), 25. Luis Alves terrane comprising the Tijucas belt (rift-to-drift Mesoproterozoic? metavolcanosedimentary sequences: Brusque and Porongos Groups) and the Archaean/Paleoproterozoic Santa Catarina granulitic complex, 26. Curitiba terrane (Paleoproterozoic gneisses and granulites) as a basement of the Rio Pien plutonic magmatic arc (0.615 Ga), 27. Grenvillian-Kibaran migmatites with western Neoproterozoic metasediments of Rojas Group, 28. Cabo Frio terrane.

At the SE extremity of the Archaean fragment, a narrow metavolcanosedimentary belt crops out (the Mossâmedes sequence) and was described by Simões and Fuck (1984). It comprises few metabasalts of low-K tholeiitic affinity followed by a calc-alkaline suite of basic/intermediate and felsic metavolcanic rocks interlain with metatuffs, metacherts and pelitic schist, being in agreement with an active volcanic arc setting (Barbosa and Jost, 1990). The Rb-Sr misgiving ages of this plate convergence felsic volcanism to come across the Paleoproterozoic Orosirian and fini-Statherian with Sm-Nd T_{DM} of ca. 2.2 Ga (Pimentel et al., 1996).

Another metavolcanosedimentary sequence occurs discontinuously as an allochthon over the mafic-ultramafic complexes (Fig. 4-2). These sequences (Juscelândia, Indaianópolis and Palmeirópolis, Marini et al., 1984) are related to a bimodal, continental-type sub-alkaline tholeitic basalt volcanism, and rhyolitic rocks derived from crustal-mantle mixing felsic magma. The uppermost volcanic layer represents basic rocks from N-MORB type basalt (Moraes et al., 1998) ascribing a rift-drift evolution, whose age unfortunately remains unknown. However these rocks were metamorphosed to the upper amphibolitic facies that is coeval with the granulitic facies metamorphism of the mafic-ultramaphic complexes (Moraes and Fuck, 1994, Ferreira Filho et al., 1998). The age of this metamorphic process, first related to the Mesoproterozoic Ectasian by Rb-Sr isochrons (Fuck et al., 1989), has been object of research and interpretation using U-Pb zircon records. Neoproterozoic Cryogenian age have been obtained (Ferreira Filho et al., 1994, Suita et al., 1994), but the SHRIMP data corroborated the Ectasian (1.3 Ga) age (Correia et al., 1999).

Neither of these processes is recorded out of this narrow domain suggest they do not belong to the São Francisco plate. Proterozoic mobile belts formed from 1.95 to 1.0 Ga surround the Archaean cratons of Laurentia and Baltica. In opposition to the São Francisco plate, Paleo-Mesoproterozoic tectonic evolution of the south Amazonas plate (Rio Negro-Juruena Province and Rondonia-San Ignácio Province, Teixeira et al., 1989) show successive accretion of juvenile, volcano-plutonic arc crusts. High-grade metamorphism with a mean U-Pb SHRIMP age at 1.33 Ga (Tassinari et al., 1999) precedes the Grenvillian (1.25-0.9 Ga) Sunsas orogeny. Slightly after all these orogenic events the rapakivi granite

genesis either in Rio Negro-Juruena Province, or in Rondonia-San Ignácio Province took place as an extensional, anorogenic episodes (Bettencourt et al., 1999). Therefore, the correlation between eastern Laurentia and western Amazonas plates (Sadowski and Bettencourt, 1996) is well constrained.

Apparently the latest U-Pb records for Barro Alto granulites and Juscelândia gneiss, and the former Rb-Sr and Sm-Nd data from Moçâmedes arc-related rocks strongly suggest that these sequence fit better in the Laurentia-Amazonas plate from Rodinia Mesoproterozoic Supercontinent.

4-3.2. The Apiaí terrane

Other Ectasian metavolcanosedimentary sequences probably belong to the northeastern boundary of the Rio de la Plata plate. They are the Serra do Itaberaba Group, overlain by the São Roque Group (Juliani, 1993) and encompassing volcanic units that record the transition from rifting to oceanic crust formation, and the Perau (Piekarz, 1981) and the Abapã Formations (Reis Neto, 1994), both basal units of the Açungui Supergroup (Campanha and Sadowski, 1999).

The Serra do Itaberaba Group (Fig. 4-3) comprises quartzite rocks from marine coastal margins of a rift environment, which almost encompass two major lithostratigraphic formations (Juliani, 1993, Juliani and Beljavskis, 1995, Juliani et al., 1996). The basal ones consist of metavolcanoclastic rocks, metabasalts and metatuffs, calc-silicate rocks, graphite-bearing schists, iron formations and metavolcanic rocks from intermediate to acid compositions. There occur hydrothermally altered tholeiitic basaltic flows of N-MORB type associated with a deep marine rock assemblage. A transition from tholeiitic to calc-alkaline volcanism is depicted by metandesite, metarhyodacite and metarhyolite magmatism, which seem to record a remote subduction of an oceanic crust. This lithostratigraphic unit is unconformity overlain by Mn-rich and Ca-rich metapelites, metavolcanoclastic rocks, carbonaceous rocks and an upper Al-rich metapelites, with intercalations of few amphibolites, metarhyolites and black, fine-grained tourmaline-bearing rocks. This upper unit that show transition to shallow marine environment may be related to the beginning of the closure of the oceanic basin.

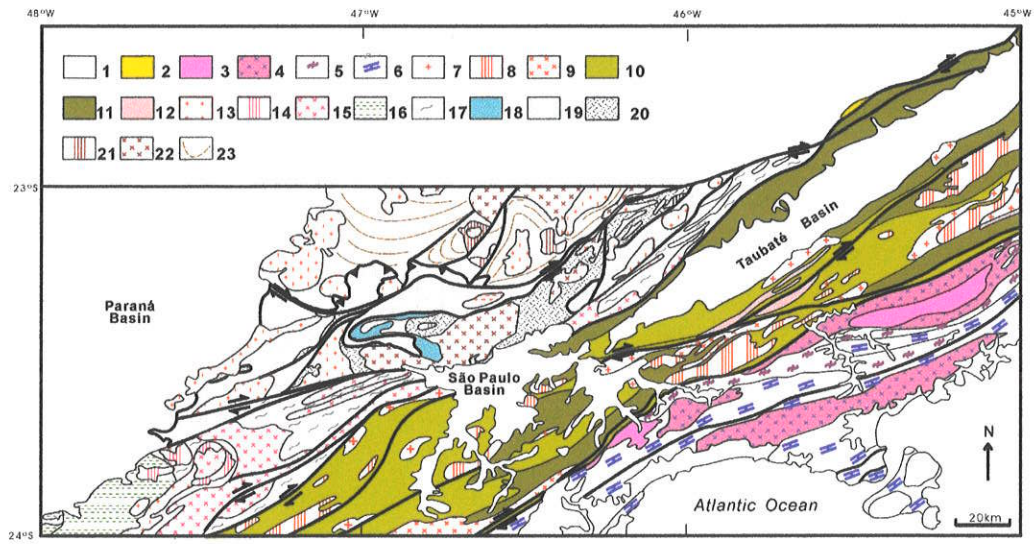

Figure 4-3: Geological Map of the Serra do Itaberaba/São Roque Groups and the Embu Complex

1. Phanerozoic covers. 2. Neoproterozoic III/Cambrian Pico do Itapeva Formation. Serra do Mar terrane: **3. Peraluminous granites (ca. 0,50-0,54 Ga), 4. Metaluminous granitoids and charnockitic suite, 5. Sil-Grt-bearing migmatites with quartzite resisters, 6. Metaluminous migmatites.** Juiz de Fora terrane: **7. Shear zone-related metaluminous granites, 8. Peraluminous granites, 9. Hbl-Bt-bearing granitoids. Embú Complex: 10. Shelf-related quartzites and schist-quartzite rhythmic succession, 11. Metavolcanosedimentary sequence, 12. Archaean-Paleoproterozoic grey gneisses. 13. A-type granites (ca. 0.575-0.580 Ga).** Apiaí terrane: **14. Peraluminous granites (ca. 0.60 Ga), 15. Metaluminous granitoids (ca. 0.61-0.605 Ga), 16. Terrigenous turbidite deposits of Açungui Group, 17. Schists and gneisses. São Roque Group (back-arc basin?): 18. Upper continental and shallow water quartzite, limestone bioherm and metavolcanic rock association, 19. Metarhythmites, quartzites, metalimestones and metabasaltes with pillow-lava structure (ca. 0.61 Ga), 20. Serra do Itaberaba Group (Ectasian).** Socorro-Guaxupé terrane: **21. Peraluminous granites (ca. 0.625 Ga), 22. Hbl-Bt-bearing granitoids (ca. 0.63 Ga), 23. Sil-Grt-bearing migmatites of Piracaia Complex.**

The São Roque Group (Fig. 4-3) is dominated by three major volcanic and depositional sequences (Bergmann, 1988). The first one comprises metavolcanic basic rocks (including tholeiitic basaltic flow with pillow-lavas structures) on a shallow water environment associated with carbonate rocks and stromatolitic bioherm (rising to 800 m thick). They were followed by cyclic, millimetric to metric alternations between metarkose and quartzite (few metaconglomerates) with metapelite (at least 1,000 m thick), having wave ripples and climbing from weak slope bottom surface of a shelf environment. Metacalcareous lenses and thicker quartzitic rock package may occur as a southweastward facies. The upper unit (up to 1,600 m thick) is dominated by a metarkose with cross-stratification and flaser bedding structures. It contains two intercalations of metabasic rocks, the former with pillow-lavas and the latter with vesicular volcanic flows. A well-sorted quartzite from offshore bars compose the upper beds. Although still uncertain, the latest U-Pb data point at a Neoproterozoic III (0.61 Ga) age for the submarine basaltic flow (Hackspacher et al., 1999). As a whole, their volcanic and sedimentary process could be related to a back-arc basin evolution.

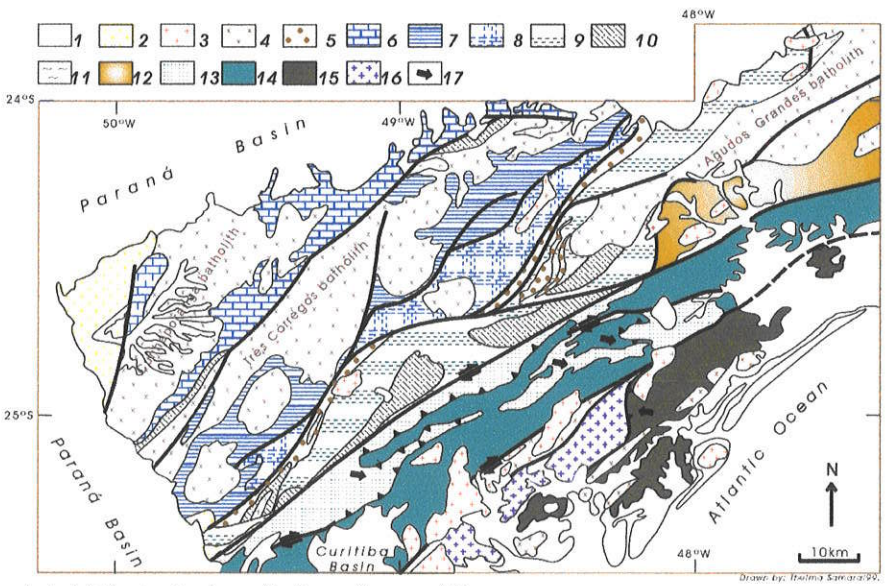

Figure 4-4: Major tectonic units from Açungui Supergroup

1. Phanerozoic covers, 2. Foreland basin (ca. 0.54 Ga), 3. A-type granitoids (ca. 0.59 Ga), 4. Hbl-Bt-bearing porphyritic syn-to-late-orogenic granitoids (ca. 0.615-0.605 Ga). **Apiaí terrane:** 5. Flysch-type deposits (Iporanga Formation), 6. Carbonatic platform (Itaiacóca Group), 7. Distal carbonatic platform (Água Clara Formation), 8. Shelf-break carbonatic ramp (Lageado SubGroup), 9. Deep-water turbidites (Votuverava Formation), 10. Rift-like volcanosedimentary sequence (Ectasian Peraú Formation, and the northern Abapã Formation), 11. Schist and gneiss from unknown environment. **Juiz de Fora terrane**: 12. Schist and gneiss from Embú Complex. **Curitiba terrane**: 13. Carbonatic-psammitic passive continental margin deposits (Cryogenian?, Capirú and Setuva formations), 14. Upper Rhyacian basic-intermediate gneisses. **Luis Alves terrane**: 15. Metasediments from Tijucas belt, 16. Santa Catarina granulite complex (Archaean-Paleoproterozoic). 17. Ca. 0.60 Ga tectonic transport.

The Açungui Supergroup (Campanha and Sadowski, 1999) apparently represents preserved paleogeographic zones of a passive continental margin environment (Fig. 4-4). The main metavolcanosedimentary sequences, which occur as windows below the basal stratigraphic level of the Açungui Supergroup, also have an Ectasian age both on U-Pb zircon and Rb-Sr whole rock isochron (E.Dantas, personal comunication and Daitx, 1996).

The northwestern belt has metasedimentary assemblage from "tropical" shallow shelf environment (up to 5,000 m thick). A pelite-carbonate marine transgression started the depositional sequences (Souza, 1990), interrupted by regression represented by restrict deposits of shelf sands. An upper transgression was related to sub-tidal carbonate platform containing bioherms of cone-shaped stromatolites (Conophyton cf. C. garganicum, Fairchild, 1977). These units, from a drift-type episode, overlap ca. 2,000 m thick rift-type deposits. Deposits that are mainly composed of metarkoses, feldspathic metawackes and metafanglomerates, and contain within-plate, ultrapotassic, alkaline metavolcanic and metavolcanoclastic layers, and flood basalts. The Sm-Nd T_{DM} of these rocks falls in the upper Archaean (ca. 2.5 Ga, Reis Neto, 1994). Southeastward the platform gave rise to the settlement of a deep-water shelf (impure carbonates, banded calcsilicate rocks and metapelites) containing tholeiitic volcanism which grades to shoshonitic metabasalts (Frascá et al., 1990). This paleogeographic zone tops, by southeastward thrust, an uppermost regressive depositional cycle (rising 2,500m thick) of a psamitic-carbonatic epeiric platform that grades to carbonates from ramp-distally steepened setting reached by storm waves (Campos Neto, 1983, Pires, 1991). Stratigraphicaly bellow the transgressive depositional cycle (ca. 1,150 m thick of metasandstones with lenses of oligomictic metaconglomerates up to thinner metarhythmites) is depicted by eastern turbidites from channel-lobe transition that grade to western proximal depositional systems. A wide deep-water basin plain dominated southeastward where large amounts of pelites (slates and phyllites) with thin, fine-grained, metasandstones rhythm enhancing distal turbidity currents.

The stratigraphic floor of the continental rise represents a shallow-water rift-basin environment (quartzite and metalimestones). It grades to a deep-water settlement (graphitic metapelites and metacherts) with remnants of oceanic crust (metabasalts from tholeiitic, sub-alkaline, T-MORB type), and iron-formation associated to high-K quartz-sericitic rocks from volcanic provenance. Isotope chemostratigraphy on Sr, C and O from calcite and baryte minerals, yield Mesoproterozoic marine source (Daitx, 1996).

A narrow belt of metarudites occurs at the boundary between the shelf-ramp carbonates and the deep-water basin. They comprise lenses of polymictic metabreccias and metaconglomerates immersed on metarhythmites (Iporanga Formation). Characteristically these metarudites have angular fragments and rounded pebbles of surrounding host rocks and already deformed phyllites, quartzites and some igneous rocks; they are devoid of limestone pebbles. This means that the Iporanga Formation could represent orogenic controlled deposits as a flysh. The metabasalts, which occur within this formation, have calc-alkaline affinity in agreement with compressive tectonic regimes.

Although the major structural framework had been built during the Neoproterozoic orogeny, the remaining metamorphic mineral assemblage locally showing kyanite ghosts (Juliani, 1993) was almost destroyed by a lower-pressure main foliation, and it was crosscut by the intrusion of the Neoproterozoic synorogenic granitoid batholiths. Among the

majority of such rift-to-drift basins some of volcanic layers depicted the transition to the plate convergent tectonic setting. The calc-alkaline volcanism marks the whole stratigraphic pile, also into the uppermost compressive driven fulfilling basin. Unfortunately the age of this orogenic process remains uncertain. On the other hand the Sm-Nd whole rock isochron for a metadolerite and Pb-Pb isotopic data for carbonate rocks from shallow and deep-water platform settings of the Açungui Supergroup strongly suggest the Stenian-Tonian transition (ca.1.0 Ga) for the first metamorphic recrystallisation (Reis Neto, 1994, Poidevin et al., 1997). Thus a Grenvillian Stenian age should have been a coherent time span for the closure of an Ectasian oceanic crust.

4-4. The São Francisco plate margins: paleotectonic approach

The beginning of the Neoproterozoic is recorded in the São Francisco, Congo and Amazonas plates by a broad extensional tectonic regime related to the Tonian taphrogeny that led to the Rodinia break-up. The paleomagnetic reconstruction of Rodinia (Weil et al., 1998) left a Panthalassan-size ocean in the remaining Earth's surface. The large Arabian-Nubian Ocean (Stern, 1994) in the west of Congo plate and the probable South Pole connection with Pharusian Ocean (Caby, 1994) in the western portion of West Africa plate were some pieces of this jigsaw. The Goianides Ocean resulted from this former Tonian break-up, rifting apart the Amazonas plate from Congo-São Francisco plate (Fig. 4-5), as well as the Rio de la Plata plate from their African counterpart and Laurentia.

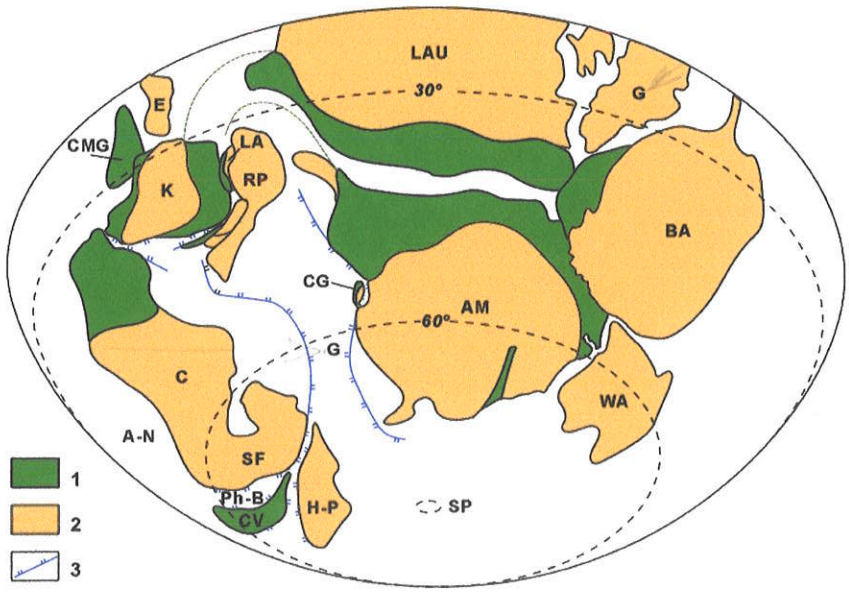

Figure 4-5: A modified view for the Rodinia reconstruction (from Weil et al, 1998).
The shape of Amazonas, São Francisco, Rio de la Plata and Western Africa continental segments of plates is modified. Speculative position of the postulate Hoggar-Potiguar plate and Cariris Velhos terrane. 1. Grenvillian orogens; 2. Continental plate segments; 3. Tonian rift lines. AM - Amazonas, BA - Baltica, C - Congo, CV - Cariris Velhos, CMG - Coates Land-Maudheim-Grune-Hogna Province, E - Ellworth-Withmore Mountain block, G - Greenland, H-P - Hoggar-Potiguar, K - Kalahari, LAU - Laurentia, RP - Rio de la Plata, WA - Western Africa. AN - Arabian-Nubian Ocean, CG - Central Goiás terrane, CV - Cariris Velhos terrane, G - Goianides Ocean, LA - Luis Alves terrane, PhB - Pharusian-Borborema Ocean, SP - South Pole.

Extensional regimes (1.1-0.97 Ga) immediately followed the vanishing of the Grenville orogeny in the Amazonas plate, as well as in the Cariris Velhos terrane (Brito Neves et al., 1995) farther to the north of the São Francisco plate. Southeast of the Amazonas plate the records of this taphrogenic episode are the Santa Clara rapakivi granitic suite and the subalkaline and alkaline suites of the Younger Granites of Rondonia. They are coeval with the eruption of alkaline basaltic flows and the deposition of intracontinental rift sedimentary sequence. These anorogenic rock assemblages yield a zircon age between ca. 0.11 and 0.98 Ga (Bettencourt et al., 1999). At this time, the northern portion of the Congo plate was also subjected to dramatic extension episode leading to the opening of the Zambezi Ocean (Wilson et al., 1993). The Rio de la Plata continent may have been rifted apart from the western Kalahari taking part in a northeastward drift. The small fragment of the Central Goiás terrane containing Mesoproterozoic rocks over an Archaean-Paleoproterozoic framework could have been separated from Amazonas plate.

In the São Francisco plate interior taphrogeny-related magmatism occurs as within-plate microgabbro dyke swarms of tholeiitic and subalkaline affinities (Dossin et al., 1993), yielding a zircon age of ca. 905 Ma (Machado et al., 1989). Although geochronological data are not available, the rift-drift psamitic-dominated megasequence was established at the western (the Paranoá and Canastra Groups) and southwestern (Carrancas Group) extensional margins of the São Francisco plate. They seem to be related to this Tonian taphrogeny. The Paranoá Group is a ca. 1,600m thick megasequence limited by major unconformities. Its basal rudaceous layers locally overlies the Statherian Araí Group, whereas its uppermost erosive boundary is overlain either by the Sturtian-age diamictites (Jequitaí Formation) or by post-Sturtian (Upper Cryogenian) carbonates of the Bambuí Group. The depositional megacycles of the Paranoá Group (Faria, 1995), represent a marine sucession of an internal N.NW-elongated rift valley domain separated from the western shelf-break by paleogeographic ridges like a marginal plateau. Carbonatic rock interlayers, at least ca. 200m thick, occur at the upper transgressive unit, and grades outward to thick bioherm buildings. The bioherms occur on the ridges at the NW and SW edges of the basin, as reef lines containing weakly branching, cylindrical and large columnar stromatolites (up to 2.5 m of vertical column) of Conophyton-type (Cloud and Dardenne, 1973) developed in a subtidal environment. These carbonatic-dominated sequences, which build a local barrier up to 2,000m thick (south of Vazante Formation, Dardenne, 1981) may be related to strong subsidence due to rift-drift transition. Westward the uppermost lithostratigraphical units of the quartzitic nappe of Canastra Group is made up by pelitic-psamitic rhythmic and graphytic-bearing pelites (Campos Neto, 1984). They were intensively engraved by paraconglomerate channel deposits followed by thin sequences of pelitic-psamitic meta-rhythmites and carbonate-bearing phyllites (Ibiá Formation, Barbosa et al., 1970), like a turbiditic depositional system. Moreover this upper terrigenous sequence show a bimodal sedimentary source, either from the shelf deposits or the internal nappes, as well as bimodal Sm-Nd signature (Fischel et al., 1999, Pimentel et al., 1999). It may be placed on an inherited upper continental rise settlement, representing flysch-type deposits related to the arrival of the orogen (accretionary thrust wedge). Discret diamictite deposits correlated with the Sturtian glaciation (Middle Cryogenian, Hoffman et al., 1998) overlie the passive continental margin sequence and were covered by an extensive carbonatic cap under a shelf platform environment (the Bambuí Group) throughout the São Francisco plate interior.

On the whole (Fig. 4-6) this assemblage represented a large "lower-plate"-type passive continental margin.

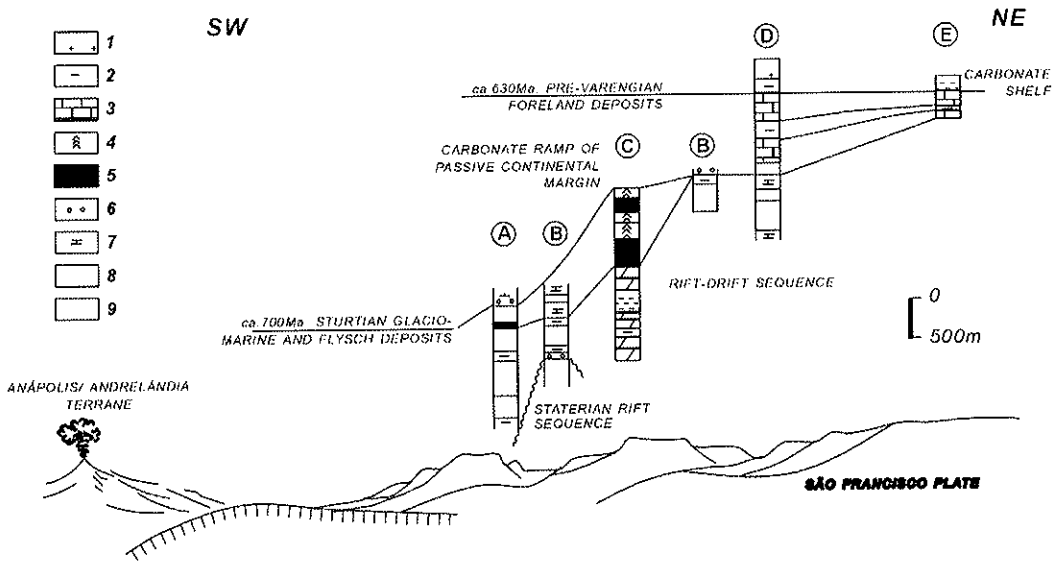

Figure 4-6: Stratigraphic and paleogeographic section through the western passive continental margin of the São Francisco plate.

1. Immature psammite and pelite, 2. Pelite, 3. Carbonates, 4. Stromatolite bioherms, 5. Graphite-rich layers, 6. Rudite, 7. Pelite and carbonate, 8. Psammite and pelites, 9. Psammite. A. Canastra Gr (Campos Neto, 1984), B. Paranoá Gr (Faria, 1995), C. Vazante Fm (Dardenne, 1981), D. Paranoá and Bambuí Grs (Dardenne, 1981), E. Bambuí Gr (Dardenne, 1981).

The pelitic micaschists and quartzites from the western upper nappes (Fig. 4-2) were intruded by small serpentinite bodies associated with podiform chromites and amphibolites, which were described as tectonically dismembered fragments of an oceanic crust, the Abadiânia-type ophiolite mélange (Strieder and Nilson 1992). Other small belts of metavolcanics have typical signatures of ocean floor basalts (Brod et al.. 1991, Seer 1999), and display a Tonian Sm-Nd whole rock isochronic age with ε_{Nd}=+5.3 (Fischel et al., 1999). Overall they form ca. 200km-long occurences of remnants of depleted mantle-derived oceanic crust.

Opposite to that, at the northeastern margin of the São Francisco plate the Sturtian age glacial deposits recorded the beginning of the passive continental margin. Up to 100m thick of massive diamictites (with some remains of tillites on striated pavements, Rocha-Campos and Hasui, 1981) from glacio-marine origin (Jequitaí Formation) grades eastward toward the basin. The basinal deposits represent up to 10km-thick glacial rocks reworked by subaqueous debris flows and turbidity currents (Macaúbas Group) that reach the deep-sea continental rise (Marshak and Alkmim, 1981, Uhlein et al., 1998). The eastern assemblage is the witness of the continental break-up. It corresponds to metamorphosed volcanic-exhalative sediments with related amphibolites, which are derived from oceanic floor basalts yielding a Middle Cryogenian age (Pedrosa-Soares et al., 1992). The shallow-water carbonates and shales of the Bambuí Group, are the thin (up to 400m thick) platform units that recovered the Jequitaí diamictites (Fig. 4-2).

An "upper-plate"-type margin seems to dominate the eastern São Francisco plate. It was characterised by a narrow continental shelf, partially represented by N-S transpression sliver of metapsammitic and metapelitic rocks (Dom Silvério Group), and by broad

occurrences of metabasic and metavolcanosedimentary sequences. The tectonic provenance of this metamorphosed basic and volcanic assemblage is still unknown, but it seems that they record a Neoproterozoic extensive episode constrained by Sm-Nd data (Pimentel et al., 1998). They were tectonically imbricated with the grey gneisses of the Paleoproterozoic Mantiqueira Complex (Figueiredo and Teixeira, 1996).

Then the occidental and oriental passive continental margins of the São Francisco plate edges were developed diachronically and display asymmetrical shape (Fig. 4-7). The basal sedimentary layer of the narrow oriental margin (the Sturtian diamictites) correlates with the uppermost stratigraphic level of the wide occidental passive continental margin.

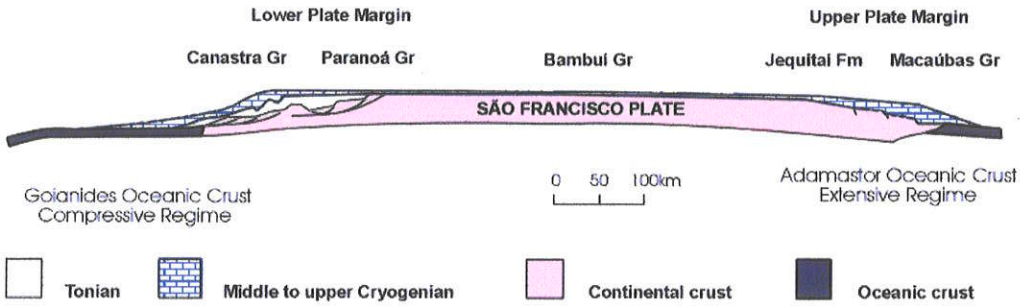

Figure 4-7: Scketche of E-W paleogeographic section through the western to eastern passive continental margins of the São Francisco Plate at ca. 700 Ma.

4-5. The Tocantins orogenic system

4-5.1. Orogens' outline

The Tocantins orogenic system is related to the closure of the Goianides Ocean. It is a long-lived (270 Ma) plate convergence motion presupposing a large oceanic basin. The plate convergence process led to magmatic arc accretion and dockage from the Upper Tonian up to the beginning of the Neoproterozoic III when the main collision of the Central Goiás terrane and Rio de la Plata plate against the western São Francisco plate took place.

The Goianides Ocean encompasses many terranes. The ancient Central Goiás terrane is a drift fragment related to the Tonian taphrogeny. The other ones are mainly orogenic terranes related to a set of subduction zones (Fig. 4-8). The main compression kinematics of oceanic plate is related to west-dipping subduction zones. This kinematics framework is constrained by geologic and geophysic records. The first one is related either to the anatomy of a "lower plate"-type passive continental margin, or the collision-related east-driven extrusion of the high-pressure nappes. The geophysic records ascribe a west-dipping gravimetric model for the linear negative anomaly related to the suture zone (Marangoni, 1994), and the direct record of seismic P-wave and S-wave velocity perturbation models (Vandecar et al., 1995). This one displays large west-dipping low-velocity anomalies (for the P-wave) extending at least to 500-600 km depth. It is interpreted as inherited thermal and chemical remnant of the original mantle-plume formed during the main metamorphic-collisional event, by coupling of the whole upper mantle and the lithospheric plate (Fig. 4-9). Fossil S-wave mantle anisotropy with the fast-polarisation directions trend WNW-ESSE could be correlated to the ancient, Neoproterozoic, plate motion (James and Assumpção, 1996).

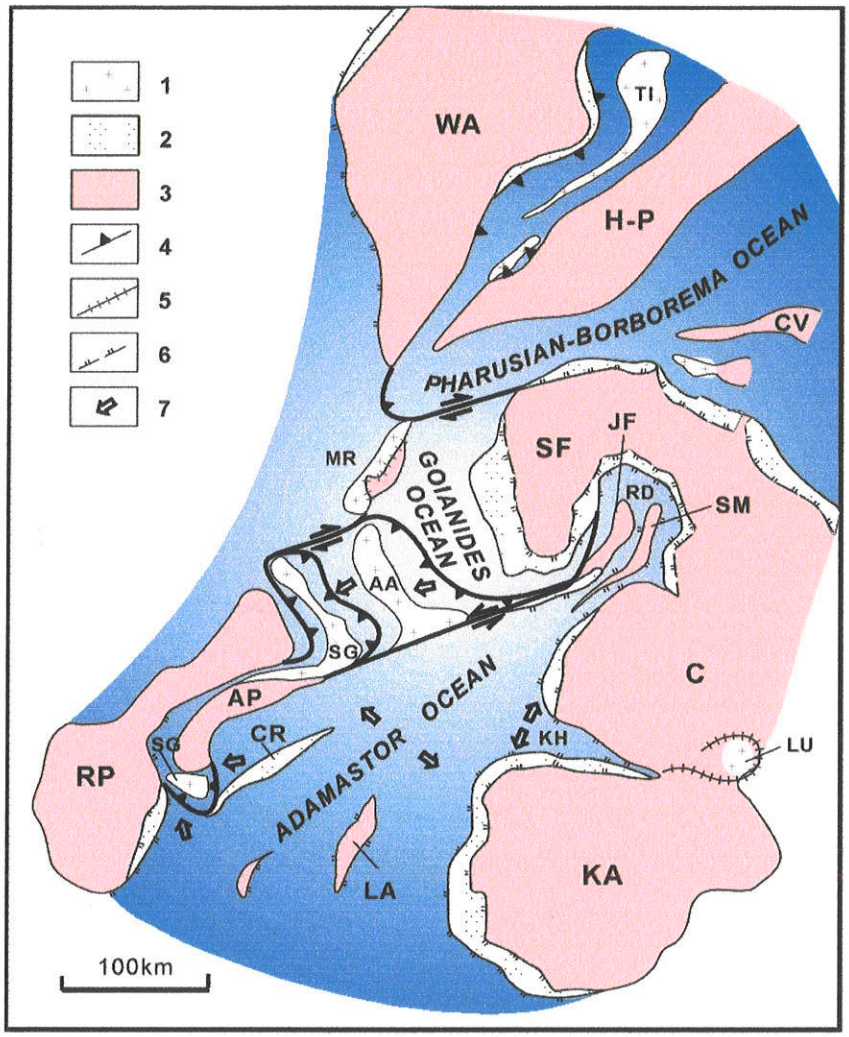

Figure 4-8: Attempt view of the lost oceans: ca. 750-700 Ma paleogeographic outline.
1. Tonian/Cryogenian magmatic arcs, 2. Passive continental margin deposits and thinner continental crust domains, 3. Mesoproterozoic belts, 4. Continental plates segments, 5. Subduction zone with sense of dip, 6. Cryogenian sutures, 7. Ancient rift lines. AA - Anápolis-Andrelândia, AP - Apiaí, C - Congo, CG - Central Goiás, CR - Curitiba, CV - Cariris Velhos, H-P - Hoggar-Potiguar, JF - Juiz de Fora, KA - Kalahari, KH - Khomas gulf, LA - Luiz Alves, LU - Lufilian, MR - Mara Rosa, RD - Rio Doce gulf, RP - Rio de la Plata, SG - Socorro-Guaxupé, SF - São Francisco, SG – São Gabriel, SM - Serra do Mar, TI - Tilemsi, WA - Western Africa.

The Upper Tonian Orogeny (0.90-0.85 Ga). It was the first subduction-related orogen recorded by the accretion of the intraoceanic Mara Rosa island arc. They are juvenile calc-alkaline volcanic belts and mantle derived metatonalites from the Arenópolis and Mara Rosa regions (Pimentel et al., 1992, 1997). Although have not supported, Pimentel et al. (1999) proposed an east-dipping subduction zone for the generation of this arc. The Lufilian arc elsewhere, in the Zambezi domain, was slightly coeval (Porada, 1989).

The Lower to Middle Cryogenian Orogeny. Two kinds of orogens seem to be related to this orogenic time. The first one is related to the dockage of the Mara Rosa arc whereas the other is related to a wide arc generation.

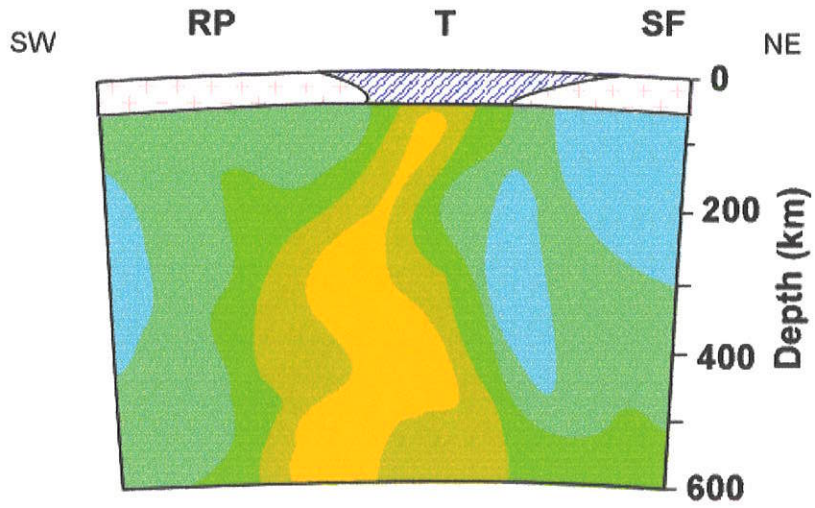

Figure 4-9: Cross-section through the P-wave velocity perturbation models. Modified from Vandecar et al (1995) with continental crust interpretation.
The low-velocity anomalies (clear grey tonalities) grade to the high-velocity anomalies (dark grey tonalities).
RP: Rio de la Plata plate, T: Tocantins orogenic system, SF: São Francisco plate.

An asymmetric subduction controlled non-continental-override-type collisional orogen could explain the dockage of the Mara Rosa island-arc on the non-destructive western edge of the Central Goiás fragment. A collection of U-Pb, Sm-Nd and Re-Os isotopic data obtained for the Central Goiás and in the Mara Rosa metasediments (Ferreira-Filho et al., 1994, Correia et al., 1996, Suita et al., 1996, Pimentel et al., 1998) support an age of 770-800 Ma for the metamorphic process. These values are not recorded in the metamorphic rocks from the passive continental margin setting. This metamorphism is mainly described as of low to medium pressure, high temperature type, interpretatively related to the lateral dockage of the hot arc crust. In spite of the poorly constrained data about the kinematics that controlled the main metamorphic structure, a dextral lateral motion is proposed based on near N-S trending mineral and stretching lineations and shear-sense indicators (Fonseca, 1996).

Two sets of arc-derived rocks dominant further south of the Mara Rosa Arc are separated by the remnants of oceanic crust in a discontinuous NW-oriented belt for at least 140-km long at Hidrolina-Morrinhos area (Fig. 4-2 and Fig. 4-8).

The western arc assemblage comprises the calc-alkaline plutonic-volcanic rocks of the Iporá-Jaupaci area (Pimentel et al., 1992), correlated by means of a NW-oriented belt (partially recovered by the Paraná Basin units) with the southernmost Socorro-Guaxupé terrane (Campos Neto and Figueiredo, 1995). The Iporá-Jaupaci area is mainly composed of tonalitic-granitic suite associated with metarhyolites both from a juvenile source (ε_{Nd} (T) positive). They are younger (0.76 Ga) and chemically more mature rocks ($K_2O/Na_2O>1.0$) than the Mara Rosa Arc (Pimentel et al., 1992, Rodrigues et al., 1998) indicating a partial intraoceanic setting and the proximity of an older and thin continental crust. The continental arc basement became isotopically recorded further to the south, in the Socorro-Guaxupé terrane (Janasi, 1999).

The eastern arc environment is depicted by the calc-alkaline volcanoclastic and volcanosedimentary derived metagreywackes (see below). Metaluminous to sightly peraluminous granitoids (0.70 to 0.78 Ga) having juvenile magmatic component have been

described in this area (Pimentel et al., 1999a). However a crustal-derived magmatism predominates westward into pelitic and pelitic-carbonaceous schists and quartzites. They are peraluminous granites and sub-volcanic felsites (0.79 Ga) having an older Sm-Nd signature (Pimentel et al., 1992b, 1999a). These contrasted magmatic environments are separated by the tectonic high of the Neoproterozoic III lower crust fragment related to the Anápolis-Itauçu granulite-granite-migmatitic complex. Characteristically the rocks of this arc domain (the Anápolis-Andrelândia terrane) display bimodal peak of Sm-Nd model ages, within the 1.16 up to 1.95 Ga edges (Pimentel et al., 1999b, Janasi, 1999, Campos Neto and Caby, 1999b). It suggests a magmatic component from a juvenile source, and low crustal residence for the immature fan deposits, as well as the local presence of an older crust as magma contaminant or as sedimentary source. The metasedimentary assemblage of the Araxá nappe (Seer et al., 1998) belongs to this tectonic setting. Nevertheless the metapelites, quartzites and few carbonate lenses from Pirinópolis area (Goiás), separated from the Anápolis-Andrelândia terrane by a metamorphic jump and by a line of oceanic crust remnants would be related to the passive continental margin deposits, rather than to the Araxá Group. On the other hand the western peraluminous granites and felsites might have derived from deep crustal fusion related to a strong back-arc stretching (Fig. 4-10-A), prior to the collision episode, as previously proposed (Pimentel et al., 1999a).

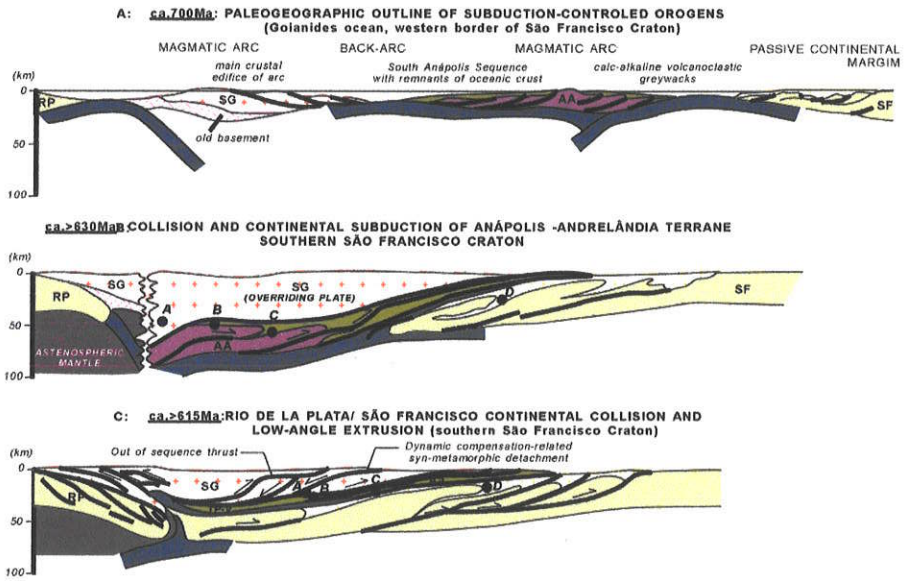

Figure 4-10: Sketchs of plate kinematics evolution of the Southern Tocantins orogenic system

The Neoproterozoic III Orogeny. The roughly northeastward motion of the Rio de la Plata plate, as well as the amalgamated Mara Rosa Arc and Central Goiás terrane, led these continental plate segments to collide against the western passive continental margin of the São Francisco plate. This continental override-type collisional orogen is characterized by strong near-horizontal displacement of nappes transported over the outer domains of the parauthocthonous passive continental margin, up to the autochthonous Bambuí platformal setting. The arc-related upper nappes underwent high-temperature metamorphic conditions override the subducted slabs subjected to high-pressure metamorphism. The shape of the lower-plate type passive continental margin favors the underthrust or continental

subduction of the continental plate subjecting the lower nappes to a medium-pressure metamorphic conditions. Except for the upper nappes, the metamorphism is typicaly reverse into each allochton (Simões, 1995, Campos Neto and Caby, 1999a). The collisional arcuate shape of the terranes, convex toward the passive continental margin (Fig.4-2), may be explained by an edentor action related to the original shape of the western São Francisco plate (Fig.4-8). This edentate process may have controlled the oblique, sinistral convergence in the generation of the spoon-like flat geometry of E-SE-displaced Araxá and Passos nappes (Fig. 4-2) associated with internal a-type, NE-verging, reverse folding (Seer et al., 1998, Valeriano et al., 1998). Collision-related peripheral foreland basin adjoins the stable edge of the continental subducted margin (the Três Marias Formation).

The internal terranes of the Tocantins orogenic system yield robust U-Pb or Sm-Nd ages at ca. 625±5 Ma related to the main metamorphic recrystallization and related to the emplacement of the synorogenic subduction-related porhyritic granitoids batholiths (Töpfner, 1996, Pimentel et al., 1999a, Campos Neto and Caby, 1999a, Fischel et al., 1999, Tassinari et al., 1999). The outward propagation of the orogen wedge and the out-of-sequence thrust sheets rise to 610 Ma (Janasi, 1999) up to their flat and ruptil emplacement over the authocthonous plataform units at ca. 600 Ma (Valeriano, 1992).

4-5.2. The Southern Tocantins orogenic system

The southernmost portion of the Tocantins Orogenic system (Fig. 4-11) comprises a flat-lying package of east-northeastward-displaced nappes. They represent a diachronic thick-skinned and frontal growing nappe system that underwent a minimum of 300 km of magnitude of aggregate displacement, accounting for deeper crustal levels progressively exposed in the western allochthons. The uppermost tectonic unit derived from the magmatic arc (Socorro-Guaxupé terrane) displays high-pressure and high-temperature basal granulites. High-pressure terranes are underlain: the Ky-granulite from the Três Pontas-Varginha nappe, and the metapelite-metagreywacke with few eclogite relicts that form the Carmo da Cachoeira and Aiuruoca-Andrelândia nappes. The lower allochthonous units are made of medium-pressure metamorphic sequence associated with polymetamorphic orthogneisses (Luminárias-Carrancas and Lima Duarte nappes) which grade, in trailing imbricate fan-type thrusts, to the parautochthonous units (Campos Neto and Caby, 1999a) both from the passive continental margin.

4-5.2.1 The upper high-temperature Socorro-Guaxupé nappe

The Socorro-Guaxupé terrane is a giant allochthon (at least 10 km thick) showing a right way up crustal section of hot and partially melted layered crust. It comprises (Fig. 4-11 and Fig. 4-12) basal banded enderbite (the Basal Granulitic Unit) partially derived from a Neoproterozoic near-juvenile immature magmatic arc setting (Sm-Nd T_{DM} of ca. 1.3 Ga). These granulites grades upward into a predominant grey to pink, metaluminous migmatites (the Middle Diatexitic Unit) identing at their top with pelitic to semi-pelitic migmatites (the Upper Migmatitic Unit). From these migmatites longitudinal dextral strike-slip shear zones control a major metamorphic span to greenschist metamorphic facies southwestward (Campos Neto and Caby, 1999b). Various syn-orogenic deformed plutonic rocks show chemical and isotopic signatures compatible with the evolved subduction-related

magmatism onto continental setting. They are porphyritic rocks from the charnockitic suite that gives way upward to batholiths of porphyritic granitoids.

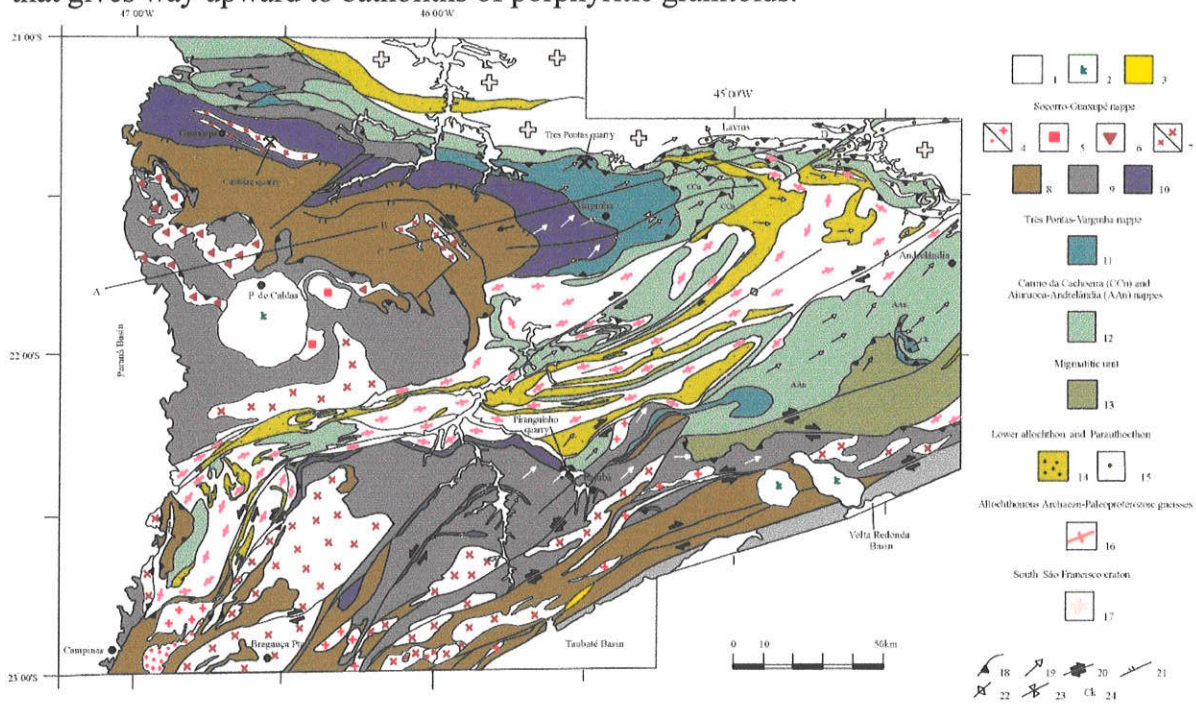

Figure 4-11: Geological map of the nappe system south of the São Francisco craton.
1. Phanerozoic deposits and basins, 2. Cretaceous alkaline plutons, 3. Pull-apart basins, 4. (small crosses) K-granites, diorites and gabros (ca.580 Ma) and (crosses) shear zone related granites (ca. 600-580 Ma), 5. Syenitic plutons (ca. 612 Ma); 6. Mangeritic-Granitic suite (ca. 625 Ma), 7. (x) K calc-alkaline porphyritic granitoids (ca.630 Ma) and (small x) Charnockitic suites (ca. 640 Ma), 8. Upper Migmatitic unit and the southern schist belt, 9. Middle Diatexitic unit, 10. Basal Granulitic unit, 11. Ky-Grt granulites, 12. Metapelites and metagreywackes. 13. Migmatites and tourmaline-bearing granites, 14. Allocthonous quartzite-schist assemblage, 15 Parautochthonous quartzite-schist assemblage, 16. Allochthonous Archaean-Paleoproterozoic gneisses: 17. South margim of São Francisco Craton: 18. Major thrusts; 19. Displacement vectors; 20. Strike-slip shear-zone; 21. Detachment zone, 22. Antiformal axis, 23. Synformal axis, 24. Carvalhos klippen.

Janasi (1999) shows that the Nd T_{DM} record into the Socorro-Guaxupé nappe define coherent domains in which an old residual migmatitic granulites can be found (Nd T_{DM} >1.8 Ga), whereas in other domains no sign of basement may be ascribed (Nd T_{DM} of ca. 1.5 Ga). Similar bimodal distribution (Fig. 4-13) accounts for Neoproterozoic magmatic arc-derived "primitive" metagreywackes (Nd T_{DM} around 1.2 Ga) and for an old basement-derived metapelites and "evolved" metagreywackes (Nd T_{DM} between 1.8 and 2.2 Ga).

High-temperature throughout the crust section is the main characteristic of the Socorro-Guaxupé nappe (Fig. 4-14 A). The garnet-ortopyroxene-bearing granulites from the base of the nappe underwent T=750-870°C and P=11.5-14.0 kbar metamorphic conditions and yield near isobaric heating evolution toward 860-920°C (Del Lama, 1994, Campos Neto and Caby, 1999b). These metamorphic data are consistent with dry melting of residual granulites in deeper levels of the crust generating anhydrous mangeritic magmas (Janasi, 1997, Campos Neto et al., 1988). The stratified behaviour of the Socorro-Guaxupé nappe is related to the higher thermal flow and controlled by the crustal level in which the widespread anatexis took place (Janasi, 1999). Thus, the pink anactetic biotite-bearing granites that belong to the Middle Diatexitic Unit were derived from metaluminous or higher Rb/Sr sources. They were generated by biotite dehydration melting at intermediate levels of the crust under ca. 850°C. On the other hand the supracrustal rocks from the

Upper Migmatitic Unit (T=800°C and P=4.5 kbar, Vasconcellos et al., 1991) are related to the shallowest muscovite dehydration melting as a magma source for the garnet-biotite parauthocthonous granites. Sm-Nd and U-Pb results point that the age of this metamorphism is in the 630-625 Ma range. The former age is related to the syn-orogenic granitoids and basal garnet granulite. The latter is well constrained for the uppermost garnet-biotite granite and the intermediate crustal level anactetic pink granites and mangeritic gneiss (Basei, 1995, Janasi, 1999). The synorogenic (ca. 0.63 Ga) batholiths comprise an extensive suite of hornblende-biotite bearing porphyritic granitoids from high-K calc-alkaline suites (Janasi and Ulbrich, 1991). They were found intrusive into the Serra do Itaberaba Group (northern of the Apiaí terrane). There they comprise porphyritic to equigranular tonalitic-granitic gneisses.

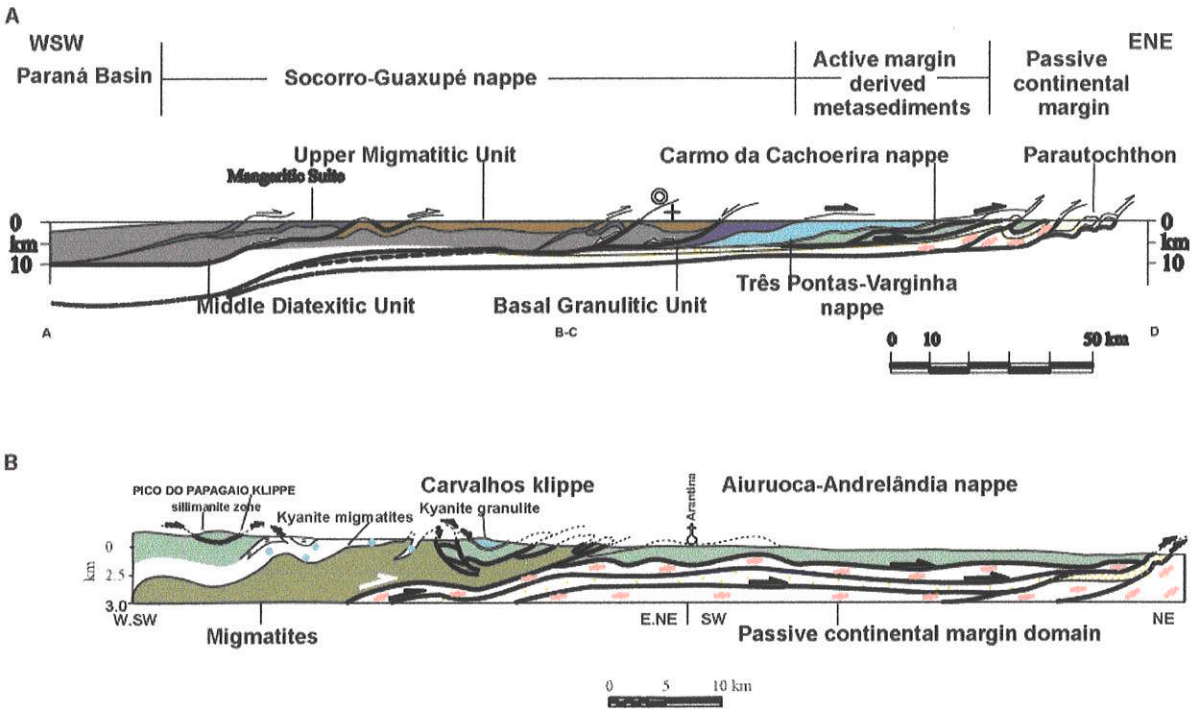

Figure 4-12: A- Cross-section across Socorro-Guaxupé, Três Pontas-Varginha, Carmo da Cachoeira and Luminárias nappes. B- Cross-section across the Aiuruoca-Andrelândia nappe. Profile A located on figure 11.

The basal thrust of the Socorro-Guaxupé nappe comprises a thick domain (up to 3 km thick) with flat-lying syn-metamorphic foliation as a strong plane-linear fabric bearing top-to-east-northeast shear sense indicators. A sole thrust overlaps the high-pressure nappes as well as the lower allochthon related to the passive continental margin units, resulting in at least 150-km of displacement. A syn-metamorphic detachment, locally accommodated by a NW-oriented oblique sinistral strike-slip fault, accounts for the direct contact of the uppermost migmatitic unit above the basal granulites where at least 5 km of the Middle Diatexitic Unit were omitted. Late metamorphic NE-displaced out-of-sequence thrusts are younger than the ca. 625 Ma old mangerites. These structures drove the stretched magmatic arc terrane toward its shallowest dept at 610 Ma, testified by the upper level intrusion of the post-kinematics potassic syenites (Janasi et al., 1993).

4-5.2.2. The high-pressure nappes

The Três Pontas-Varginha nappe is a thick sheet that crops out for 170 km parallel to its E.NE displacement direction. The nappe package comprises mainly coarse-grained rutile-kyanite-garnet granulites, lesser impure quartzites, and few calc-silicate rocks, gondites, lenses of metabasic rocks and rare sills of mafic-ultramafic rocks. Upward the Ky assemblage gives way to Sil-bearing granulites up to migmatites. The underlying Aiuruoca-Andrelândia and Carmo da Cachoeira nappes are chiefly made up of a layered sequence of peraluminous rutile-kyanite-garnet-muscovite schists and dark-grey, massive garnet-biotite-plagioclase gneisses and schists. Small lenses of metabasic rocks rise to eclogitic metamorphic assemblage. As the metasedimentary sequence of the Socorro-Guaxupé nappe, the chemical and isotopic characteristics of these rocks (Campos Neto et al., 1990, Janasi, 1999), either under granulitic or amphibolitic metamorphic facies conditions, is characteristically bimodal (Fig. 4-13). The rocks from pelitic source have Sm/Nd T_{DM} and U-Pb ages on detrital zircon at 1.9 Ga (Söllner and Trouw, 1997). The metagreywacke record Nd T_{DM} between 1.16 and 1.55 Ga, becoming to unravel their Neoproterozoic juvenile volcanic arc source.

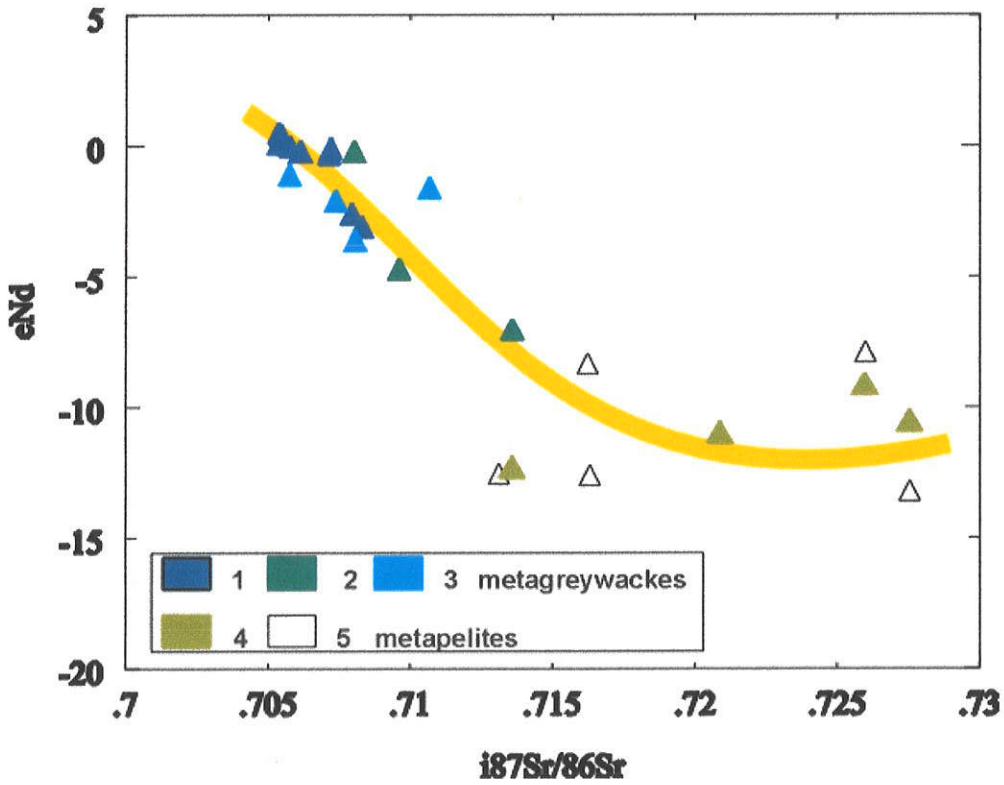

Figure 4-13: $\varepsilon_{Nd\,(625)}$ X $i^{87}Sr/^{86}Sr$ diagram for metasedimentary rocks (modified from Janasi, 1999). Metagreywackes: 1. Grt-Bt-Pl gneisses from Aiuruoca-Andrelândia nappe, 2. (Crd)-Sil-Grt-Bt- gneisses from Middle Diatexitic Unit of Socorro-Guaxupé nappe, 3. Ky-Grt-Pl granulites from Três Pontas-Varginha nappe. Metapelites: 4. Sil-Ky-Gr-Kf granulites from Três Pontas-Varginha nappe, 5. Grt-Bt gneisses from Upper Migmatitic Unit of Socorro-Guaxupé nappe.

A coherent inverted metamorphic pattern is supported by these nappes (Fig. 4-14). Lower temperatures (650°C) were attained under high-pressures (12-14 kbar) related to the decompression stage of eclogite conditions (660°C-17.5 kbar). Upward the temperature

increase to 700°C (P=15 kbar) on Ky-granulites to get 830-950°C in a near-isobaric heating path. The syn-kinematics decompression related to the outer propagation of the out-of-sequence thrusting varies from 600-690°C and 9-11 kbar (Campos Neto and Caby, 1999b). The syn-kinematic cooling of the high-pressure pelitic granulites depicted by the closure temperature of monazite in U-Pb system done at 612 Ma (Janasi, 1999). It could be related to the outward propagation of the out-of-sequence thrust system.

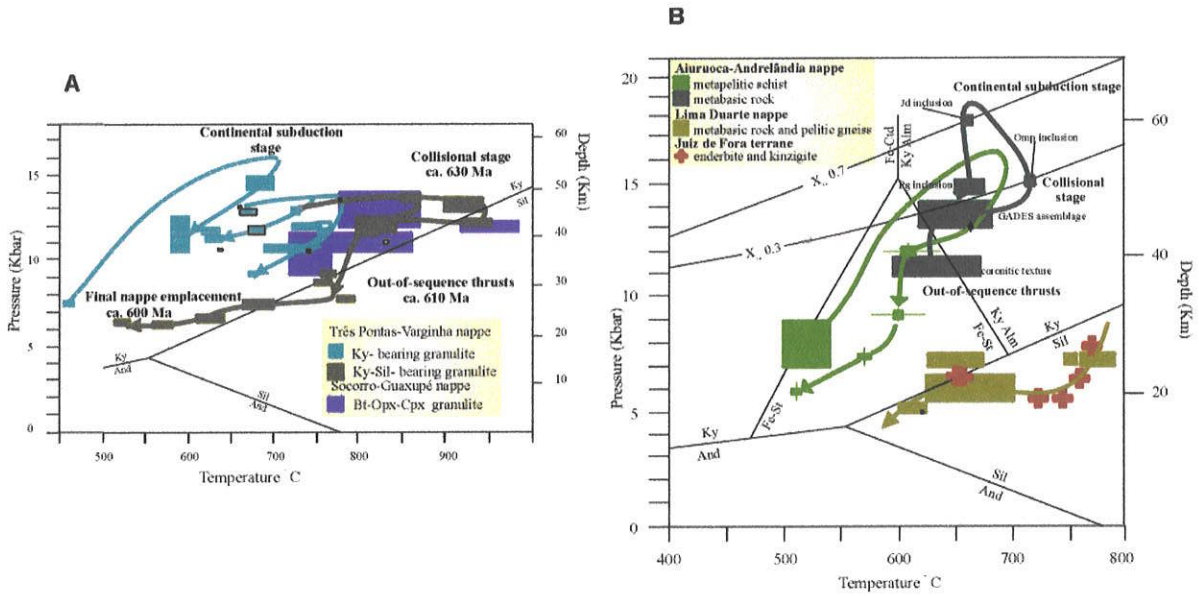

Figure 4-14: Metamorphic paths: A- Três Pontas-Varginha nappe; B- Aiuruoca-Andrelândia nappe and Lima Duarte nappe.

4-5.2.3. The medium-pressure lower nappes and foreland orogen propagation

The psamitic rock associations that are related to the passive continental margin deposits occur as the lower allochthon and parautochthonous units (Fig. 4-11). The flat-lying sheet of Luminárias-Carrancas nappe shows an eastward minimum transport of ca.140-km, and it is composed mainly of white and green mica quartzites grading upward into well bedded to laminated quartzite interlayered with graphitic and aluminous metapelites (Ribeiro et al., 1995, Paciullo, 1997). Polymetamorphic orthogneisses and migmatites also belong to the nappe package, and a barrovian-type mineral succession was described (Trouw et al., 1986).

In the parautochthonous units the ramp and flat thrust pattern prevail, involving basement ortogneisses and interbedded quartzites and grey phyllites. Locally the metapelite displays a metamorphic assemblage which accounts for medium to high-pressure conditions (P=7kbar and T=500°C) that may control the appearance of Zn-staurolite and kyanite in the absence of garnet and biotite (Campos Neto and Caby, 1999a).

Eastward, the main psamitic rock package with sillimanite-bearing metapelites is organised in a large, basement involved allochthon: the Lima Duarte nappe (Fig. 4-15). This is also subjected to medium-pressure metamorphism reaching granulite facies and late anatexis. Garnet-clinopyroxene bearing amphibolites (with IBC-type coronitic textures) and sillimanite-bearing gneiss show the metamorphic peak under Tmax=700°C and Pmax=7

kbar. Nevertheless the syn-metamorphic structures account for north-displaced unrooted thrust system exibing monazite U-Pb age of 570 Ma (Machado et al., 1996). A thin-skinned duplex displaying the same northward displacement overprints the Lima Duarte nappe. Thus, the Lima Duarte nappe seems to be related to the foreland propagation of transpressive deep structures related to a collisional orogen of the newer Mantiqueira orogenic system. It represents the Ribeira/Brasilia belts interaction of Trouw et al. (1998).

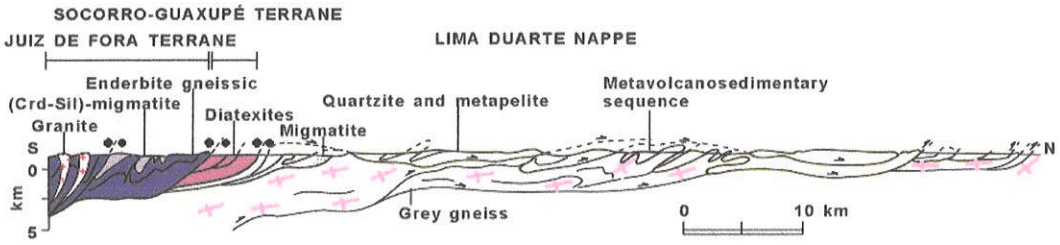

Figure 4-15: Cross-section through Lima Duarte nappe

4-5.3. Tectonic evolution of the Southern Tocantins orogenic system

The Southern Tocantins orogenic system results from the agglutination of three major geodynamic environments during the Neoproterozoic III Orogeny. The western and uppermost tectonic setting is related to the Socorro-Guaxupé Magmatic Arc terrane, which may represent deep crustal level of the Iporá-Jaupaci Arc developed during the Middle Cryogenian Orogeny. The high-pressure metasedimentary terranes (Três Pontas-Varginha, Carmo da Cachoeira and Aiuruoca-Andrelândia nappes) are the records of an active margin setting as the source area for wacke deposits, probably upon a forearc-thinned crust belonging to the Anápolis-Andrelândia terrane. The Tonian-Lower Cryogenian metasedimentary sequence from the southwestern passive continental margin environment of the São Francisco plate comprises the metapsammitic-dominated, medium-pressure lower nappes and parauthocthon.

The high-pressure metamorphic conditions recorded by the kyanite-bearing granulites and eclogites from Três Pontas-Varginha nappe and Aiuruoca-Andrelândia nappe imply a low thermal gradient (ca. 11°C/km), which can only be achieved in an ocean closure (Spear, 1995) through a west-dipping subduction scenario. The microplate segment conformed by these nappes was subducted to a minimum depth of 60±5 km. It is assumed that great amounts of oceanic crust and continental crust material from southern Anápolis-Andrelândia terrane were lost by subduction. Only a small portion of the subducted slabs is preserved within the high-pressure nappes. Modern analogues could be seen in the Alpine Tertiary subduction of great portion of the paleo-European margin bellow the Apulian plate (Schmid et al., 1996).

An inverted metamorphic field gradient is brought about from the perturbed paleogeotherm to an upper steady state thermal gradient (20°C/km) of the upper sillimanite-bearing granulites toward the base of the high-temperature Socorro-Guaxupé nappe (Campos Neto and Caby, 1999b). This thermal pattern related to diachronic equilibration at different temperatures throughout the metamorphic prism, as evidenced in the Indian Greater Himalayan zone (Vannay and Grasemann), requires the rapid emplacement of the

upper hot allochthon onto the Três Ponta-Varginha nappe. It resulted from the subduction driven arrival of the Socorro-Guaxupé terrane displaying, at their base, similar dT/dP gradient (Fig. 4-10-B).

At the shallow levels of the Socorro-Guaxupé terrane (T=820°C and P=4.5 kbar) the metamorphic high-thermal flow argue for a compressed paleogeotherm pattern (ca. 50°C/km). This steeper thermal gradient could be related to a lithospheric extension resulting from astenospheric mantle upwelling with considerable amounts of basic magma underplating. Those processes were in the origin of the widespread crustal magmatism into the Socorro-Guaxupé terrane, and occurred in a short-lived metamorphic peak robustly confined at 625±5 Ma. Though nearly contemporaneous the "cold"-subduction scenario depicted by the kyanite granulite beneath the Socorro-Guaxupé terrane attests for initial different tectonic environment for both terranes. A roughly east-dipping subduction of an oceanic segment of the Rio de la Plata plate might be envisaged (Fig. 4-10-B). This subduction could be in agreement with the northwestward-displaced syn-metamorphic structures in the western area of the Socorro-Guaxupé nappe, as well as to the steepen pattern of isotherms.

The collisional outward propagation of the nappe pile (Fig. 4-10-C) submitted significant thinning was accompanied by temperature-decrease at each thrusted rock-package. The preservation of an inverted metamorphic gradient equilibrated in the kyanite-field requires rapid exhumation. This short-lived tectonic scenario began around 630 Ma and ended shortly before 612 Ma. Thus, part of the lower crust was exhumed from subduction prism and driven horizontally and thinned above the passive continental margin domain resulting a mean cooling rate of about 15°C/Ma. These subducted crustal slabs moved back up to the surface at a critical stage of the subduction while continuing underthrusting of the denser lithosphere (Chemenda et al., 1995, Matte et al., 1997). The hinterland-driven syn-metamorphic detachment may result from internal extension by dynamic compensation (Hodges et al., 1996) in reponse to the possible building of mountain range of Himalayan size.

The post-orogenic history started early in the inner terranes at 610 Ma extending thoughout 580 Ma up to 550 Ma (Pimentel, et al., 1996, Töpfner, 1996, Wernick, 1998). It was pictured by a dramatic change in the character of the plutonic magmatism. A K-rich granitoid association was recognized conforming roughly with a N.NE-oriented belt (the Itú belt, Vlach et al., 1990). They are mostly undeformed high-K calc-alkalic hornblende and biotite-bearing porphyritic monzogranites, syenogranites locally with wiborgitic texture, pink inequigranular monzogranite, muscovite and fluorine-bearing granites. Basic and intermediate rocks occur as enclaves and syn-plutonic dykes, and also as some plutons of K-rich diorites and K-syenites. Beyond the large amount of magma contribution from crustal materials, an important contribution is allowed from two fundamentally different mantle-derived magmas. A strongly oxidised magma, poor in basaltic component in the origin of the K-syenites, and the K-dioritic magmas with shoshonitic affinities (Janasi et al., 1993). This post-orogenic episode seems to represent the reactivation and melt of the subcontinental lithospheric mantle involved in extension regime on the inner orogens.

4-6. Paleotectonic approach for the Mantiqueira orogenic system

That above-mentioned phases of convergence are related to the global break-up of Rodinia and dispersion of their descendants, that commenced at ca. 0.75 Ga, including the

separation of East Gondwana from the western margin of Laurentia (Park, 1994). Accordingly (and differently from the orogenic conditions of the Goianides oceanic realm), in the São Francisco-Congo plate taphrogenic processes predominated during the mid-Cryogenian. The Sturtian glacial deposits were widespread and they were related to the main rifting stage in the Congo and Kalahari plates, as well as in the São Francisco plate. Normally they were succeeded by passive continental margin settings and the post-glacial marine cap dolomites have covered the São Francisco plate.

At the African side the first stage of Damaran extensional basin was recorded by the rift-related continental sediments of Nosib Group associated with alkaline bimodal volcanic rocks that are older than 0.75 Ga. At the western of Kalahari craton eruption of felsic volcanic have been dated at ca. 745 Ma. The supercontinental break-up and opening of the Adamastor Ocean was constrained by the major marine transgression recorded by the deposition of Octavi Group which contains basal volcanic interlayers yielding U-Pb zircon ages between 745-758 Ma. Iron-rich diamictites (Chuos Formation) have been regarded as Sturtian, once they overlie a shelf ramp facies of the base of the Octavi Group. Farther to the south this oceanic opening process was diachronically younger. At the Gariep belt the Sturtian diamictites (Kaigas Formation, ca. 720 Ma) precedes the passive continental margin succession (Hilda Subgroup) and the oceanic assemblage. Later still, the opening of the intracontinental branch of the Khomas Sea took place following the uppermost glacio-marine diamictites (Ghaub Formation) considered as Varangian (ca. 600 Ma) in age (Stanistreet et al., 1991, Frimmel et al., 1998, Hoffman et al., 1998, Kennedy et al., 1998).

As it was seen before, at the eastern portion of the São Francisco plate (South American side) the beginning of the passive continental margin was recorded by the Sturtian-related glacial deposits (Macaúbas Group) and turbidities fans (Salinas Formation) up to oceanic remnants (Ribeirão da Folha Formation) placed in the Neoproterozoic at the Middle Cryogenian (Pedrosa-Soares et, al, 1998). Nevertheless an early oceanic basin (the Charrua Ocean, Fragoso-Cesar et al., 1997) seems to precede the main opening of the Adamastor Ocean, and it was recorded locally at the east of Rio de la Plata plate during the Early Cryogenian.

Several narrow and elongated (Fig. 4-8) small plate fragments (descendants of Rodinia) played an important role in the history of this orogenic system (Fig. 4-2).

The Apiaí terrane comprising the Mesoproterozoic Ectasian series is overlain by carbonatic shelf and terrigenous deep-sea turbidity fan from ramp and rise of a passive continental margin (the Açungui Super Group described above). These rocks and the orogenic granitic batholiths record a Paleoproterozoic (ca. 1.9 Ga) Nd (T_{DM}) signature (Sato, 1998). It is possible that the Apiaí terrane had been connected with the northeastern Rio de la Plata plate after the Grenvillian orogenies.

The Luis Alves terrane conforming an Archaean-Paleoproterozoic lower-crust fragment (the Santa Catarina granulite complex) southeastern facing by a terrigenous and narrow shelf-type passive continental margin deposits of the Brusque Group and Porongos Group (Basei et al., 1998). Mesoproterozoic Calymmian/Ectasian Sm-Nd isochronal ages are suggested for the basal volcano-sedimentary sequences (Basei, 1985). Farther to the south the metasedimentary belt override Paleoproterozoic aged gneiss and the continuity of the Santa Catarina granulite complex was tectonically omitted. In spite of the northern Archaean foreland domain, these sequences, and also the later intrusive granites, display a Paleoproterozoic (2.0 Ga) Nd (T_{DM}) signature (Basei et al., 1997).

The Pelotas terrane comprising a fragment of Paleoproterozoic crust, which was mainly recognized through the evolved arc-related granitoids by the Sm-Nd studies (Basei et al., 1997, Silva et al. 1999).

Besides all that, there is a small anonymous fragment/terrane composed of migmatites with a Kibaran age of metamorphism that has preliminarily been identified in southeast Uruguay, east of the Pelotas terrane (Precciosi et al. 1999).

The Curitiba and the Juiz de Fora terranes forming a narrow and elongated crustal fragment with a general framework of juvenile Paleoproterozoic calc-alkaline intermediate plutonic rocks partially as a granulitic belt, which became more evolved further to the south (Sollner et al., 1991, Sato, 1998, Basei et al., 1997, Heilbron et al., 1998). It seems that these terranes might be derived both from the rifting and break-up of the eastern São Francisco plate. Somehow the Juiz de Fora terrane is regarded as belonging to the Paleoproterozoic juvenile within-oceanic to active margin accretion (Duarte et al., 1997, Valladares et al., 1997), which could be related to the Mineiro mobile belt, southern of São Francisco craton (Figueiredo and Teixeira, 1996, Alkimim and Marshak, 1998). Thus the Middle Cryogenian break-up of the eastern São Francisco plate may followed the weakness line related to an ancient Rhyacian suture zone.

Beyond the wide granite occurrences, high-temperature metamorphic rocks from sedimentary provenance prevail north of the Juiz de Fora terrane, associated with a few stratiform bodies of mafic-ultramafic rocks. To the south, the Paleoproterozoic Rhyacian partially melted gneisses (Machado et al., 1996), derived from plutonic rocks of calc-alkaline affinities, are tectonically associated with a metasedimentary assemblage (the Paraíba do Sul Complex) made chiefly by immature quartzite, sillimanite-garnet bearing gneiss and migmatite, and marble. An admixture of Paleoproterozoic Rhyacian and Statherian sources for these metasediments could be admitted based on ^{207}Pb-^{206}Pb age and Nd (T_{DM}), whereas some interbedded metabasic rocks display Neoproterozoic magma provenance (Valladares et al., 1997). Further to the south (Fig. 4-3). The metasediments (the Embu Complex) prevail over a narrow and thinned strip of an Archaean tonalitic-granodioritic gneisses (Tassinari and Campos Neto, 1988). They comprise three major units showing metamorphic spans from green-schist facies to higher anfibolite metamorphic facies across steep and lateral displaced shear zones. They are (Fig. 4-3) shelf-related quartzites, a distal rhythmic succession of pelitic schists and quartzites, and metavolcanic-volcanosedimentary rocks (amphiboles, calc-silicate gneiss, metagreywackes) with restricted marbles and immature quartzites (Fernandes et al., 1990). Although isotopic and geochemical data are not available, these sequences are supposed to have derived from a Neoproterozoic tectonically active environment.

The Curitiba terrane is mainly composed of basic/intermediate banded gneiss and migmatites, and subordinately charnockitic gneiss, related to the Paleoproterozoic Atuba complex (Basei et al., 1992, Siga Jr. et al., 1993). The metasedimentary cover consists of a marine regressive sequence of shallow water carbonates (Capiru Formation) associated with quartzite-schist assemblage (Setuva Formation) grading eastward to rhythmic deep-sea type terrigenous sequence. They have characteristics of an extensional basin related to a narrow and asymmetric rift reaching a passive continental margin (Yamato, 1999).

The Serra do Mar terrane is on the whole mainly composed of migmatites and elongated and diffuse bodies of (garnet)-biotite-bearing granites with nebulitic and schilieren structures with variable strain rate. Sometimes they contain enclaves and/or resisters of quartzites, calc-silicatic marbles and amphibolites. North of Rio de Janeiro

State, preserved from the wide and deep strike-slip shear belt, three distinct crustal segments can be recognized (Sluitner and Weber-Diefenbach, 1989, Campos Neto and Figueiredo, 1995, Wiedemann et al., 1997). They are: the westernmost and basal supracrustal unit, the overlying gneiss-migmatite unit, and the eastern and upper granulite-granite-migmatite unit, displaying an inverted structural pile related to a westward nappe displacement. Immature quartzite, garnet-sillimanite-bearing quartzite and quartz-schists, marbles and calc-silicate rocks, and gneiss from wacke provenance constitute the majority of the supracrustal unit. Slices of metabasic and meta-intermediate rocks display protoliths chemically identified with high-Ti and low-Mg tholeiitic basalts and alkaline basalts associated with an arc-type calc-alkaline andesites (Sad and Dutra, 1988). These assemblages come together with an active continental margin environment. The gneiss-migmatitic unit is made up of (cordierite-sillimanite)-garnet-biotite stromatic migmatite having a wacke-pelitic provenance, whereas the upper granulite-granite-migmatite terrane is mostly composed of sin to late-kinematics peraluminous (cordierite-sillimanite-garnet-bearing kinzigites) and metaluminous diatexites, normally associated with enderbite series.

The contrasted Sm/Nd isotopic signature (data from Sato, 1998) between Serra do Mar and Juiz de Fora terranes being prominent projecting the low $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratio for the Serra do Mar rocks than those from the Juiz de Fora terrane (Fig. 4-16). On the other hand, the Mesoproterozoic T_{DM} age that dominates all over the Serra do Mar terrane concurs to an African rifting-apart.

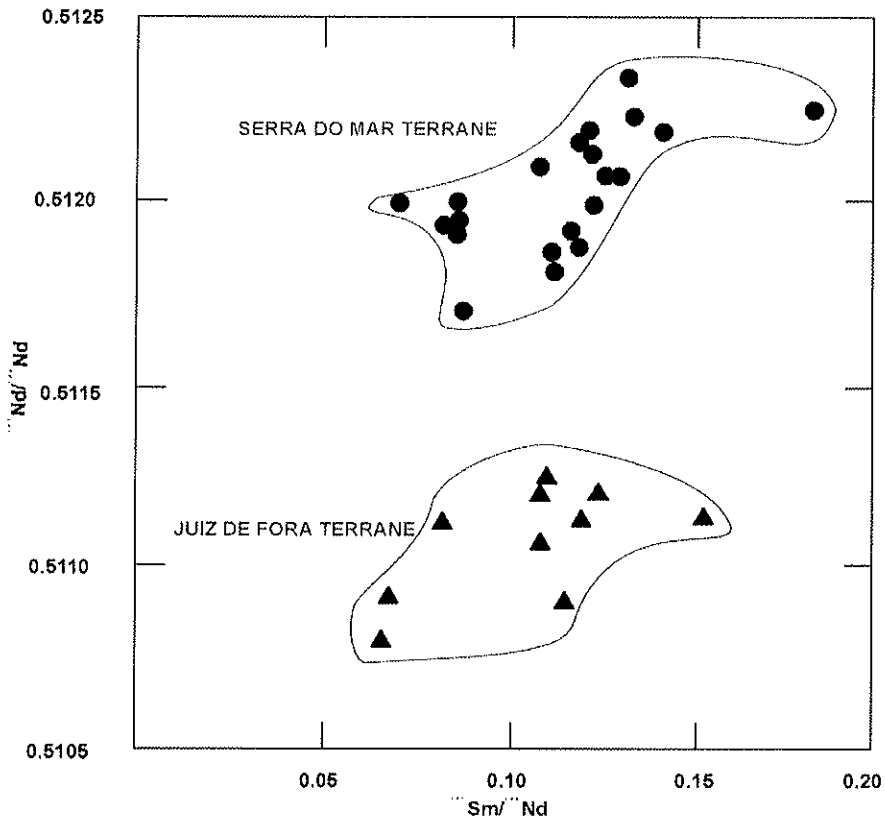

Figure 4-16: $^{143}Nd/^{144}Nd$ X $^{147}Sm/^{144}Nd$ relationships between Serra do Mar and Juiz de Fora terranes.

The Cabo Frio terrane comprises orthogneisss from diorite-tonalite-granite series associated with orthoamphibolite slices of Paleoproterozoic age (Zimbres et al., 1990, Schimitt et al., 1998). The orthogneissic complex overrides a metasedimentary sequence mainly composed of paragneiss and quartzite, with subordinated lenses of calc-silicate rock and amphibolite (Heilbron et al., 1982). These metasediments have a Mesoproterozoic Nd (T_{DM}) signature suggesting a Neoproterozoic aged deposition.

4-7. The Mantiqueira orogenic system

The geological scenario of the south-southeastern Atlantic coastal area of Brazil and Uruguay (up to the Mantiqueira Range on the continent interior) is a NE-trending orogenic system, mostly controlled by steep, strike-slip shear zones. It comprises a series of terranes that have diachronically collided against the just-assembled (0.63-0.62 Ga) São Francisco-Rio de La Plata plates, so forming the orogenic system related to the closure history of the Adamastor Ocean.

4-7.1. Regional view on plate convergence in the Southern Mantiqueira orogenic system

The plate convergence started with the closure of the small (?) Charrua oceanic basin. It was recorded by the metavolcanic and metaplutonic rocks from calc-alkaline affinities (the Vila Nova belt, Silva Filho and Soliani, 1987) yielding U-Pb on zircon age of 705 Ma and a $\varepsilon_{Nd\,(t)}$ rising to +7.8 (Babinsky et al., 1996). It was the first well-constrained plate interaction record for an Upper Cryogenian intraoceanic subduction-controlled orogen (the São Gabriel Orogeny) in the southern of Mantiqueira Orogenic system.

Sedimentary and volcanic belts from Brusque and Porongos Groups which underwent medium to low-pressure metamorphism are associated with W-NW verging collision-related structures. Although scarce and imprecise geochronological data the metamorphic peak must have been reached around 630 Ma (Silva et al., 1999) slightly before the late-kinematics granite batholiths (Basei, 1985). Many pieces of the plate interactions for this collision-controlled orogen seem to have been disguised by or concealed under the ca. 460km-long Phanerozoic Paraná Basin (Fig. 4-2).

The Neoproterozoic III subduction-controlled Pelotas magmatic arc orogen (0.61 to 0.60 Ga) took place facing the southeastern edge of the Brusque and Porongos orogen. This arc comprises a series of calc-alkaline plutonic rocks and high-K porphyritic granites mingled with coeval migmatites, all of them displaying flat-lying foliation related to W-NW tectonic transport (Basei, 1985, Tommasi et al., 1994, Fernandes et al., 1995). Based on the extrusion vector of the collision structures and the eastward zonation toward the post-collision pink granites (ca. 595 Ma), an southeastward-dipping subduction could be admitted.

The main collisional orogenic interaction ca. 0.6 Ga was responsible for the juxtaposition of Pelotas magmatic arc, Luis Alves terrane, and the southeastern boundary of Rio de La Plata plate. The major strike–slip shear zones define the main collision boundary: a northern, dextral and a southern, sinistral shear zones that contained and controlled the emplacement of peraluminous and metaluminous granites. Impactogenic processes were related to the origin of the undeformed volcano-sedimentary basins that were associated

with alkaline-peralkaline granitic intrusion. This process took place mostly in the Luís Alves and Curitiba terranes at ca. 0.6-0.57 Ga (Siga Jr. et al., 1997).

The development of the collision-related foreland basins at the southern of Luis Alves terrane and the eastern of Rio de la Plata plate are recorded by remnants of continental environments up to deep marine deposits. Unconformity and volcanic episode separated these sedimentary environments. They are the Itajaí, Camaquã and Arroyo del Soldado Groups, which were pierced by intrusive granites and volcanic felsites (0.56 Ga), and which contain several Vendian species of palynomorphs. Their stratigraphic history was broken at 0.53 Ga, related to the age of the thin-skinned deformation (Basei et al., 1997, Gaucher et al., 1998, Rostirolla et al., 1999).

4-7.2. The Central and Northern Segments of the Mantiqueira orogenic system

The tectonic evolution of the Central and Northern segments of the Mantiqueira orogenic system is related to the diachronous kinematics of oceanic plates convergence generating widespread magmatism. Collisions and dockage processes leading to the closure of the oceanic spaces between the major terranes controlled the geometry of this tectonic scenario. Thus the knowledge of the petrology and plutonic stratigraphy for the magmatic rocks (Söllner et al., 1987, Söllner et al., 1988, Offman and Weber-Diefenbach, 1989, Soares et al., 1990, Söllner et al., 1991, Janasi and Ulbrich, 1991, Figueiredo and Campos Neto, 1993, Wiedmann, 1993, Gimenez Filho et al., 1995, Machado et al., 1996, Wiedmann et al., 1997), and the knowledge about the structural framework (Heilbron et al., 1982, Campos Neto and Figueiredo, 1990, Machado and Demange, 1990, Pedrosa–Soares et al., 1992, Campos Neto and Figueiredo, 1995, Heilbron et al., 1998, Ebert and Hasui, 1998) were taken as the principal tools to unravel the tectonic history.

The Rio Negro subduction-controlled orogeny (ca. 0.63 Ga) was the first record of the Central Mantiqueira Orogenic system of an orogen related to a plutonic magmatic arc. It was accreted on the Serra do Mar terrane (Oriental Terrrane for Tupinambá et al., 1998) as a batholithic complex of gabbro-diorite-tonalite from high-Ca and low-K calc-alkaline magma provenance, yielding a $(\varepsilon_{Nd})_{0.6\ Ga}$ of –0.9 (Tupinambá et al., 1998, Tupinambá, 1999). These rocks display a horizontal to NW gently dipping foliation related to a low-pressure, amphibolite facies metamorphism. The blockage of the subduction and docking of the Rio Negro orogen against the southeast portion of the Juiz de Fora terrane was admitted herein. The dockage process was laterally-controlled developing variable steep to low-angle dipping mylonitic foliation with NE-trending stretching and mineral lineation related to a main dextral displacement, leading to a local override of the Juiz de Fora terrane upon the magmatic arc (Heilbron et al., 1998, Tupinambá, 1999). This main tectonic edge ("the central tectonic boundary") was developed coeval with the generation of the post-arc metaluminous to peraluminous leucogranites (ca. 0.60 Ga). The oblique juxtaposition of the arc and the Juiz de Fora terrane released, further to the north, remnant of oceanic basin (see Fig. 4-18 below).

The Paranapiacaba orogen is related to a complex subduction and extensional tectonic setting that took place farther to the south attaining the domains of Apiaí and Curitiba terranes (Fig. 4-17). It was coeval or slightly younger than the Pelotas orogen. This orogenic scenario is pictured by huge and elongated batholiths corresponding to syn-orogenic intermediate to felsic metaluminous, high-K calc-alkaline granitic series. Hornblende-biotite porphyritic quartz monzonite and monzogranite prevails upon the fine-

to medium-grained, grey colored, biotite-bearing monzogranites. Tonalitic rocks are subordinated. They correspond to an evolved magmatism that reworked Paleoproteozoic lithospheric crust (Reis Neto, 1994, Harara et al., 1997). The Rio Pien Magmatic Arc southeastern facing the Curitiba terrane yields an age of about 0.615 Ga (Harara et al., 1997). It slightly preceded the 0.61 Ga age of the Agudos Grandes high-K calc-alkaline batholiths facing the southeast of Apiaí terrane. Inequi to equigranular muscovite-biotite granites with porphyritic facies normally wrap up the terminations of the calc-alkaline batholiths. They are 0.60-0.605 Ga and are followed by the younger, post-kinematic (0.565 Ga), porphyritic biotite syenogranite with an "A-type" chemical signature (Janasi et al., submitted). Farther to the interior of the Apiaí terrane the westernmost Três Córregos and Cunhaporanga batholiths (Fig. 4-4) are associated with high-temperature and low-pressure amphibolite facies metamorphism of the country rocks and detachment structures could be recognized. At this domain U-Pb zircon ages are still poorly constrained and the preliminary data display strong variable values suggesting roughly a westward age decreasing from 0.61 Ga up to 0.57 Ga for the calc-alkaline granites (Prazeres, personal communication). The metasedimentary sequences of São Roque Group that occur at the northwestern edge of the Apiaí terrane (Fig. 4-3) contain at their base bodies of metabasalts derived from sub-alkaline tholeiitic volcanism, locally displaying pillow-lava structures. The zircon U-Pb age for this submarine volcanic flow has the same value (0.61 Ga) of the magmatic arcs suggesting a narrow back-arc basin setting (Hackspacher et al., 1999). The collisions between the Luis Alves and the Curitiba terranes and between the Curitiba and the Apiaí terranes led to the closure of the São Roque back-arc basin amalgamating the continental fragments at the southeastern portion of the Rio de la Plata plate segment. At the Curitiba terrane the collision led to strong shortening by low-angle, east-southeastward transported ductile shear upon overall crust. It is associated with ca. 0.6 Ga (Siga Jr. et al., 1995) metamorphic slices that underwent geenschist to high-grade amphibolite, up to granulite metamorphic facies. Double vergence and contrasted tectonic regimes are admitted for the Apiaí terrane. A steep dextral strike-slip shear zone controlled the major geometry of the structures normally disguising an early flat-lying foliation. At their southeastern boundary the flat-lying foliation is roughly related to an eastward thrusting transport. Toward the hinterland the low-grade metamorphic shallow-dipping foliation is related to a northwest-direct transport (Campos Neto and Basei, 1983, Juliani, 1993). The central magmatic arc seems to be related to many hinterland and foreland driven detachments, the major ones bordering the batholiths and displaying a strong strike-slip component. An alternative tectonic scenario is also considered: a high-angle, west-dipping subduction zone under the Curitiba terrane gave way to an active continental margin setting (the Rio Pien Magmatic Arc). Toward the hinterland strong lithospheric extension might be related to the generation of the huge batholithic zone comprising the wide calc-alkaline plutons nearly coeval with peraluminous magma, both intrusive in older units from a passive continental margin setting. This lithospheric extension rises, on the plate interior, to rifting and break-up of the São Roque back-arc basin. For both tectonic scenarios the main collision-controlled orogen took place at 0.60 Ga and was followed by post-orogenic lithospheric extensional regimes around 570 Ma.

The main 0.60 Ga collision episode related to the Paranapiacaba and Rio Negro orogens were described elsewhere in the main magmatic arcs. It has been recorded in peraluminous monzogranites and migmatites from the southern Juiz de Fora (Embu Complex) and the southernmost termination of Serra do Mar terranes.

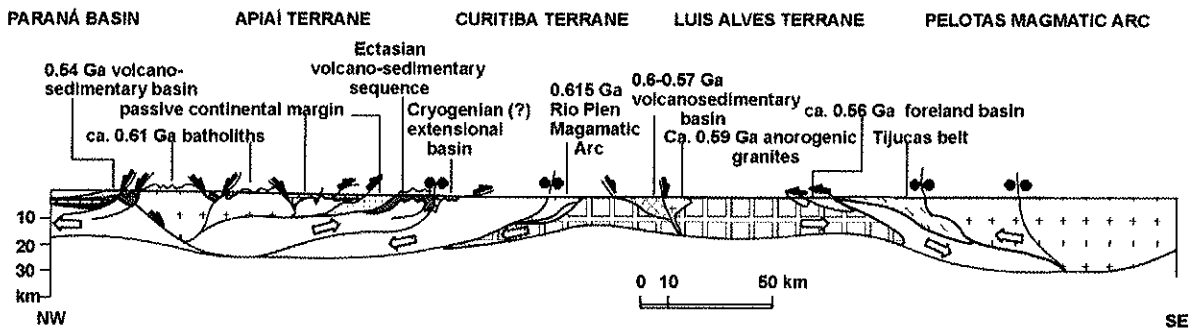

Figure 4-17: Profile through Apiaí and Curitiba Terranes.

To the north, this collisional amalgamation released an oceanic branch between the eastern São Francisco passive continental margin and the Juiz de Fora terrane (Fig. 4-18), which is by this time closed. The beginning of the *Araçuaí Orogeny* took place with the growing of the Galiléia Magmatic Arc in an active margin setting west-facing the Juiz de Fora terrane through east-dipping oceanic lithosphere subduction. The granitoids from Galiléia Batholiths (Nalini Jr. et al., 1998) show a relativelly extensive compositional trend (tonalite-granodiorite-granite), containing amphibole and biotite as major mafic mineral phase, and grossular-rich garnet characterizing a deep crust (up to 10 kbar) magma crystallization. They have a zircon U-Pb age at 595 Ma (Nalini et al., 1998) and they were followed by semi-circular plutons of the peraluminous Urucum Suite comprising monazite, tourmaline, garnet and/or two micas granite types. The Urucum granites are thought to be a collision-type suite yielding an age of about 580 Ma (Nalini et al., 1998). The collisional development of the Araçuaí orogen (Pedrosa-Soares et al., 1998, Ulhein et al., 1998) is pictured by foreland-driven nappes depicting relatively high-pressure metamorphic rocks at the suture zone (kyanite-garnet-bearing schist). The cratonic edge was reached by the westward thrusting of the Espinhaço Range up to the thin-skinned behavior of the platform cover. Southward the Abre Campo discontinuity (Fischel et al., 1998) represented the suture boundary between the active margin of Juiz de Fora terrane and the western Archaean-derived thinned continental crust from passive margin domain (the Mantiqueira Gneiss). A ductile and oblique, dextral strike-slip shear zone delineates it.

The Rio Doce Orogeny developed early in the Serra do Mar terrane, renewed as a microplate after the complete consumption of the oceanic lithospheric plate segment at the eastern São Francisco passive continental margin domain. It resulted from the final convergence episodes leading to the closure of the Adamastor Ocean. Thus its record may be pursued, with variable intensity, overall in the Mantiqueira orogenic system. As a variance of Campos Neto and Figueiredo's (1995) tectonic scenario, a V-shape oceanic branch must have been released northwest of Serra do Mar terrane and the first record of its lithosphere resorption was the Rio Doce Magmatic Arc (Figueiredo and Campos Neto, 1993). This assumption could be let by the west-direct low-angle extrusion of the roots of the magmatic arc (Fig. 4-19A). Elsewhere, in the African side, the structural patterns of the West-Congolian belt (Trompette, 1994), and farther to the south, the oceanic nappe of the Marmora terrane (Frimmel et al., 1998), both displaying east-displacement toward the cratonic areas, are the converging diagnose for a west-dipping oceanic lithosphere subduction. This process has been constrained at 575 Ma in the Gariep and Damara belts (Frimmel et al., 1998). Based upon the chemical and compositional zonation of the main

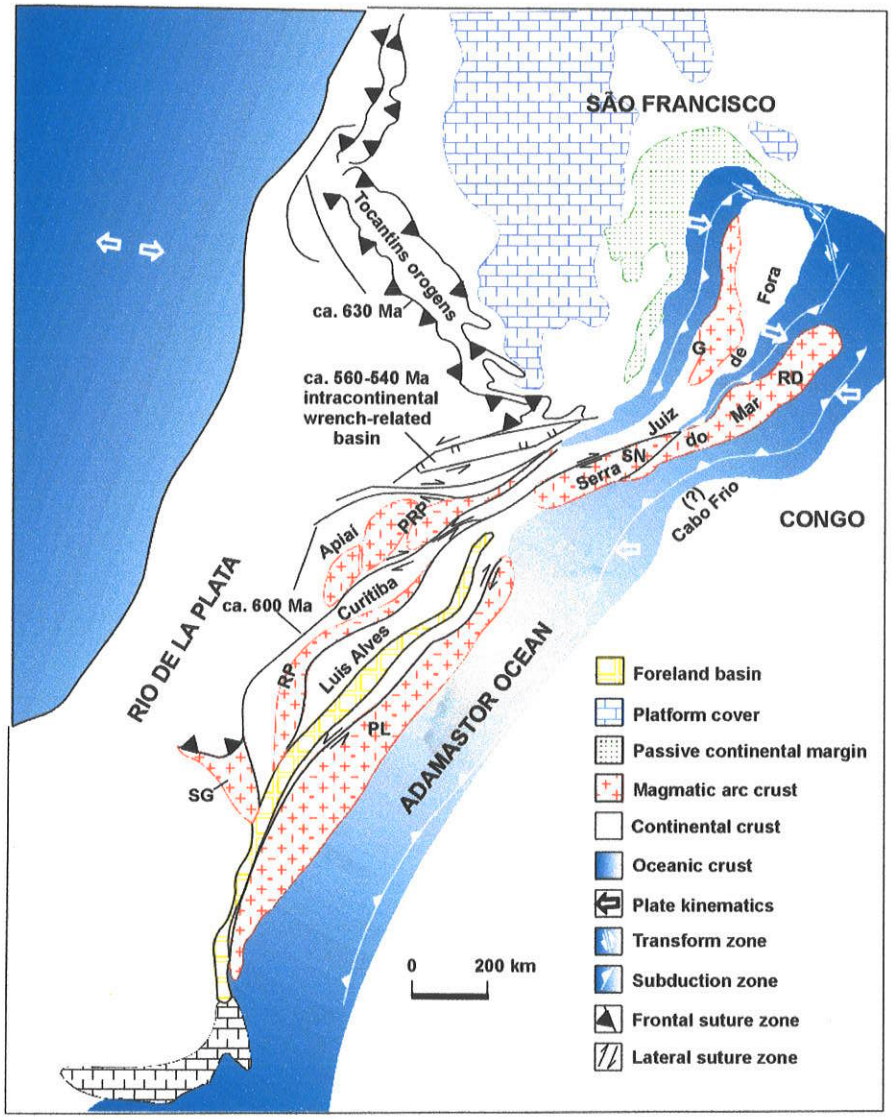

Figure 4-18: Vestiges of the lost Adamastor Ocean at ca. 590 Ma: paleogeographic sketch of oceanic plate interactions

plutonic rock types of the Rio Doce Magmatic Arc, Figueiredo and Campos Neto (1993) also admitted a west-dipping subduction-controlled regime. The steeping of the paleo-isotherms depicted by the close relations between the plutonic calc-alkaline rocks and peraluminous garnet, sillimanite and/or cordierite-bearing diatexites (Wiedmann et al., 1986, Rego, 1989, Campos Neto and Figueiredo, 1990, Fritzer, 1991, Campos Neto and Figueiredo, 1995) might be related to the asthenosphere upwelling below the arc ascribed by subduction at both sides of the northern Serra do Mar terrane. The calc-alkaline plutonic rocks of the arc comprise expanded suites of norite-enderbite-charnoenderbite and gabbro-diorite-tonalite-granodiorite forming elongated batholiths. They are mostly a low-K, high-Al calc-alkaline series, for both the western and the easternmost suites. More evolved K-rich tonalite and enderbite also occurs within a NE-oriented trend (Sluitner and Weber-Diefenbach, 1989, Rego, 1989, Figueiredo and Campos Neto, 1993, Wiedemann et al., 1997). These gneissic batholiths have intrusive contacts into metasedimentary and

migmatitic sequences. At the deeper granulitic units they generally show diffuse boundaries with the country rocks, although containing xenoliths of peraluminous migmatites. The life span of this subduction-related plutono-metamorphic orogen is robustly constrained between 580-565 Ma (Söllner et al., 1987, Söllner et al., 1989, Söllner et al., 1991). To the south, the Rio Negro Magmatic Arc was being renewed by the tonalite-granodiorite-granite suite from Serra dos Órgãos batholith (Machado and Demange, 1994). It is a thick stratiform-shaped and high-Ca calc-alkaline massif displaying mostly magmatic flow foliation, and having an age of 560 Ma (Tupinambá, 1999).

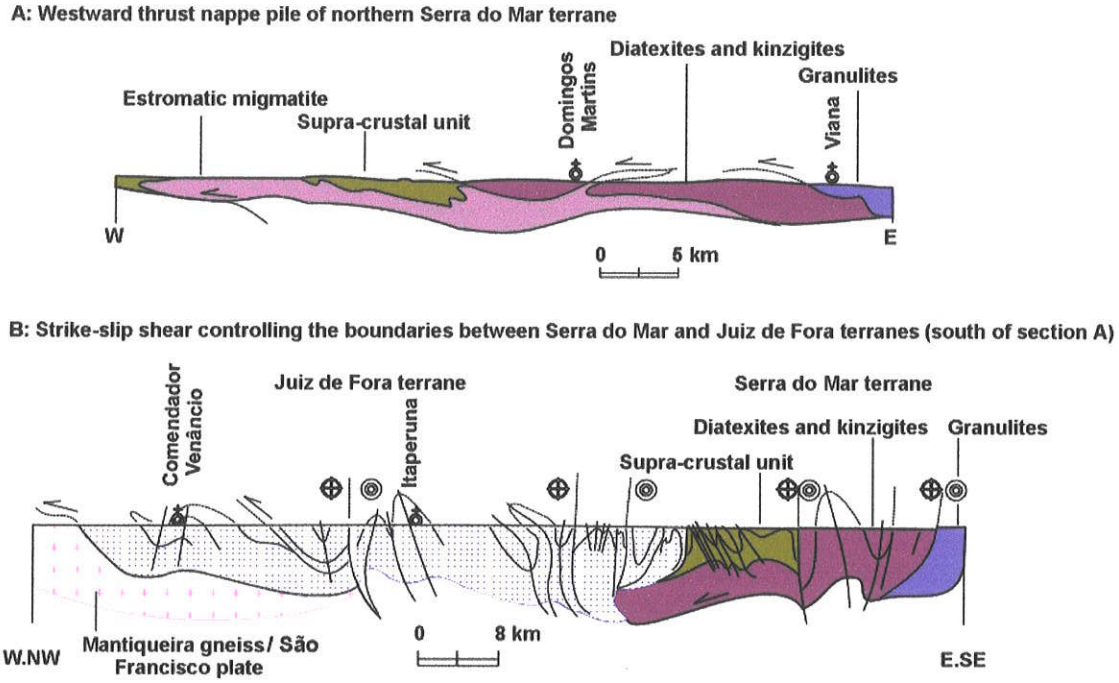

Figure 4-19: Cross-sections across Serra do Mar and Juiz de Fora terranes.

A widespread series of syn-kinematic peraluminous diatexites, and I-type granite and mangerite suites occur in the Serra do Mar terrane. They are related to the collision closure of the oceanic remnants. The apparently conflicting low-angle direction of displament is found in the main rock package of the Serra do Mar terrane. To the north, a westward high-temperature ductile shearing was followed by thrusting and the building of an inverted crustal pile. Further to the south, east-verging structures are in agreement with the east-verging, near-isoclinal recumbent folds (Heilbron et al., 1982) and eastward-displaced low-angle ductile shear zones and thrusting at the Cabo Frio terrane (Machado and Demange, 1990). The Cabo Frio terrane resembles a small fragment of passive margin related to a southwestern promotory of the Congo plate.

However these structures record diachronic collision episodes.

The voluminous ultra-high metamorphic, crustal magma generation and its upper related migmatitic fingers took place coeval with the western overriding of the Serra do Mar terrane, mostly at its northern extension. They were related to the closure of the V-shaped oceanic remnant between Serra do Mar and Juiz de Fora landmasses. This collision episode is recorded in the Neoproterozoic III-Cambrian boundary (ca. 550-540 Ma) by

zircon and monazite U-Pb gechronology (Delhal et al., 1969, Söllner et al., 1989, Söllner et al., 1991). At the African counterpart the widespread foreland deposits of the Nama Group and the unconformable uppermost cover of the Fish River Group were the cratonic record of a collision tectonics at the same time (Frimmel et al., 1998).

Nevertheless the final closure of the Adamastor Ocean was later in the Cambrian times. The high-pressure metamorphic conditions depicted by the kyanite-bearing assemblages in high-temperature metasediments from Cabo Frio terrane are incompatible with the low-pressure, high-temperature rocks at its neighbor Rio Negro and Serra dos Órgãos superposed batholiths. These different metamorphic belts are related to an eastern displacement and apparently ascribing a northwestward continental subduction of the western promontory of the Congo plate under the Serra do Mar terrane. This collision-related metamorphism is recorded by monazite and zircon U-Pb geochronology at 520 Ma. (Schimitt et al., 1999).

Pb/Pb isotopic studies carried out on undeformed carbonate rocks from the Bambuí Group in the cratonic area evidenced an incorporation of Pb-fluid phase promoting isotopic resetting and severe remagnetization at about 530-500 Ma (Babinsky et al., 1999, Agrella Filho et al., 1999). These data ascribe the continent-scale record for the last Mantiqueira collision, although most of the suture lines must have been hidden by the Atlantic drift.

Thus, the estimated life span of the Adamastor Ocean is at least of ca. 230 Ma from the Middle Cryogenian to the Middle Cambrian (750-520 Ma). Their complex plates and microplates interaction make it compatible with the Cordilleran-type evolution.

4-7.2.1. Late-orogenic basins

A series of pull-apart basins occur at the northwestern suture boundary of the Mantiqueira Orogenic system, reaching the Tocantins orogens up to the northern edge of the extrusion-related strike-slip shear zones. The development of these basins evidence several pulses of shear zones displacements. After the high-temperature dextral motion (ca.575 Ma, Machado et al., 1996) of the shear zones, and the exhumation of the metamorphic belt, a main sinistral displacement took place developing the pull-apart basins at their releasing bends. The sedimentation was storm-dominated with alluvial fans reaching the asymmetrical basin border and grading to alluvial plain deposits up to distal lacustrine environment though seaward conection (Juliani et al., 1990, Teixeira, 1995). They were weakly deformed by dextral transpression and metamorphosed under very low grades during the Mid-Cambrian last collision.

4-7.2.2. Post-orogenic transition from compressive to extensional collapse

Mixing-mingling of mantle and crustal derived magmas strongly characterized the post-orogenic plutonic rocks accreted mainly in the Serra do Mar terrane. They are coeval to circular zoned plutons of monzogabbro-norites and diorites partially wrapped by granites that characteristically display a wide and discontinuous central commingling and mixing zone. More mature magmatic phases comprise diorite-tonalite and granodiorites surrounded by granites (Wiedmann at al, 1993). Allanite granite from the zoned Angelica pluton displays a zircon age at the Upper Cambrian (ca. 513 Ma, Söllner et al., 1987). This magmatic event could be connected with the maintenance of the high-thermal gradient inducing metamorphism up to Lower Ordovician times (Siga Jr., 1986, Wiedmann et al.,

1993, Schimitt et al., 1999, Machado et al., 1996) that followed the final ca. 520 Ma collision episode.

4-7.3. General framework: the Ribeira Belt

The Ribeira Belt describes the main geometric features produced by the complex and diachronic kinematics plates interaction at the northern Mantiqueira orogenic system (Fig. 4-20).

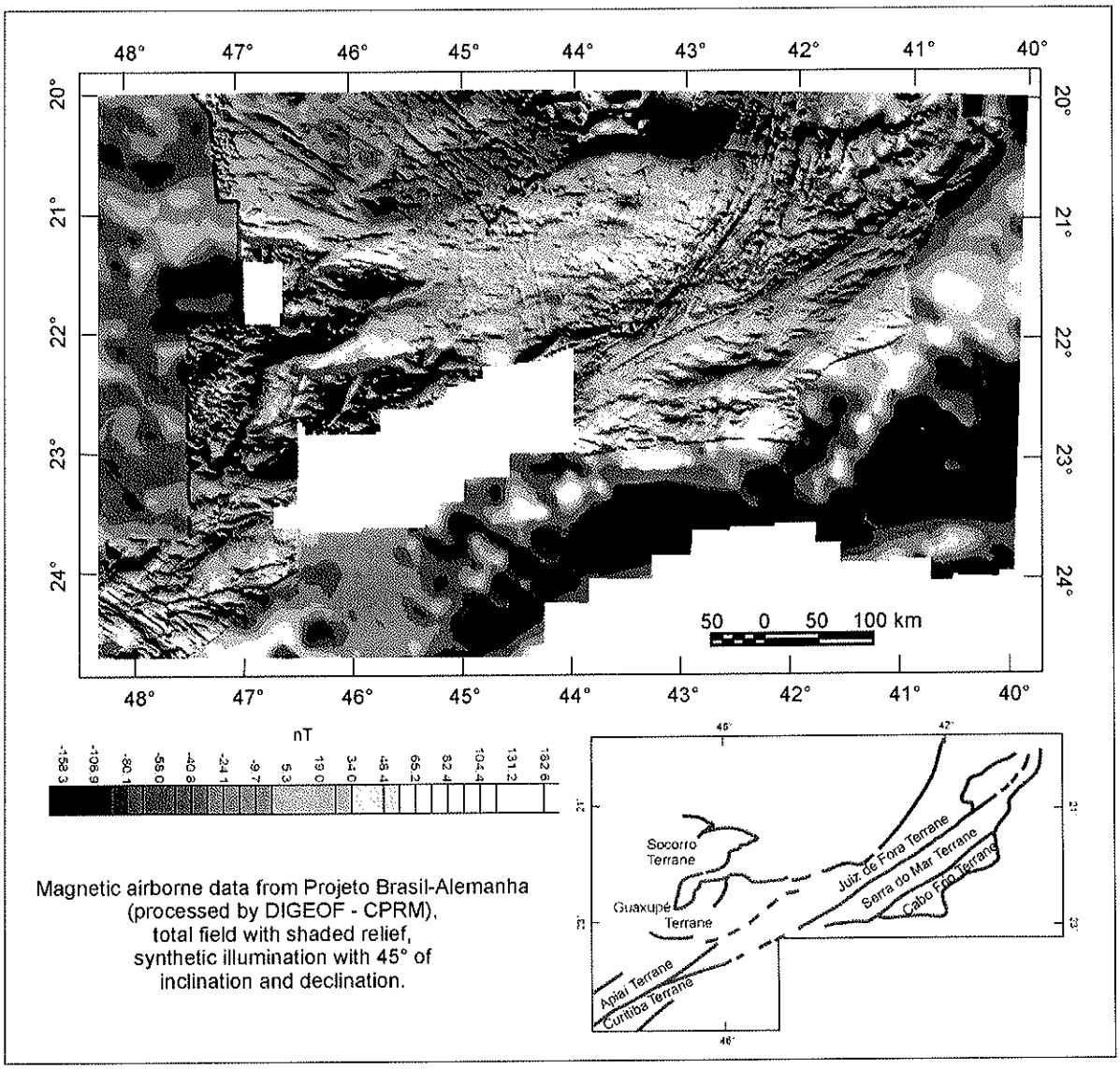

Figure 4-20: Aeromagnetic map from SE-Brazil. The NE-trending anomalies correspond to major shear-zones of the Ribeira belt.

The São Paulo Shear Belt (Hasui et al., 1984), up to 100 km wide, extends for 1000 km, delineating the boundaries between the terranes and normally overprinting low–angle metamorphic slices (Campos Neto and Figueiredo, 1995, Heilbron et al., 1995). The linear

belts of strong non-coaxial strain resulted from several pulses of mostly dextral strike–slip motion. They are a crust-scale shear-strain ascribed by an early high-temperature amphibolite to granulite facies metamorphism that decreases up to low greenschist facies toward the southwest. Most of the granites (Machado and Demange, 1998) display a shear zone-controlled emplacement. They are equigranular to porphyritic biotite-bearing metaluminous granites, and deeper garnet bearing coarse-grained to porphyritic granites associated with partial melting of the country rocks. They grade to shallow muscovite-bearing granites farther to the south, into the Embú Complex. Likewise the diachronous southeastward step up of the collision episodes, the granites related to the shear zones are older (590-565 Ma) in the Juiz de Fora terrane than the other ones emplaced in the Serra do Mar terrane (535-520 Ma). There the high-thermal gradient prevailed up to Lower Ordovician at 503-492 Ma (Ebert et al., 1996, Machado et al., 1996, Schimitt et al., 1999).

Toward the south the strike-slip shear zones display relict sinistral displacement. They are related to an amphibolite facies metamorphic condition at the northwestern of Apiaí terrane (Garcia and Campos Neto, 1997) contrasting with the low-grade mylonites from Lancinha shear zone at the southeastern edge of this terrane. Both shear zones were reprinted by later dextral displacement.

It results from dramatic episodes of lateral extrusion controlled by the kinematics of plate interaction related to the closure of the Adamastor Ocean acting against an oblique plate and microplates margins (Vauchez et al., 1994). The main west-oriented compression related to the northern Adamastor Ocean plate convergence explains the dextral vector of the shear zones. On the other hand the north-northeastern oriented compression related to the precedent southern closure of the oceanic branches results in a sinistral shear zone motion. The ca. 520 Ma-old westward collision controlled the locally intense dextral strike-slip overprint.

4-8. From Rodinia to Gondwana: SE-Brazil geodynamic evolution

Extensional regimes immediately followed the Grenvillian orogens in the Amazonas plate. They were also recorded in the São Francisco plate, and related to the Tonian-age taphrogeny (1.1-0.9 Ga), leading to the former break-up of Rodinia. A NW-elongated rift-valley dominates the western border of the São Francisco plate. A wide lower plate-type passive continental margin settlement is the record of the rift-drift evolution. These basin-forming tectonic processes were related to the Tonian taphrogeny and the opening of the Goianides Ocean. The spreading life of this ocean was early and locally replaced by intra-oceanic plate convergence triggering the Tocantins Orogenic system. A set of west-dipping subduction plates occurred diachronously generating island arcs, evolved magmatic arcs, and back-arc basins. The Rio de la Plata plate and Central Goiás terrane were driven against the western margin of the São Francisco plate. The early orogenies are recorded by the Mara Rosa Island Arc accretion (0.90-0.85 Ga) further docking over the western boundary of the Central Goiás terrane (0.80-0.77 Ga), promoting local metamorphism and relief. Farther to the south a back-arc spreading basin could have been nearly coeval with the Mara Rosa docking, separating two other magmatic arc built at the Middle Cryogenian: the eastern Anápolis–Andrelândia terrane, and the western active continental margin related to the Iporá-Jaupací/Socorro-Guaxupé terranes. The supracrustal units of these magmatic arcs were preserved at the opposite termination of both terranes. The southernmost comprises the collisional-related low-angle slices of high-pressure subducted continental slab of the

Anápolis-Andrelândia terrane, suggesting an oblique west-southwest driven plate subduction. At this time, the Upper Cryogenian diamictites correlated with the Sturtian-age glacial deposits preceded the carbonate cap toward the São Francisco plate interior and overlaying, unconformable, the western passive continental margin. The east-northeastward displacement of the southernmost high-pressure nappes seems to be controlled by the back up extrusion at a critical state of the west-dipping lithosphere subduction from the western edge of the São Francisco plate. The magmatic, metamorphic and depositional records of this main collision-controlled orogeny, juxtaposing the Rio de la Plata and the São Francisco plates and closing the Goianides Ocean, can be found everywhere in the Tocantins orogens, robustly constrained at 0.63-0.62 Ga. South of this orogenic system, the outward propagation of the high-pressure nappe system (comprising Ky-granulites and eclogites) reaching 200-km of displacement, was subjected to strong thinning, and temperature decrease at each thrusted slice. The overriding of the high-temperature root of the Socorro-Guaxupé nappe controlled an inverted metamorphism related to a near-isobaric heating throughout the upper high-pressure nappe. The external passive continental margin sequences following roughly this nappe kinematics displayed a medium-pressure metamorphic pattern. They attained the platform setting as a stretched, flat-lying, spoon-like, metamorphic nappe. The post-orogenic relaxation, at the inner nappe, took place at 612 Ma. Thus, a long life span (Fig. 4-21) of oceanic plate convergence (ca. 270 Ma) and the rapid overriding-type collision episode (ca. 18 Ma) required to preserve the high-pressure metamorphic slices are the main characteristic of the Tocantins orogenic system, having as modern analogous the India-Asia collision.

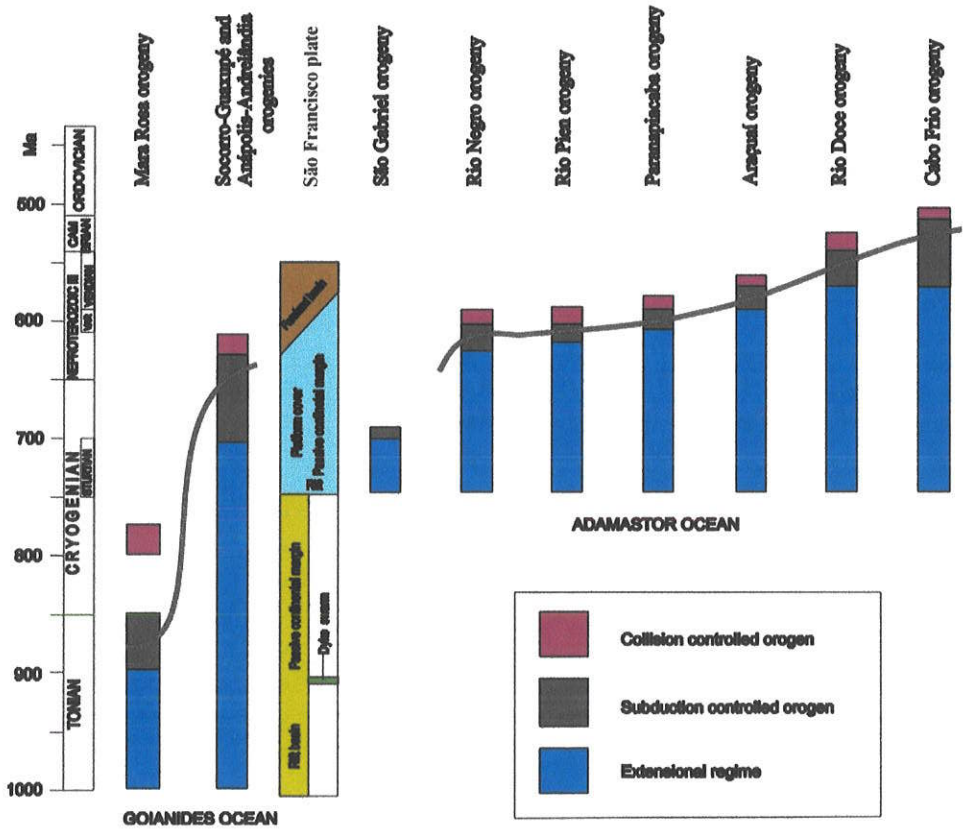

Figure 4-21: An attempt to a tectonic correlation table.

At the eastern margin of the São Francisco plate the Sturtian-age glacial deposits triggered the rift stage that evolved eastward to a deep marine basin connected with the Adamastor oceanic crusts. This extensional tectonic regime was coeval with the African counterpart rifting. Thus, the Mid-Cryogenian global break-up of Rodinia coexisted with the Tocantins orogenies. The diachronism of the succeding orogenic processes was a key characteristic of the Mantiqueira orogenic system. It was wholly related to complex interaction between several small continental plate fragments mostly turned to microplates closing the Adamastor oceanic branches.

The first record of plate convergence occurred early and locally (?) south of the Brazilian counterpart of this oceanic context, as a juvenile island arc accretion at 0.70 Ga (the São Gabriel intra-oceanic subduction-controlled orogeny). Therefore the plate interaction kinematics with an apparent northwest motion caused the closure of the southern Adamastor Ocean. The southern Mantiqueira orogens, mainly associated with evolved magmatic arcs and high-temperature metamorphic conditions recorded Neoproterozoic III subduction-controlled orogenies decreasing in age toward the eastern Rio de la Plata boundary, up to the 0.61 Ga back-arc basin. The main collisional period that closed the southern oceanic branches between terranes and the just-amalgamated Rio de la Plata-São Francisco plate took place at 0.60 Ga. NE-oriented sinistral shearing accommodated the crustal shortening. A wide peripheral foreland basin, containing Vendian palinomorphs, reached deep sea conditions and was contemporaneous with felsite volcanic up to 0.56 Ga. Small succeeding volcanosedimentary basins associated with extensive alkaline-peralkaline plutonism occurs essentially within this time span, up to younger (0.54 Ga) elsewhere farther the plate interior.

The northern Mantiqueira orogens started with the plate convergence and docking between Juiz de Fora and Serra do Mar terranes (the Rio Negro orogen 0.63-0.61 Ga) advancing the east-dipping subduction of the eastern margin of the São Francisco plate. The Araçuaí orogen that started at 0.60 Ga was ascribed to be responsible for the inversion of this passive continental margin and the eastward continental growing related to the subduction-controlled Galiléia Magmatic Arc (northwest-facing the Juiz de Fora terrane) and their collision against the eastern São Francisco passive continental margin (0.58 Ga). The Serra do Mar terrane was overprinted by newly magmatic arc (0.58-0.565 Ga) further overriding the northeastern of the Araçuaí orogen (~0.54 Ga) ascribing, as a whole, the Rio Doce orogen in a continued continental growing. NE-oriented dextral shearing mostly accommodated the strong east-west shortening and crustal thickening. This orogeny seems to have been wide in the Mantiqueira system on account of their shortening propagation controlling the inversion of the NE-trending foreland basins. At the African counterpart the major episode of continent-continent collision and oceanic crust obduction was essentially contemporaneous. Nevertheless the final consumption of the oceanic lithosphere was related to the collision of the western promontory of the Congo plate (the Cabo Frio terrane) against the just-amalgamated eastern Brazil, at the Middle Cambrian (0.52 Ga). The post-kinematic magmatism proceeded up to the Ordovician boundary. Excluding the early São Gabriel juvenile orogenic accretion the main convergence life span of the Adamastor Ocean lasted for 100 Ma (Fig. 4-21). The continent growth by long-lived succession of orogens, related to arc-derived crust accretions and docking against an older

plate enhancing the analogies between Mantiqueira orogens and the Cordilleran-style tectonics Clowes et al. (1999).

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