THE TECTONO-MAGMATIC EVOLUTION OF THE OCCIDENTAL TERRANE AND THE PARAÍBA DO SUL KLIPPE WITHIN THE NEOPROTEROZOIC RIBEIRA OROGENIC BELT, SOUTHEASTERN BRAZIL

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ABSTRACT The Occidental Terrane is envisaged as the eastern/southeastern reworked margin of the São Francisco/Rio de La Plata plate associated with an E-trending subduction under the Congo plate. The Paraíba do Sul *Klippe* is part of the Oriental Terrane, envisaged as a portion of the Congo plate. A collisional-stage resulted in intense westward deformation of the Occidental Terrane under intermediate pressure metamorphism (syn-D1+D2 events). A late-collisional stage resulted in subvertical folding and steep shear zones (D3 event). Both stages were associated with voluminous crustal-derived granites. U-Pb and Sm-Nd geochronology as well as geochemical and structural data point to three magmatic episodes: 1) a syn-collisional stage 1; 2) a syn-collisional stage 2; and 3) a late-collisional stage. This paper presents a magmatic evolutionary model for this crustal segment of the Ribeira orogenic belt based on new geological data of Brasiliano granites and data available in the literature.

Keywords: Ribeira belt, Brazilian granitoids, geochemistry, Sm-Nd isotopic data

INTRODUCTION The crustal structure of the Ribeira orogenic belt can be defined by two major tectono-stratigraphic terranes, as such: a) the Occidental Terrane is interpreted as the reworked margin of the São Francisco Plate and comprises an autochthonous domain, the so-called Andrelândia thrust system (which records Brasília belt-related deformation previous events), and the Juiz de Fora thrust system; b) the Oriental terrane is envisaged as part of the Congo Plate and encompasses the Paraíba do Sul *Klippe* as well as the Costeiro and Cabo Frio tectonic domains.

This paper presents new field, petrographic, geochemical and geochronological (Sm-Nd) data for six Brasiliano-related granitic plutons within the Occidental terrane and the Paraíba do Sul *Klippe* (Heilbron *et al*. 1998). These new data, together with published mineral U-Pb geochronology (Machado *et al*. 1996), field and geochemical data (Junho *et al*. 1999, Almeida, 1995) support the presently proposed model of three stages (syn-collisional 1, syn-collisional 2 and late collisional), associated with the collision of the São Francisco-Rio de la Plata and Congo plates (Heilbron *et al*. 1999) during the Brasiliano Orogeny (700-450Ma).

RESULTS The Neoproterozoic magmatism in the Occidental terrane and Paraíba do Sul *Klippe* (Fig. 1) within the Ribeira belt is of calc-alkaline nature (Fig. 2A) and is mostly represented by granites and subordinated granodiorites (Fig. 2B). Three collisional-related magmatic episodes can be recognized: 1) syn-collisional stage 1 (595-565 Ma); 2) syn-collisional stage 2 (565-540 Ma); and 3) late-collisional stage (540-520 Ma).

Syn-collisional 1: (Syn D1+D2 plutons) This stage is represented by abundant peraluminous S-type and metaluminous I-type, strongly foliated and mylonitic granites which occur as NE-SW elongated intrusions within the Juiz de Fora thrust system and Paraíba do Sul *Klippe***.** These features indicate that they were affected by the main deformation phase (D1+D2). The S-type plutons display characteristically abundant supracrustal xenoliths and transitional contacts with the metasedimentary country rocks. These features are suggestive of an anatectic origin. The largest S-type batholith is the syn-D2 Rio Turvo Granite located northwest of Volta Redonda and Barra Mansa (RJ). No geochemical data were yet published for the Rio Turvo Granite. A U-Pb concordant monazite age of 579±6 Ma (Machado *et al*. 1996.) is interpreted as the age of emplacement of the pluton, whereas a discordant titanite $^{207}Pb/^{206}Pb$ age of 551 Ma suggests that titanite crystallization took place during a later thermal pulse. The peak of metamorphism M1occurred at c. 579 Ma and can be associated with the main D1+D2 deformation event which in turn is taken as the period of main tectonic activity at the central segment of Ribeira orogenic belt. Preliminary Sm-Nd data for the Rio Turvo Granite (Table 1) indicate that some degree of fractionation might have occurred, as pointed out by the low $^{147}Sm/^{144}Nd$ values (about 0.07) a common value in garnet- and monazite-bearing S-type granites. As a result the T_{DM} obtained for this granite may be unrealistic. Alternatively, they might have been generated by melting of mixed sources such as Paleoproterozoic metasediments and 1,0-0,9 Ga basic rocks or still another unknown Mesoproterozoic source.

The Matias Barbosa Granite is the largest I-type pluton in the area occurring south of Juiz de Fora. Contacts between this pluton and the country rocks are mainly tectonic. Biotite is the main mafic phase although hornblende clots occur locally. The granite is generally granoblastic but K-feldspar megacrysts indicate a primary porphyritic nature. Whole-rock geochemistry data (Table 2) show variable composition, ranging from quartz-monzodiorite, granodiorite to granite (Fig. 2B) of predominantly metaluminous nature (Fig. 2C). The REE patterns are strongly fractionated with small Eu anomalies (Fig. 3A).

Syn-collisional 2: (late-D2 plutons) These are isotropic to slightly foliated I and S-type granites, which outcrop within the Juiz de Fora thrust system. The Pedra Selada, Serra do Lagarto (Junho *et al*. 1999), and Taquaral (Valladares 1996) I-type plutons are porphyritic to augen granites, whereas the S-type plutons are represented by the Salvaterra Charnoenderbite (Duarte 1998) and Capivara (Almeida 1995) granites, both mainly granular to granoblastic and locally porphyritic.

I-type granites are mainly (hornblende)-biotite porphyritic granites with microcline megacrysts, being homogeneous in composition (granites *s.s*; Fig. 2B). They often have mafic enclaves and lenses and consist of large NE-SW lenticular bodies. The Pedra Selada and Serra do Lagarto plutons are found nearby Visconde de Mauá (RJ), Bocaina de Minas and Passa Vinte (MG) whereas Taquaral pluton occurs southeast Resende (RJ). The porphyritic fabric of the Taquaral pluton is interpreted as resulting from magmatic syn-deformational flow of a partially crystallized magma. Titanite of the Taquaral Granite (Machado *et al*. 1996) yields a minimum U-Pb age of 553 Ma (4% discordant). No geochemical data were yet published for the Taquaral Granite. Geochemical data for the Pedra Selada and Serra do Lagarto plutons (Junho *et al.* 1999) point to metaluminous to slightly peraluminous magmas (Fig. 2C) with a strongly fractionated REE pattern and negative Eu anomaly (Fig. 3B).

The S-type granites are isotropic to slightly foliated and show granoblastic to porphyroblastic textures. The Salvaterra

Table 1 - Sm-Nd data for the Rio Turvo and Getulândia granites.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 1\sigma$)	$f_{Sm/Nd}$	T_{DM} (Ga)	ε_{Nd} (t) [a]
Rio Turvo Granite (Juiz de Fora thrust system)							
sample 1	18.48	143.43	0.0779	0.511599±09	-0.60	1.61	-11.50
sample 2	13.18	110.74	0.0719	0.511584±16	-0.63	1.56	-11.51
Getulândia Granite (Paraíba do Sul *Klippe*)							
sample 1	21.28	119.82	0.1079	0.511722±11	-0.45	1.97	-11.89

Total procedure blank was lesser than 0.2 ng for Nd. Values for La Jolla Nd standard $^{143}Nd/^{144}Nd = 0.511853 \pm 7$ (1σ).
Nd isotopic compositions were normalized to $^{146}Nd/^{144}Nd = 0.7219$. For location of the plutons see Figure 1.
[a] t = crystallisation age.
Analytical procedures: The Sm/Nd isotopic analyses were carried out at the Laboratory of Geochronology of the University of Brasília (UnB), Brazil. Sm and Nd concentrations were obtained by isotope dilution, using a mixed ^{149}Sm - ^{150}Nd spike. Measurements were performed on a Finnigan MAT 262 mass spectrometer in static multicollection mode. Samples were loaded as phosphates on double Re filament.

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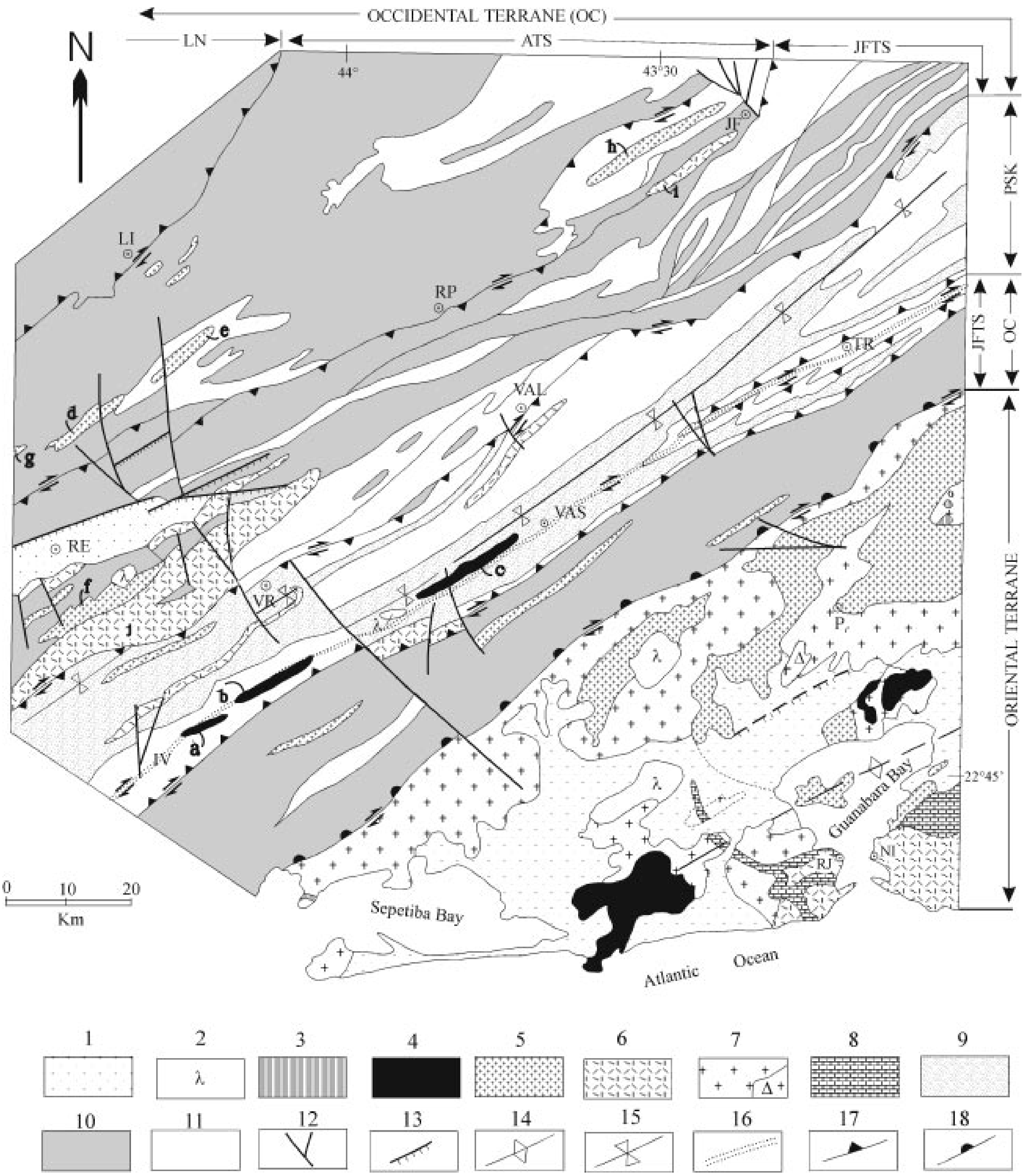

Figure 1 - Geological map of the central segment of the Ribeira belt (modified from Heilbron 1995; Heilbron et al. 1999) 1-Cenozoic cover; 2- Mesozoic-Cenozoic alkaline rocks; Brasiliano granites: 3- Slab detachment-related granites; 4- Late-collisional granites: a-Getulândia Granite, b- Fortaleza Granite, c- Serra do Ipiranga Granite; 5- Syn-collisional granites- late-D2 I-type plutons: d- Pedra Selada pluton, e- Serra do Lagarto pluton, f- Taquaral Granite; S-type plutons: g- Capivara Granite, h- Salvaterra Charnoenderbite; 6- Syn-collisional (syn D1+D2 I-type plutons): i- Matias Barbosa pluton; S-type plutons: j- Rio Turvo batholith; 7 - Magmatic arc rocks including alkaline rocks (D). Basin successions: - 8-Italva; 9- Paraíba do Sul and 10- Andrelândia. 11- pre-1.8 Ga basement associations. Tertiary faults: 12- transfer faults and 13- normal faults; 14- Rio de Janeiro mega-antiformal; 15- Paraíba do Sul megasynformal; 16- Paraíba do Sul shear zone; 17- Major thrusts; 18- Central tectonic boundary. Towns: JF-Juiz de Fora, LI-Liberdade, RP-Rio Preto, RE-Resende, VAL-Valença, VR-Volta Redonda, VAS-Vassouras, TR-Três Rios, P-Petrópolis, RJ-Rio de Janeiro, NI-Niterói. Abbreviations: LN-Liberdade Nappe, ATS-Andrelândia Thrust System, JFTS - Juiz de Fora Thrust System, PSK-Paraíba do Sul Klippe.

Charnoenderbite pluton is located on the west side of Juiz de Fora (MG). Fieldwork indicates that its most striking feature is the transition to paragneisses. Oriented schlieren structures, which are parallel to the main regional foliation, resemble ghost features inherited from the pre-existing gneisses. An igneous porphyritic texture is locally preserved and phenocrysts include feldspars, garnet and orthopyroxene. Close to the thrust planes and/or sheets, the Salvaterra Charnoenderbite acquires a mylonitic texture resulting from D2 thrusting. Modal analysis and geochemical data (Table 2) reveal a granodioritic composition (Fig. 2B) and a calcalkaline, peraluminous character (Fig. 2A and C). Among the studied granites, the Salvaterra Charnoenderbite displays the least fractionated REE pattern and an either negative or positive Eu anomaly (Fig. 3B).

The Capivara granite (Almeida 1995) is located near Itamonte (MG) and occurs as a NE-SW lenticular intrusion. Geochemical data (Almeida 1995) indicate a homogeneous granite composition (Fig. 2B) as well as a strongly peraluminous nature (Fig. 2C). This pluton displays a moderate fractionated REE pattern and negative Eu anomaly (Fig. 3B).

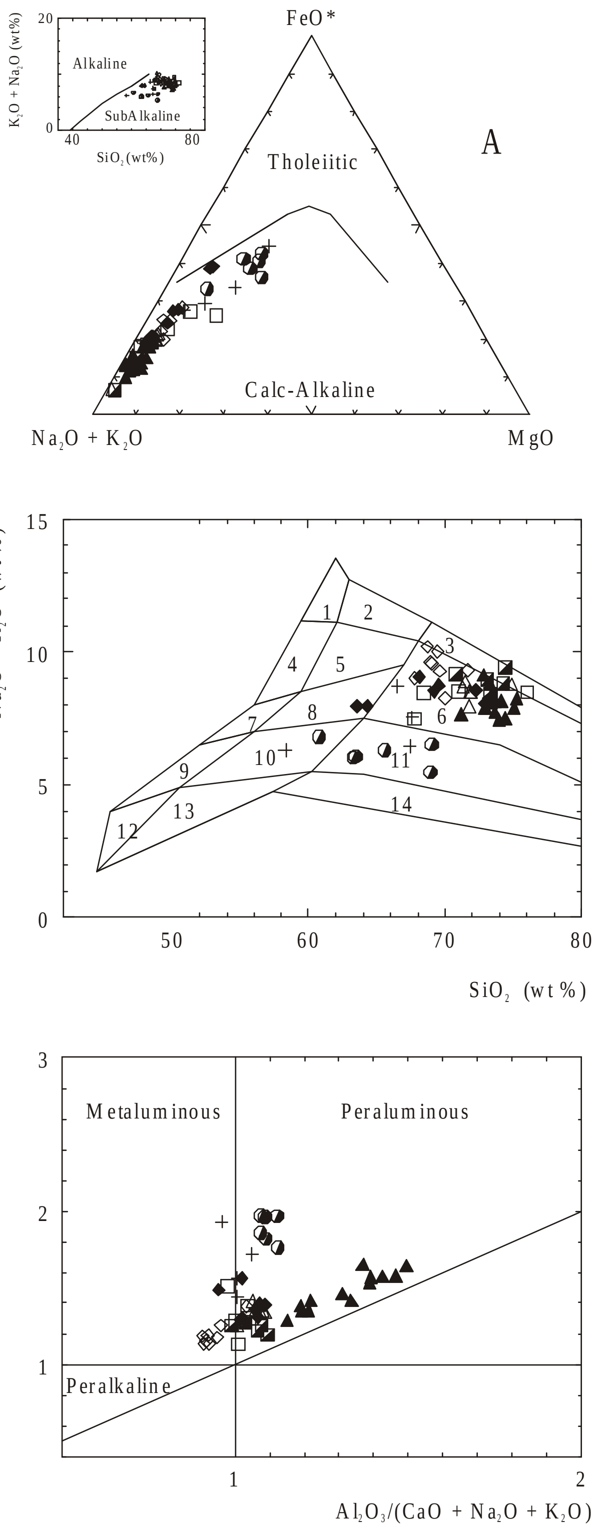

Figure 2 - A-TAS and AFM diagrams. B- Chemical classification (Middlemost 1985); Fields: 3- Alkali-feldspar granite; 6- Granite; 8- Quartz monzonite; 10- Quartz monzodiorite; 11- Granodiorite. C- Shand's index diagram. Symbols: Syn-collisional (syn D1+D2 I-type) Matias Barbosa Granite (cross); Syn-collisional - late D2 I-type plutons: Pedra Selada Granite (closed diamond), Serra do Lagarto Granite (open diamond); Syn-collisional - late D2 S-type plutons: Salvaterra Charnoenderbite (half-closed circle), Capivara Granite (closed triangle); Late-collisional plutons: Getulândia Granite (open square), Fortaleza Granite (half-closed square), Serra do Ipiranga Granite (open triangle).

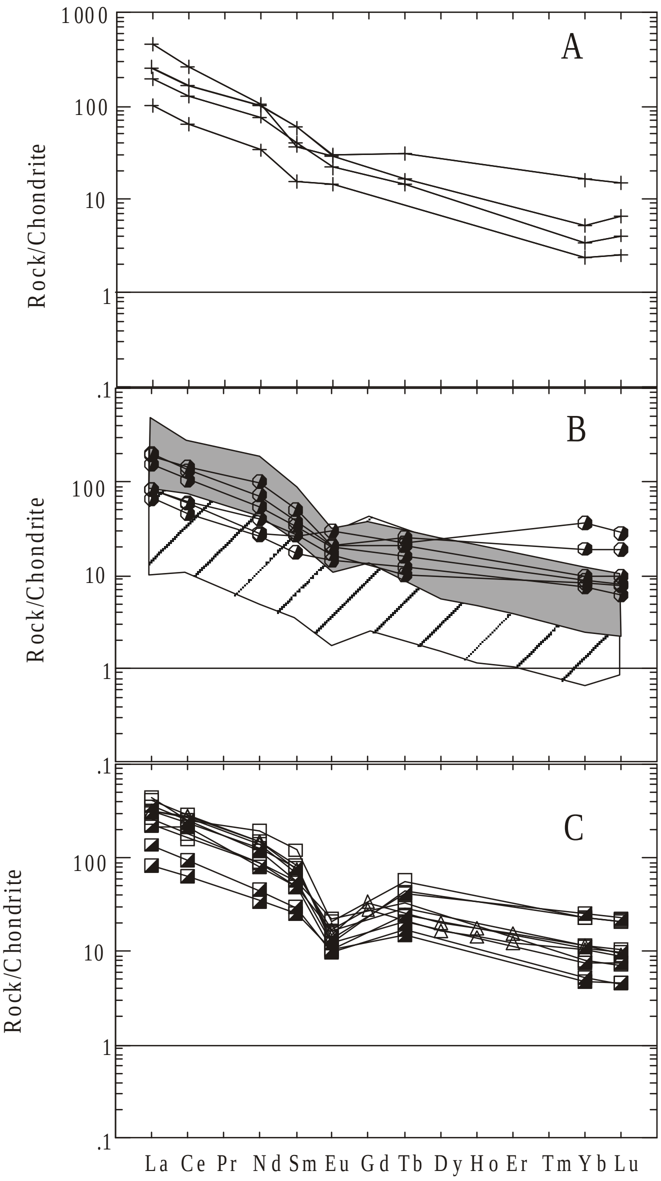

Figure 3 - Chondrite-normalized (Boynton 1984) REE patterns of the studied granites. A - Syn-collisional (syn-D1+D2 I-type) Matias Barbosa Granite (cross); B- Syn-collisional (late-D2 I-type) plutons: Pedra Selada Granite and Serra do Lagarto Granite (gray fill); Syn-collisional (late-D2 S-type) plutons: Salvaterra Charnoenderbite (half-closed circle), Capivara Granite (hatched pattern); C - Late-collisional plutons: Getulândia Granite (open square), Fortaleza Granite (half-closed square), Serra do Ipiranga Granite (open triangle).

Table 2 - Chemical composition of the syn-collisional (syn D1+D2 pluton) Matias Barbosa Granite (samples 1 to 5) and the syn-collisional (Late-D2) Salvaterra Charnoenderbite (samples 6 to 10).

Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SiO_2	57.57	66.09	66.52	66.62	68.27	58.85	61.34	63.17	65.37	69.44
TiO_2	1.14	0.67	0.69	0.71	0.52	0.99	0.72	0.66	0.73	0.52
Al_2O_3	16.87	15.95	15.10	15.00	14.41	16.96	15.64	16.42	15.50	15.57
$Fe_2O_3{}^t$	8.22	4.07	4.06	4.70	5.53	6.16	6.90	6.55	6.01	4.26
MnO	0.15	-	0.05	0.05	0.09	0.06	0.09	0.09	0.07	0.05
MgO	3.02	0.97	1.37	2.01	1.70	3.14	2.55	2.58	2.34	1.12
CaO	4.85	2.62	2.93	3.07	3.05	3.68	3.66	3.72	3.15	2.76
Na_2O	3.57	3.03	2.90	3.22	2.58	3.51	2.86	3.27	3.07	3.10
K_2O	2.65	5.64	4.53	3.17	2.84	3.08	2.98	2.76	3.20	3.46
P_2O_5	0.68	0.30	0.28	0.21	0.09	0.46	0.18	0.34	0.24	0.32
LOI	0.95	0.60	0.45	1.20	0.60	0.63	0.74	0.59	0.76	0.29
Total	99.67	99.94	98.88	99.96	99.68	97.52	97.80	100.15	100.44	100.89
Cr	-	-	-	-	-	110	88	80	68	36
Ni	5	2	10	12	21	48	37	38	40	23
V	114	55	53	77	53	79	65	62	71	31
Rb	165	125	123	114	110	103	115	79	82	82
Ba	1787	2998	986	840	825	857	735	723	845	1311
Sr	1003	854	326	339	272	408	265	284	286	330
Hf	2.60	7.80	5.10	4.40	7.90	3.50	5.30	3.20	4.20	5.50
Zr	91	338	213	186	267	155	160	471	247	276
Y	46	13	14	7	44	14	36	26	28	36
La	78.60	139.00	59.00	31.10	25.30	57.50	59.70	25.80	20.70	47.40
Ce	133.00	211.00	102.00	51.00	47.00	113.00	105.00	49.00	37.00	86.00
Nd	60.00	63.00	45.00	20.00	17.00	58.00	42.00	24.00	16.00	33.00
Sm	11.20	7.23	7.80	3.02	5.16	9.40	7.10	5.30	3.40	6.60
Eu	2.17	2.10	1.60	1.07	2.20	1.50	1.50	1.24	1.07	1.50
Tb	1.50	0.80	0.70	-	1.10	1.00	1.20	0.50	0.60	0.80
Yb	3.40	1.10	0.70	0.50	7.50	2.00	3.90	1.75	1.57	1.85
Lu	0.48	0.21	0.13	0.08	0.91	0.31	0.59	0.25	0.20	0.26

Analyses carried out at ACTLABS (Canadá): major and trace elements - ICP fusion; REE - INAA. XRF and ICP analyses for the Serra do Ipiranga Granite were carried out at GEOSOL Laboratory (Brazil). Major and trace elements are expressed in %wt and ppm, respectively.

Table 3 - Chemical compositions of the late-collisional granites from the Paraíba do Sul Klippe. Getulândia Granite (samples 11 to 14), Fortaleza Granite (samples 15 to 19) and Serra do Ipiranga Granite (samples 20 to 25).

Sample	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
SiO_2	66.19	67.45	69.62	74.63	70.13	70.38	71.34	73.05	73.48	70.50	70.80	70.80	71.20	71.20	74.30
TiO_2	0.74	0.55	0.39	0.18	0.30	0.17	0.09	0.24	0.23	0.31	0.32	0.33	0.33	0.34	0.06
Al_2O_3	14.36	15.19	14.16	11.98	14.48	14.18	13.79	13.83	13.44	14.60	14.60	14.40	14.40	14.80	13.80
Fe_2O_3	3.85	3.69	2.93	2.07	2.51	1.35	0.70	2.20	1.75	0.70	0.83	0.82	0.59	0.74	0.17
FeO										1.80	1.50	1.50	1.90	1.40	0.49
MnO	0.06	0.06	0.07	0.03	0.04	0.03	0.03	0.03	0.06	0.03	0.03	0.03	0.03	0.03	0.01
MgO	1.12	1.93	0.69	0.20	0.50	0.35	0.19	0.37	0.29	0.49	0.41	0.51	0.49	0.50	0.11
CaO	1.93	3.03	1.74	0.71	1.68	1.03	0.59	1.43	0.88	1.50	1.50	1.50	1.40	2.00	1.50
Na_2O	2.66	3.50	3.49	2.81	3.10	3.49	3.12	3.11	2.87	2.80	3.00	2.70	2.90	3.40	2.80
K_2O	5.52	3.96	4.88	5.52	5.98	5.14	5.92	5.28	5.84	5.80	5.80	5.70	5.50	4.50	5.90
P_2O5	0.32	0.20	0.18	0.06	0.34	0.16	0.10	0.10	0.08	0.10	0.11	0.11	0.10	0.11	0.05
PF	1.05	1.20	1.53	0.89	0.98	1.42	2.06	1.17	0.87	0.85	0.62	1.17	0.68	0.63	0.72
Total	97.80	100.76	99.68	99.08	100.04	97.70	97.93	100.81	99.79	99.48	99.52	99.57	99.52	99.65	99.89
Cr	11	55	2	1	9	7	4	2	4						
Ni	5	20	2	1	3	2	1	2	2						
Rb	284	206	168	244	343	301	234	297	409	310	300	310	290	250	260
Ba	737	861	729	468	1184	529	796	1248	382	770	710	730	760	680	680
Sr	153	305	365	59	193	139	263	199	87	170	170	170	170	210	190
Zr	328	191	267	248	164	114	76	213	205	330	360	380	330	390	60
La	135.4	70.91	82.02	126.29	96.31	42.27	25.66	111.4	67.23		98.17			97.51	
Ce	203.62	130.57	147.73	234.24	191.8	75.82	51.11	204.74	174.89		224.70			220.40	
Nd	117.83	54.24	52.98	89.62	75.71	27	20.86	71.26	48.52		88.96			85.00	
Sm	23.77	11.05	9.58	16.29	15.14	5.71	4.9	11.04	9.6		14.50			13.02	
Eu	1.56	1.64	1.21	0.9	1.02	0.72	0.78	0.9	0.76		1.08			1.24	
Gd											8.61			7.27	
Tb	2.79	1.61	1.43	2.14	2.02	0.83	0.73	1	1.21						
Dy											6.48			5.27	
Ho											1.26			1.02	
Er											3.19			2.60	
Yb	4.83	1.69	2.38	4.77	5.35	1.09	0.99	1.6	2.29		2.37			2.16	
Lu	0.67	0.23	0.34	0.68	0.73	0.15	0.15	0.24	0.31		0.30			0.29	

Analyses were carried out at ACTLABS (Canadá): major and trace elements - ICP fusion; REE - INAA. XRF and ICP analyses for the Serra do Ipiranga Granite were carried out at GEOSOL
Laboratory (Brazil). Major and trace elements are expressed in %wt and ppm, respectively.

Late-collisional magmatism This widespread magmatism within the Paraíba do Sul *Klippe* can be characterized by subvertical dykes and NE-SW elongated plutons related to the late deformation event structures (D3 shear zones). Expressive examples include the Serra do Ipiranga pluton (Heilbron *et al*. 1992), nearby Barra do Piraí, and the Getulândia and Fortaleza granites (Valladares *et al.* 1995, Valladares 1996) between Barra Mansa and Rio Claro. These intrusions are homogeneous in composition, being granites *s.s.* (Fig. 2B), and bear biotite as the mafic mineral. These plutons have a NE-SW weak foliation interpreted as magmatic flow foliation in the Serra do Ipiranga (Heilbron and Machado 1995) and Fortaleza intrusions. Geochemical data (Table 3) are typical of I-type granites with a slightly peraluminous character (Shand's index between 1,0 and 1,1). Chondrite-normalized REE patterns are fractionated and display a pronounced negative Eu anomaly (Fig. 3C). The most reliable geochronological data representing this magmatic event are the two U-Pb monazite analyses of presented by Machado *et al.* (1996) and Valladares (1996) for the Getulândia Granite. These data yield concordant ages of 527± 3Ma and 535± 3 Ma and are taken as the minimum age for movement in the shear zone along which the Getulândia pluton was emplaced during stage D3. The only available Nd isotopic data yield a Transamazonian depleted mantle model age (T_{DM}, Table 1), suggesting that it might have derived from reworked basement rocks.

CONCLUDING REMARKS Granite magmatism in the study area can be divided into three stages based on U-Pb geochronology, geochemistry and structural geology (Table 4): 1) the syn-collisional stage 1 (595-565 Ma) is represented by foliated, peraluminous S-type and metaluminous I-type granites; 2) the syn-collisional stage 2 (565-540 Ma) comprises weakly foliated metaluminous I-type granites with basic enclaves, peraluminuous S-type granites and minor leucogranites; 3) the late-collisional stage (540-520 Ma) includes alkali-calcic, slightly peraluminous leucogranites which occur as subvertical dykes and late shear zones-related plutons. Preliminary Sm-Nd isotopic data indicate that the late-collisional granites might have derived from reworked basement rocks. The syn-collisional 1 S-type granites were generated by melting of mixed sources, possibly Paleoproterozoic metasediments and 1,0-0,9 Ga basic rocks, or yet another unknown Mesoproterozoic source.

Table 4 summarizes the relationships between magmatism and tectonics within the central segment of the Ribeira fold belt, including a comparison between the magmatic record on the Occidental and Oriental terranes. The time span proposed for the pre-collisional stage (restricted to the Oriental terrane) is based on U-Pb geochronological data in Tupinambá (1999).

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Table 4 - General characteristics of the Brasiliano granites of the Occidental and Oriental terranes, according to the stage of orogeny and time relationships with deformation phases.

Stage of orogeny / deformation	Time span (Ma)	Geochemistry	Plutons/Age (Ma)	Structures	Tectonic Domains	Tectonic setting	Selected references
Slab detachment - related granites	< 520	• Calc-alkaline to alkali-calcic plutons • Tholeiitic gabbros and diorites		Non-foliated and mostly zoned stocks and sheets. Primary flow foliation and layering. Dykes. Possible mingling and mixing processes	Recorded in both tectonic terranes	Extensional collapse of the orogenic belt	(1) (2) (3) (4), (5), (12) (18)
Late-collisional (syn-D3)	540-520	• Alkali-calcic stocks of slightly peraluminous leucogranites	• Getulândia (535-528Ma) Fortaleza and Serra do Ipiranga.	D3 shear zones-related subvertical dykes and weak foliation along contacts	Recorded in both tectonic terranes	Crustal reworking of basement and cover rocks	(5), (6), (7), (8), (9), (10), (11), (12), (19)
Syn-collisional 2 (Late-D2)	565-540	• Abundant metaluminous I-type granites with basic enclaves • Peraluminous S-type granites • Subordinated two-mica peraluminous S-type leucogranites	• Serra do Lagarto; Pedra Selada and Taquaral (553Ma) • Salvaterra Charnoenderbite • Capivara	Weakly foliated plutons and sheets	Recorded in both tectonic terranes	Crustal reworking of basement and cover rocks	(8), (9) (10), (13) (14) (15) (17) (20)
Syn-collisional 1 (Syn-D1+D2)	595-565	• Abundant peraluminous S-type granites • Metaluminous I-type granites	• Rio Turvo batholith (579Ma) • Matias Barbosa	Foliated and mylonitic plutons	Recorded in both tectonic terranes	Crustal reworking of basement and cover rocks	(5) (8) (9) (10),(17)
Pre-collisional (Pre-D1)	630-595	• Tonalites to granodiorites and tholeiitic gabbros		Foliated plutons. Mylonitic structures associated with tectonic boundaries	Only within Oriental terrane	Cordilleran Magmatic Arc	(4) (16)

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