



Anais da Academia Brasileira de Ciências

ISSN: 0001-3765

aabc@abc.org.br

Academia Brasileira de Ciências

Brasil

Machado, Rômulo; Dehler, Nolan M.; Vasconcelos, Paulo
40Ar/39Ar ages (600-570 Ma) of the Serra do Azeite transtensional shear zone: evidence for
syncontractional extension in the Cajati area, southern Ribeira belt
Anais da Academia Brasileira de Ciências, vol. 79, núm. 4, 2007, pp. 713-723
Academia Brasileira de Ciências
Rio de Janeiro, Brasil

Available in: <http://www.redalyc.org/articulo.oa?id=32779411>

- How to cite
- Complete issue
- More information about this article
- Journal's homepage in redalyc.org

redalyc.org

Scientific Information System

Network of Scientific Journals from Latin America, the Caribbean, Spain and Portugal

Non-profit academic project, developed under the open access initiative



$^{40}\text{Ar}/^{39}\text{Ar}$ ages (600-570 Ma) of the Serra do Azeite transtensional shear zone: evidence for syncontractional extension in the Cajati area, southern Ribeira belt

RÔMULO MACHADO¹, NOLAN M. DEHLER² and PAULO VASCONCELOS³

¹Instituto de Geociências/USP, Rua do Lago 562, 05508-900 São Paulo, SP, Brasil

²PETROBRAS – E & P- EXP, Av. República do Chile, 65, 13º andar, 20031-912 Rio de Janeiro, RJ, Brasil

³University of Queensland, Brisbane Qld 4072, Australia

*Manuscript received on April 17, 2006; accepted for publication on March 21, 2007;
presented by ALCIDES N. SIAL*

ABSTRACT

This paper presents $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the rocks from the Serra do Azeite transtensional shear zone in the southern part of the Ribeira belt, between the States of São Paulo and Paraná, and also discusses the regional correlations and the tectonic implications for other parts of the belt. The geochronological data suggest that transtensional deformation was active between 600 and 580 Ma (hornblende and muscovite apparent ages, respectively). This time span is considerably older than previous proposals for the period of activity of these structures (520-480 Ma) in the northern segment of this belt and in the Araçuaí belt. Kinematic analysis of the dated mylonites shows extensional structures with top-down movement to ESE compatible with structures found in other tectonic segments in the eastern portion of the Quadrilátero Ferrífero and in the Rio Doce Valley region. Our ages are situated in the same time interval defined for the alkaline magmatism of the Serra do Mar suite. We suggest that the regional tectonic framework was developed during continental-scale extension. This process has been coeval with convergent strain in the adjacent Neoproterozoic shear zones of the Apiaí/Ribeira and Araçuaí belts, which make up significant segments of these belts. The available data show that these structures may not be simply related to post-orogenic gravitational collapse, but must involve a more complex process probably related to dynamic balance between crustal thickening and thinning during tectonic convergence, basin formation and exhumation processes.

Key words: syncontractional extension, $^{40}\text{Ar}/^{39}\text{Ar}$ ages, Ribeira belt.

INTRODUCTION

Extensional structures have been described in several regions closely associated, temporally and/or spatially, with compressive tectonics (Coney and Harms 1984, Royden and Burchfield 1987, Ratschbacher et al. 1991a, b, Wheeler and Butler 1993, Braathen et al. 2002). These structures have been commonly interpreted as derived from gravitational instabilities generated by crustal overthickening and progressive uplift that accompany mountain building (e.g. Malavieille 1993). Such a frame-

work may result from complex tectonic processes that involve dynamic plate interactions, in which extension may be contemporaneous with, later than, or decoupled from crustal shortening and deformation, either due to the steep downward slope of the oceanic slab in a subduction zone, in under the back-arc region, or from uplift of the asthenospheric mantle wedge (Doglioni 1996). Other processes, such as changes in the kinematic vectors between plates and post-collisional rifting, may also explain the occurrence of extensional regimes (see also Glazner and Bartley 1985, Dewey 1988).

Correspondence to: Rômulo Machado
E-mail: rmachado@usp.br

The tectonic framework of southeastern Brazil, also called the Mantiqueira Province, has been attributed mainly to the Brasiliano/Pan-African orogeny developed between 1.0 and 0.5 Ga (Almeida et al. 1973, Brito Neves and Cordani 1991). Marginal to this province a stable Neoproterozoic nucleus, the São Francisco craton, has been recognized (Almeida 1977), surrounding by Brasiliano fold-thrust belts such as the Araçuaí and Ribeira belts. Several well-preserved examples of extensional structures have been described in different segments of the São Francisco craton, presenting east/south-east-verging extension (Fig. 1), such as in the eastern portion of the Quadrilátero Ferrífero (Endo 1997), in the Araçuaí fold belt (Nalini 1997, Machado et al. 2001, Alkmim et al. 2002) and in the Costeiro Granite Belt (Basei et al. 2000), which crops out as a distinct unit within the Ribeira belt.

Records of the extensional settings in the Ribeira and Araçuaí belts are also interpreted as result from orogenic collapse postdating the regional contractional strain (Pedrosa Soares et al. 2000, Trouw et al. 2000, Heilbron et al. 2004).

In the southern segment of the Ribeira belt, extension is thought to have occurred between 610 and 570 Ma on the basis of indirect evidence (i.e. ages of alkaline granitic magmatism and sedimentary tectonic basin sedimentation (Siga Jr. et al. 1999, Basei et al. 2000).

In the central and northern parts of this belt, extension is believed to have occurred between 520 and 480 Ma, although detailed geochronological and structural data are still not available (Trouw et al. 2000, Heilbron et al. 2004).

In the Cajati region, kinematic indicators related to ductile deformation, such as S-C foliation planes, asymmetric porphyroclasts and boudins, and asymmetrical extensional shear bands are quite consistent with oblique, E to SE extension towards east-to south, with important sinistral strike-slip motion (Dehler et al. 2000). These structures are related to a mid- to deep-crustal transtensive shear zone which developed after the main crustal thickening event under compressive tectonic regime of the Ribeira belt.

In this paper we present $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric data for the mylonitic rocks related to the Serra do Azeite

shear zone, and describe the extensional structures in the southern segment of the Ribeira belt (see Fig. 1). We also discuss regional structural correlations and tectonic implications for the Precambrian between São Paulo and Paraná states.

GEOLOGICAL SETTING AND STRUCTURE OF THE SERRA DO AZEITE TRANSTENSIONAL SHEAR ZONE

The studied area is located in the southern part of the Ribeira belt – northern edge of a high grade terrain called of Costeiro Granite belt by Basei et al. 2000 – where the Serra do Azeite shear zone is one of the main structures together with other subparallel shear zones (Figs. 1A and B).

Semi-detailed geological cartography (scale 1: 50.000) carried out in the Cajati region (Fig. 1b) (Vasconcelos et al. 1999) identified three major lithostratigraphic sequences: 1) marbles, aluminous schists and gneisses metamorphosed in the amphibolite facies; 2) orthogneisses with inclusions of amphibolites and meta-ultramafic rocks; 3) and amphibolites and interlayered anorthosites, with subordinated tonalitic orthogneiss.

The first sequence is composed of (kyanite)-(garnet)-(sillimanite)-biotite-muscovite schists and gneisses. The metapelitic units are locally migmatitic, and deformed two-mica granites are also present. Marbles, amphibolites and calc-silicate rocks are also common (Vasconcelos et al. 1999). These units are correlated with the Turvo-Cajati Sequence of Silva and Algarte (1981a, b).

The second sequence is characterized by banded and laminated orthogneisses that vary in composition from granite to tonalite in the felsic parts, and amphibolite, diorite and ultramafic in the dark bands or inclusions. This unit was correlated by Vasconcelos et al. (1999) with the Atuba Complex, yielding U-Pb zircon ages between 2100 to 1800 Ma, and was reworked during the Brasiliano Orogeny (Siga Jr. 1995, Picanço et al. 1998).

The third sequence is composed by coarse-grained and mylonitic gabbro, and anorthosites that are correlated with the Serra Negra Complex (Vasconcelos et al. 1999).

The Serra do Azeite shear zone was previously described as having recumbent to isoclinal folds, refolded by inclined folds, oriented with E-W to ESE trending axes with NNW or N to NNE vergences, respectively

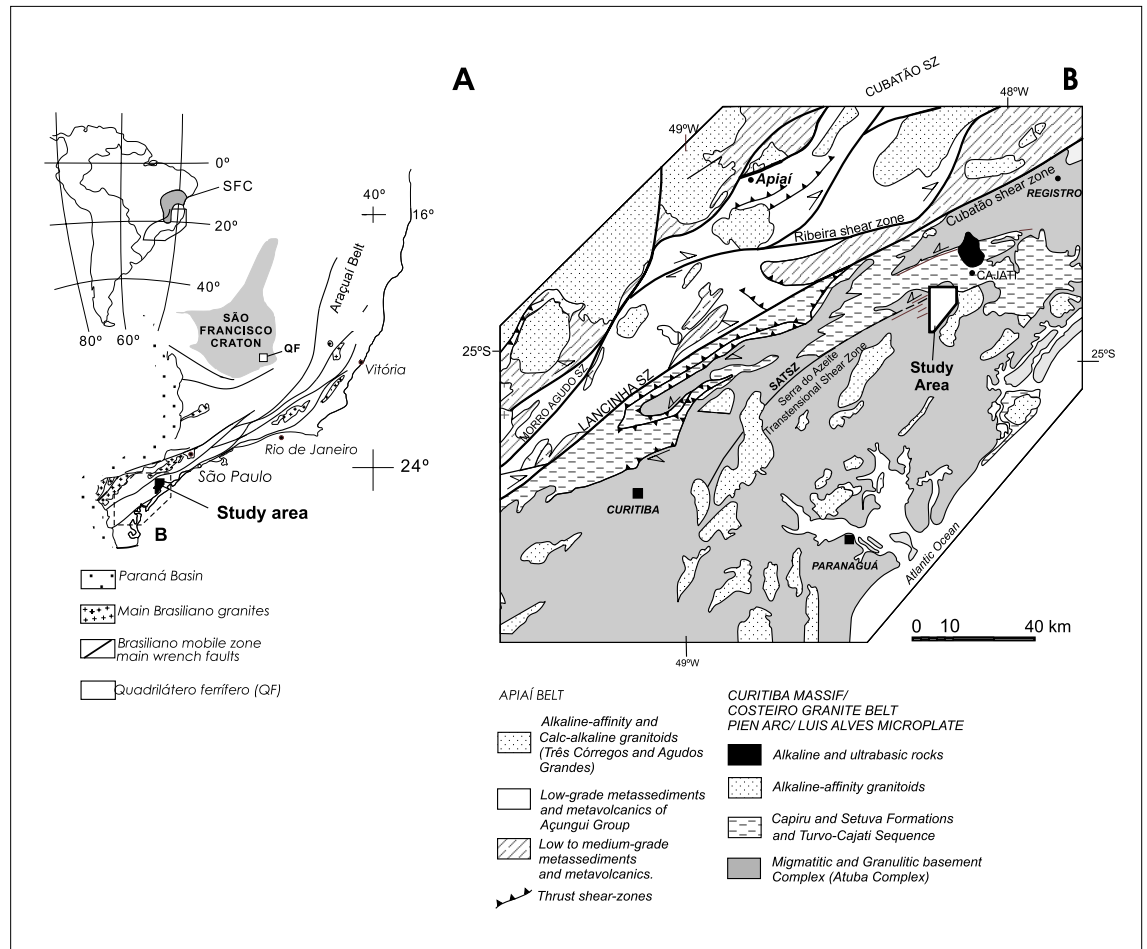


Fig. 1 – (A) Tectonic sketch of the Ribeira and Araçuaí belts, southern Brazil; (B) Geological-structural map of the northern portion of the Costeiro Granite belt, and localization of the study area (modified from Machado et al. 2001, Dehler et al. 2000, Basei et al. 2000).

(Campos Neto 1983). The author recognized that the orthogneissic units overthrust the metasedimentary rocks, with top-to-northwest sense of motion.

Recent kinematic studies, however, have described ductile sinistral transtensional tectonics with top-down-to-ESE for the same region (Dehler et al. 2000) associated with the Serra do Azeite shear zone. These authors described mylonites with foliation dipping to southeast, associated with a well-developed SE-SSE plunging stretching lineation. The foliation exhibits shallow to moderate dips (in the first sequence and part of the second) in the northern part of the studied area, and steeper dips in the third sequence on top of mylonites in the southern part

(see Figs. 2 and 3). The geometry shown by the disposition of the mylonitic foliation resembles an incomplete fan-shape (Fig. 3: A-A'), usually reported as a structure associated with transpressive/transpressive regimes.

Petrographic and microtectonic data for the peraluminous mylonitic association mainly show kyanite reequilibration to sillimanite (fibrolite) in the presence of primary muscovite. This suggests that mylonitization developed under medium-grade metamorphic conditions, at medium pressure (Silva and Algarte 1981a, Vasconcelos et al. 1999). The unstable kyanite was replaced by sillimanite which marks the transtensional stretching lineation, suggesting a higher pressure, pri-

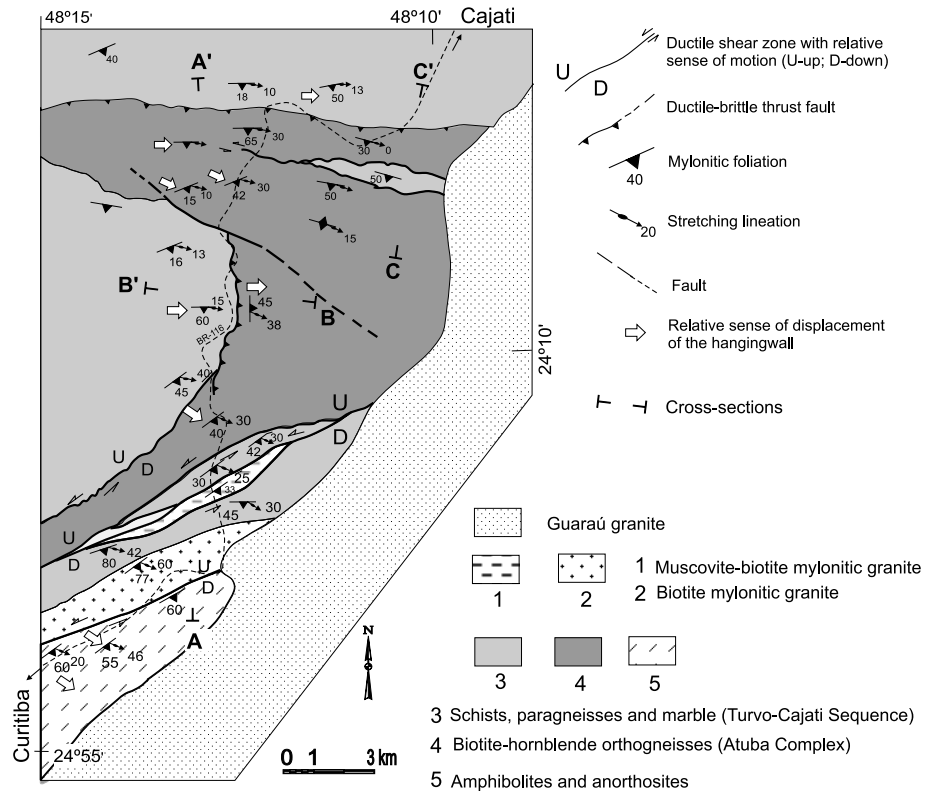


Fig. 2 – Geological map showing the distribution of main lithostructural units in the Cajati region (modified from Dehler et al. 2000). For localization see map and caption of Figure 1B.

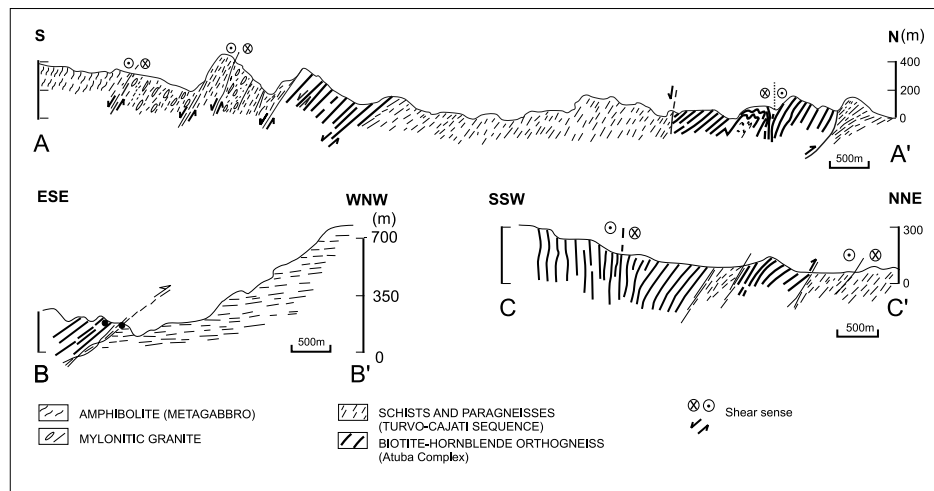


Fig. 3 – Structural cross-sections of the study area: (A'-A) N-S section; (B-B') E-W section; (C-C') SSW-NNE section. For location see Figure 2.

mary metamorphic environment, followed by lower pressure and/or higher temperature. This microtectonic evidence suggests a previously shortened crust affected by transtensional deformation along a clockwise P-T-t path (Dehler et al. 2000).

Microstructures also show evidence of dynamic recrystallization, with features such as core-mantle and deformation bands in quartz porphyroclasts. Polygonized quartz grains with irregular boundaries occur in the matrix. These features suggest that ductile deformation probably occurred both during and after the metamorphic peak, contemporary with the retrograde metamorphic path (Dehler et al. 2006).

These features show that the deformation was generated under amphibolite facies metamorphic conditions, and that its development continued during the progressive uplift and the regional crustal cooling. This situation produced extensional ductile to brittle structures under the same regional stress field. A K/Ar investigation of mylonites in this area yielded cooling ages of 565 ± 39 Ma in hornblende, 521 ± 26 Ma in biotite, and 587 ± 21 Ma in phlogopite (Campagnoli 1996).

ANALYTICAL PROCEDURES

$^{40}\text{Ar}/^{39}\text{Ar}$ isotopic measurements were carried out in the MAP-215-50 mass spectrometer of the Geochronological Laboratory of the Institute of Geosciences of São Paulo University. The mass spectrometer is linked online to a stainless steel extraction system which operates under ultra-high vacuum conditions. For technical details see Vasconcelos et al. (2002).

$^{39}\text{Ar}/^{40}\text{Ar}$ analyses were performed using a laser source, and a routine step heating procedure. Other details about the analytical procedures, including mineral separation, irradiation, reliable calibration tests, standards, accuracy and precision are given by Vasconcelos et al. (2002).

RESULTS AND DISCUSSION

$^{40}\text{Ar}/^{39}\text{Ar}$ dating was made on crystals from two samples of Costeiro Granite belt (Figs. 4A, B and C). One of the samples is a late kinematic pegmatite (NM-200B and C), while the other is a mylonitic orthogneiss (NM-0200-A). The pegmatite cross-cut mylonitic foliation of the orthogneiss (Fig. 5A). Two isotopic analyses were per-

formed in muscovite (pegmatite) and one in hornblende (orthogneiss) (see Fig. 4).

The two muscovite crystals from the pegmatite yielded plateau ages of 579.2 ± 1.2 Ma (NM-200C) and 574.5 ± 1.3 Ma (NM-200B), while the hornblende from the orthogneiss yielded a plateau age of 594.7 ± 1.3 Ma (NM-200A) (Figs. 4A, B and C; Table I). An ideogram plotted for muscovite two crystals (crystals NM-200C + NM-200B) yields a high probability peak at 579.1 and a weighted mean age of 577 ± 3 Ma (Fig. 4D).

GEOCHRONOLOGICAL DATA AND KINEMATIC ANALYSIS

A previous kinematic analysis carried out in the Serra do Azeite shear zone suggested a transtensional tectonic regime in the northeast-trending sinistral shear zones (Dehler et al. 2000). The mylonites exhibit heterogeneous deformation, zones with constrictional (L-tectonites), flattening, and simple shear strains occur, with a well marked stretching lineation plunging to SE-E. Kinematic indicators such as S-C fabrics, σ -porphyroclasts, asymmetric boudins and shear bands, are quite consistent with an oblique east-to southeast-directed extension, with a significant sinistral slip motion (Dehler et al. 2000).

The $^{40}\text{Ar}/^{39}\text{Ar}$ data obtained here for the hornblende of the mylonitic orthogneiss show a plateau age of 594 ± 1.3 Ma (NM-200A; Fig. 4C). The muscovite grains from the late kinematic pegmatite yielded middle age of 577 ± 3 Ma (NM-200C, Fig. 4D). This muscovite age constrains the time of mylonitic foliation of the orthogneisses in the Serra do Azeite shear zone, because the pegmatite cross cuts one to this structure (Fig. 5). By extrapolation, we consider this age as a lower limit for the development of transtensional structures in Cajati region.

The slightly younger plateau age of 574.5 ± 1.3 Ma (NM-200 B) (Fig. 4B) is interpreted to mark the regional metamorphic cooling. Allowing for the larger errors the previously reported K/Ar ages for phlogopite (587 Ma) and hornblende (565 Ma) are consistent with the $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained here, except for the biotite age (see Campagnoli 1996). This age range is older than the upper limit of previous estimates for the collision in the Ribeira and Araçuaí orogens, considered between 580 and 520 Ma (Heilbron et al. 2004). The

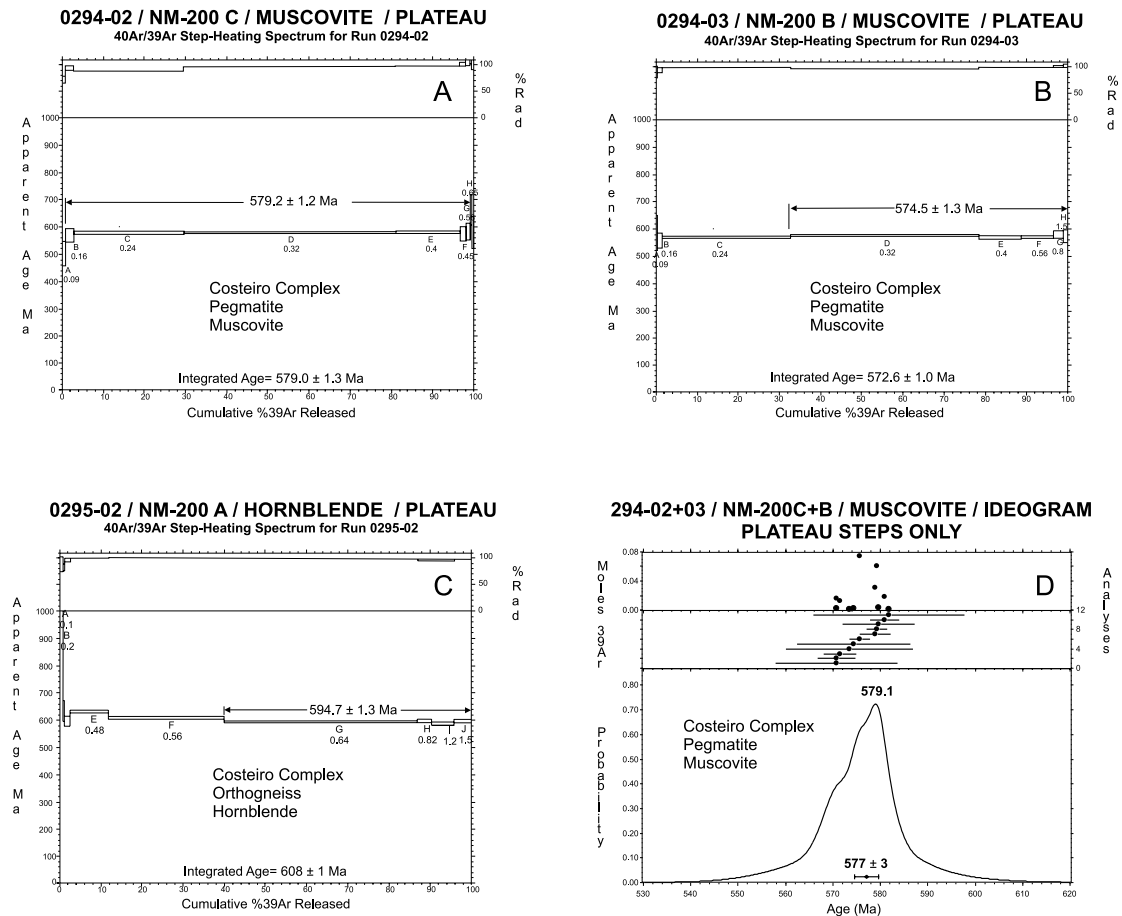


Fig. 4 – Degassing curve for the $^{39}\text{Ar}/^{40}\text{Ar}$ method using muscovite from pegmatite and hornblende from orthogneiss of the Serra do Azeite region, Costeiro belt, and correspondent ideogram.

580 Ma age may correspond to the peak of metamorphism and deformation. Our $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data suggest that ductile extension took place between 594 to 574 Ma.

In the studied area, field relations suggest that the ductile extensional shearing predates the emplacement of Guaraú granites, and may be associated to previous crustal thinning and melting which generated the magmas. This model also accounts for the ages of the alkaline granites of the Serra do Mar suite (600 and 570 Ma: Siga Jr. 1995) in the region. The model apparently explains the coexistence in the same orogenic space of extensional and compressional structures that overprinted the orogenic belts during convergence against the São Francisco Craton.

TRANSTENSIONAL STRAIN AND THERMAL HISTORY

The hornblende cooling age data presented here (584 Ma) is probably close to that of the regional medium-grade metamorphic peak of the Ribeira belt (between 500 e 600°C: Winkler 1967). On the other hand, taking into account the critical blocking temperature of muscovite ($350^\circ\text{C} \pm 50^\circ\text{C}$: Berger and York 1981), the $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained (between 574 and 579 Ma: middle age of 577 ± 3 Ma) represent the time at which the metamorphic conditions reached to incipient grade of Winkler (1967) (between 200 and 350°C). The $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained here suggest a cooling rate at around $10^\circ\text{C}/\text{Ma}$ for this time interval (~ 20 Ma), being this value compatible with a crustal exhumation up to 6 Km.



Fig. 5 – Photographs of pegmatite cross-cutting mylonitic foliation of the orthogneiss in the Serra do Azeite region, southern portion São Paulo State.

Extensional structures have been also described in different marginal domains of the southern São Francisco Craton (Endo 1997, Nalini 1997, Alkmim and Marshak 1998, Machado et al. 2001, Alkmim et al. 2002). They have been described in the Quadrilátero Ferrífero area and adjacent regions of Furquim and Dom Silvério toward the east (Chemale et al. 1994, Endo and Nalini 1992, Hippertt et al. 1992, Endo 1997). The age of these extensional structures is still uncertain, but in the Quadrilátero Ferrífero (i.e. Moeda syncline) they have been assigned to the Transamazonian (2100 Ma), linked with the “orogenic collapse” of the Minas Orogeny (Chemale et al. 1994, Marshak et al. 1997, Alkmim and Marshak 1998). Other workers, however, have recently identified extensional structures in the eastern region of the Ferrífero Quadrilátero as Brasiliano (Endo 1997), supported by geologic arguments. In the southern portion of the Ribeira belt, the temporal relationship between magmatism and the extensional structures suggests the emplacement of Neoproterozoic alkaline plutons during this extensional tectonic event.

In the Furquim region, an extensive and thickened

mylonitic quartzite with extensional fabric, including S/C foliation and shear bands, crops out (Endo 1997). This mylonite zone has a N-S trend with a mineral stretching lineation plunging down-dip to east. In the Dom Silvério region, east of Furquim, discontinuous mylonite zones have top-to east extension (Endo 1997). Although some of these extensional shear zones, especially those in the western portion of the Quadrilátero Ferrífero (Moeda syncline), apparently are Transamazonian in age (Marshak et al. 1997), Endo (1997) considered that the extensional structures of the eastern border of the Quadrilátero Ferrífero were developed after the compressional peak of the Brasiliano orogeny (~600 Ma).

In the southern portion of the Ribeira belt (Costeiro Granite Belt and Luis Alves terrane), the alkaline magmatism of the Serra do Mar Suite has ages between 594 and 570 Ma (Siga Jr. 1995). This magmatism has been considered as recording an extensional tectonic event (Siga Jr. 1995). Recently, conventional U/Pb ages of 582 ± 4 Ma and 582 ± 9 Ma were obtained for the Serra do Cordeiro and Votupoca granites, respectively, which are correlated with this suite (Passarelli et al. 2004).

TABLE I
³⁹Ar/⁴⁰Ar analytical data obtained from muscovite (pegmatite) and hornblende (mylonitic orthogneiss) of the Costeiro Granite Belt in the Cajati region.

Sample/ Material	Lab #	Laser (W)	⁴⁰ Ar/ ³⁹ Ar	³⁸ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar	⁴⁰ *Ar/ ³⁹ Ar	% Rad	⁴⁰ Ar (mols)	Age (Ma)
NM-200C/ Muscovite	0294-02A	0.09	95.10	0.05490	0.32454	0.08637	69.64	73.2	9.61E-16	505.1
	0294-02B	0.16	84.23	0.02096	0.26330	0.01382	80.20	95.2	1.97E-15	570.8
	0294-02C	0.24	90.49	0.01735	0.00000	0.03029	81.54	90.1	2.82E-14	578.9
	0294-02D	0.32	83.83	0.01182	0.00000	0.00761	81.58	97.3	5.04E-14	579.2
	0294-02E	0.40	82.94	0.01183	0.00035	0.00363	81.87	98.7	1.48E-14	580.9
	0294-02F	0.48	79.89	0.00335	0.00000	-0.00253	80.64	100.9	1.22E-15	573.4
	0294-02G	0.56	78.61	0.00443	0.22919	-0.01131	82.00	104.3	8.86E-16	581.7
	0294-02H	0.65	85.57	-0.01113	0.03490	-0.03491	95.90	112.1	4.91E-16	664.1
	0294-02I	1.30	80.84	0.02813	0.64305	-0.00254	81.72	101.0	5.10E-16	580.0
NM-200B/ Muscovite	0294-03A	0.09	90.17	0.00059	0.00000	0.02619	82.43	91.4	5.15E-16	584.3
	0294-03B	0.16	83.23	0.00999	0.00000	0.01748	78.07	93.8	1.84E-15	557.7
	0294-03C	0.24	81.36	0.01136	0.00000	0.00502	79.87	98.2	4.07E-14	568.8
	0294-03D	0.32	83.19	0.01217	0.00000	0.00741	81.00	97.4	6.14E-14	575.6
	0294-03E	0.40	80.60	0.01087	0.00000	0.00133	80.21	99.5	1.31E-14	570.8
	0294-03F	0.56	80.42	0.01071	0.01295	0.00031	80.32	99.9	1.03E-14	571.5
	0294-03G	0.80	80.18	0.00904	0.00000	-0.00499	81.65	101.8	2.95E-15	579.6
	0294-03H	1.50	78.32	0.01831	0.00000	-0.00841	80.80	103.2	1.35E-15	574.4
NM-200A/ Hornblende	0295-02A	0.10	499.16	0.13713	0.00000	0.12729	461.55	92.5	2.34E-15	2065.2
	0295-02B	0.20	182.29	0.04122	0.00000	0.07440	160.31	87.9	1.54E-15	1003.2
	0295-02C	0.30	110.99	0.02736	0.13784	0.06890	90.66	81.7	1.36E-15	633.5
	0295-02D	0.40	87.25	0.02377	1.57004	0.01141	84.20	96.3	2.90E-15	595.0
	0295-02E	0.48	90.87	0.02738	2.87628	0.00452	90.14	98.8	2.08E-14	630.4
	0295-02F	0.56	86.39	0.02557	2.77943	0.00189	86.40	99.6	5.94E-14	608.2
	0295-02G	0.64	83.82	0.02500	2.91350	0.00117	84.06	99.8	9.64E-14	594.2
	0295-02H	0.82	85.38	0.02510	2.64170	0.00398	84.74	98.8	6.90E-15	598.3
	0295-02I	1.20	84.06	0.02706	2.69286	0.00293	83.73	99.2	1.14E-14	592.2
	0295-02J	1.50	84.98	0.02549	3.94828	0.00214	85.15	99.6	9.20E-15	600.7

*radiogenic argon.

SUMMARY AND CONCLUSIONS

The extensional structures described in the Cajati region show similar kinematic features similar to those of the extensional structures described in the Araçuaí belt in the eastern portion of the Quadrilátero Ferrífero, in the Furquim and Dom Silvério regions (Endo 1997). In spite of the uncertainty concerning the timing of these structures, they are clearly younger than the extensional ones found in the western portion of the Quadrilátero Ferrífero (Chemale et al. 1994, Marshak et al. 1997, Alkmim and Marshak 1998).

A previous kinematic analysis carried out in the

Serra do Azeite shear zone, southeastern Brazil, suggests sinistral transtension for the main movement phase of an E-NE trending ductile shear zone (Dehler et al. 2000). The deformation of the mylonites is heterogeneous. The domains present constriction (L-tectonites), flattening, simple shear strains. A well marked stretching lineation plunging to SE-E is observed. Kinematic indicators such as S-C fabrics, σ -porphyroclast, asymmetric boudins and shear bands are quite consistent with an oblique east-to southeast-directed extension, and significant sinistral slip motion (Dehler et al. 2000). As a whole, the oblique extensional tectonics was responsible for the generalized hanging-wall collapse, followed by

lateral rock-mass extrusion and uplift/exhumation of the northern Apiaí belt (Dehler et al. 2000), as suggested by the overall kinematics of the Serra do Azeite shear zone.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages in hornblende and muscovite confirm the relatively fast cooling after the metamorphic peak in agreement with the previous microstructural and metamorphic studies (Dehler et al. 2000).

The scarcity of geochronological data does not permit us to define the exact time of formation of these structures. The development of alkaline magmatism (Suíte Serra do Mar) mainly in the southern region of the Costeiro Granite Belt, dated between 600 and 570 Ma (Siga Jr. 1995), suggests that a tectonic relationship between them may exist.

In conclusion, we suggest for the Cajati region, and probably for a large part of the Costeiro Granite Belt in southern São Paulo and northern Paraná, a diachronic tectonic evolution in the orogenic space at least between ~ 620 to 570 Ma. During this interval, while in the Cajati domain an extensional tectonic regime operated, in the adjacent ones (i.e. Apiaí and Araçuaí belts) a compressive regime occurred, suggesting that distinct tectonic regimes may have been active at the same time interval as a function of the orogenic dynamics rather than a function time. In the first setting, the tectonic regime was dominantly transtensional and may have been accompanied by crustal thinning, while the second was dominantly transpressive, and may have been accompanied by crustal thickening.

Finally, we consider that extension related with the emplacement of post-collisional plutons found in the Araçuaí and Paraíba do Sul belts with age between 520 and 500 Ma (Alkmim et al. 2002, Pedrosa-Soares et al. 2003, Heilbron et al. 2004) is the youngest extensional event.

ACKNOWLEDGMENTS

The authors are grateful to Thelma Samara for drafting the figures, to Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (Grants 93/1830-1; 95/01204-9) for supporting field work, to Dr. Ian McReath and Tariana Brocardo Machado for reviews of the manuscript, to two anonymous reviewers of the ABC for their constructive comments and suggestions. RM acknowledges CNPq research fellowship (30.0423/82-9).

RESUMO

Este trabalho apresenta idades $^{40}\text{Ar}/^{39}\text{Ar}$ de rochas da Zona de Cisalhamento Transtrativa Sinistral da Serra do Azeite, situada na parte sul do cinturão Ribeira, entre os Estados de São Paulo e Paraná, bem como discute a correlação regional e as implicações tectônicas com outras partes do cinturão. Os dados geocronológicos sugerem que a deformação extensional foi ativa entre 600 e 580 Ma (idades aparentes obtidas, respectivamente, em hornblenda e muscovita). Este intervalo de idades é relativamente mais antigo do que o proposto anteriormente para o período de atividade destas estruturas (520-480 Ma) no segmento norte deste cinturão e do cinturão Araçuaí. A análise cinemática dos milonitos datados mostra estruturas extensionais bem preservadas com movimento de topo para ESE, compatível com o de estruturas encontradas em outros segmentos tectônicos na porção leste do Quadrilátero Ferrífero e na região do Vale do Rio Doce. Nossas idades situam-se no mesmo intervalo de tempo definido para o magmatismo alcalino da Suíte Serra do Mar. Sugerimos que o arcabouço tectônico regional tenha sido desenvolvido durante um processo de extensão em escala continental. Este processo teria sido contemporâneo da deformação em condições de convergência ligada a zonas de cisalhamento Neoproterozóicas dos cinturões Apiaí/Ribeira e Araçuaí, as quais compõem segmentos importantes destes cinturões. Os dados disponíveis mostram que estas estruturas não podem ser relacionadas simplesmente ao colapso gravitacional pós-orogênico, mas devem envolver um processo mais complexo relacionado provavelmente ao balanço dinâmico entre espessamento e afinamento crustal durante os eventos de convergência tectônica, formação de bacias e exumação.

Palavras-chave: extensão sincontracional, idades $^{40}\text{Ar}/^{39}\text{Ar}$, Cinturão Ribeira.

REFERENCES

- ALKMIN FF AND MARSHAK S. 1998. Transamazonian Orogeny in the Southern São Francisco Craton region, Minas Gerais, Brazil: evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrífero. *Prec Res* 90: 29–58.
- ALKMIN FF, MARSHAK S, PEDROSA SOARES AC AND WHITTINGTON A. 2002. O registro estrutural do colapso da porção brasileira do orógeno Araçuaí-Congo. In: ANAIS DO 41º CONGRESSO BRASILEIRO DE GEOLOGIA, João Pessoa, PB, Brasil, p. 287–288.

- ALMEIDA FFM. 1977. O Cráton do São Francisco. *Rev Bras Geocienc* 7: 349–364.
- ALMEIDA FFM, AMARAL G, CORDANI UG AND KAWASHITA AK. 1973. The precambrian evolution of the south American cratonic margin south of Amazon river. In: NAIRN EM AND STEHLI FG (Eds), *The ocean basins and margins*, Plenum, New York, p. 411–446.
- BASEI MAS, SIGA JR O, MASQUELIN H, HARARA OM, REIS NETO JM AND PORTA FP. 2000. The Dom Feliciano Belt and the Rio de la Plata Craton: tectonic evolution and correlation with similar provinces of southwestern Africa. In: CORDANI UG, MILANI EJ, THOMAZ FILHO A AND CAMPOS DA (Eds), *Tectonic Evolution of South America*, p. 311–334.
- BERGER GW AND YORK D. 1981. Geothermometry from $^{40}\text{Ar}/^{39}\text{Ar}$ dating experiments. *Geochim Cosmochim Acta* 45: 795–812.
- BRAATHEN AOS, MUNDSSEN PT, NORDGULEN Ø, ROBERTS D AND MEYER GB. 2002. Orogen-parallel extension of the Caledonides in northern Central Norway: an overview. *Norwegian J Geol* 82: 225–241.
- BRITO NEVES BB AND CORDANI UG. 1991. Tectonic evolution of South America during the Late Proterozoic. *Precam. Res* 53: 23–40.
- CAMPAGNOLI F. 1996. Considerações sobre a geologia da Sequência Turvo-Cajati, na região do alto Rio Jacupiranguinha, SP. Dissertação de Mestrado, Instituto de Geociências, Universidade de São Paulo, SP, Brasil, 93 p.
- CAMPOS NETO MC. 1983. Os gnaisses do alto Jacupiranguinha e xistos Cajati: relações estruturais e estratigráficas. *Atas IV Simp Reg Geol*, SP, Brasil, p. 91–102.
- CHEMALE JR F, ROSIÈRE CA AND ENDO I. 1994. The tectonic evolution of the Quadrilátero Ferrífero, Minas Gerais, Brazil. *Precam. Res* 65: 25–54.
- CONEY PJ AND HARMS TA. 1984. Cordilleran metamorphic core complexes: Cenozoic extensional relicts of Mesozoic compression. *Geology* 12: 550–554.
- CUNNINGHAM WD, MARSHAK S AND ALKMIN FF. 1996. Structural style of basin inversion at mid-crustal levels: two transects in the internal zone of the Brasiliano Araçuaí Belt, Minas Gerais, Brazil. *Precam Res* 77: 1–15.
- DEHLER NM, MACHADO R AND VASCONCELOS CS. 2000. Tectônica extensional oblíqua no sul do estado de São Paulo. *Rev Bras Geoc* 30: 699–706.
- DEHLER NM, MACHADO R, DEHLER HRS, MCREATH I AND NUMMER AR. 2006. Kinematics and geometry of structures in the southern limb of the Paraíba do Sul divergent structural fan, SE Brazil: a true transtensional shear. *An Acad Bras Cienc* 78: 373–389.
- DEWEY JF. 1988. Extensional collapse of orogens. *Tectonics* 7: 1123–1139.
- DOGLIONI C. 1996. Geological remarks on the relationships between extension and convergent geodynamic settings. *Tectonophysics* 252: 253–267.
- ENDO I. 1997. Regimes tectônicos do Arqueano e Proterozóico no interior da placa Sanfranciscana: Quadrilátero Ferrífero e áreas adjacentes, Minas Gerais. Tese de Doutorado, Instituto de Geociências, Universidade de São Paulo, SP, Brasil, 243 p.
- ENDO I AND NALINI JR HA. 1992. Geometria e cinemática das estruturas extensionais e compressionais na borda oeste do Sinclinal Moeda, Quadrilátero Ferrífero. *Rev Escola de Minas* 45(1/2): 15–17.
- GLAZNER AF AND BARTLEY JM. 1985. Evolution of lithospheric strength after thrusting. *Geology* 13: 42–45.
- HEILBRON M, PEDROSA-SOARES AC, CAMPOS NETO MC, SILVA LC, TROUW RAJ AND JANASI VA. 2004. Província Mantiqueira. In: MANTESSO-NETO V ET AL. (Orgs) *Geologia do Continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida*, p. 203–235.
- HIPPERTT JF, BORBA RP AND NALINI JR HAF. 1992. O contato da Formação Moeda-Complexo Bomfim: uma zona de cisalhamento normal na borda oeste do Quadrilátero Ferrífero. *Rev Esc Minas* 45(1/2): 32–34.
- MACHADO R, DEHLER NM AND ENDO I. 2001. Tectônica extensional neoproterozóica na Província Mantiqueira. *Anais Simp Nac Est Tect e II Internat Symp*, PE, Brasil 8: 69–71.
- MALAVIEILLE J. 1993. Late orogenic extension in Mountain belts: Insights from the Basin and Range and the late Paleozoic Variscan belt. *Tectonics* 12: 1115–1130.
- MARSHAK S, TINKHAM D, ALKMIN FF, BRUECKNER H AND BORNHORST T. 1997. Dome-and-keel provinces formed during Paleoproterozoic orogenic collapse: Diapir clusters or core complexes? Examples from the Quadrilátero Ferrífero (Brazil) and the Penokean Orogen (USA). *Geology* 25: 415–418.
- NALINI JR HA. 1997. Caractérisation des suites magmatiques néoproterozoïques de la région de Conselheiro Pena et Galiléia (Minas Gerais, Brésil). Thèse de Doctorat, École des Mines de Saint-Etienne, Saint-Etienne, France, 237 p.
- PASSARELLI CR, BASEI MAS, CAMPOS NETO MC, SIGA

- JR O AND PRAZERES FILHO HJ. 2004. Geocronologia e geologia isotópica dos terrenos Pré-Cambrianos da porção sul-oriental do Estado de São Paulo. *Geol USP: Sér Cient* 4: 55–74.
- PEDROSA-SOARES AC AND WIEDEMANN-LEONARDOS CM. 2000. Evolution of the Araçuaí Belt and its Connection to the Ribeira Belt, Eastern Brazil. In: CORDANI UG, MILANI EJ, THOMAZ FILHO A AND CAMPOS DA (Eds), *Tectonic Evolution of South America*, p. 265–285.
- PEDROSA-SOARES AC, NOCE CM, ALKMIM FF, SILVA LC, CORDANI U, MARSHAK S, WHITTINGTON A, MARTINS-NETO MA AND CAMPOS CMP. 2003. Orógeno confinado: conceito, exemplo e candidatos. *Anais IX Simp Nac Est Tect e III Intern Symp*, p. 40–43.
- PICANÇO J, TASSINARI CCG, CORDANI UG AND NUTMAN AP. 1998. Idades U-Pb (SHRIMP), Sm/Nd e Rb/Sr em rochas do Maciço de Itatins (SP): Evidências de Evolução Policíclica. *An Acad Bras Cienc* 70: 139–150.
- RATSCHBACHER L, MERLE O, DAVY P AND COBBOLD P. 1991a. Lateral extrusion in the eastern Alps, part I: Boundary conditions and experiments scaled for gravity. *Tectonics* 10: 245–256.
- RATSCHBACHER L, FRISCH W, LINZER H AND MERLE O. 1991b. Lateral extrusion in the eastern Alps, part II: Structural Analysis. *Tectonics* 10: 257–271.
- ROYDEN LH AND BURCHFIELD BC. 1987. Thin-skinned N-S extension within the convergent Himalayan region: gravitational collapse of a Miocene topographic front. In: COWARD MP, DEWEY JF AND HANCOCK PL (Eds), *Continental Extensional Tectonics*. *Geol Soc Special Publication* 28: 611–619.
- SIGA JR O. 1995. Domínios tectônicos do sudeste do Paraná e nordeste de Santa Catarina: geocronologia e evolução crustal. Tese de Doutorado, Instituto de Geociências, Universidade de São Paulo, SP, Brasil, 212 p.
- SIGA JR O, BASEI MAS, SATO K, CITRONI SB, REIS NETO JM, WEBER W, LIMA PS AND SPROESSER WM. 1999. Post-Orogenic magmatism and sedimentation in Neoproterozoic extensional regimes in the Brazilian Southern Region. *Actas II Simposio Sudamericano Geologia Isotópica, Córdoba, Argentina*, p. 367–370.
- SILVA ATS AND ALGARTE JP. 1981a. Contribuição à geologia da sequência Turvo-Cajati entre o Rio Pardo e Pariqueira-Açu, Estado de São Paulo I: litologia e petrografia. *Atas III Simp Reg Geol, Curitiba, PR, Brasil*, p. 109–120.
- SILVA ATS AND ALGARTE JP. 1981b. Contribuição à geologia da sequência Turvo-Cajati entre o Rio Pardo e Pariqueira-Açu, Estado de São Paulo. II: estrutura, metamorfismo e evolução geotectônica. *Atas III Simp Reg Geol, Curitiba, PR, Brasil*, p. 121–132.
- TROUW RAJ, HEILBRON M, RIBEIRO A, PACIULLO FVP, VALERIANO CM, ALMEIDA JH, TUPINAMBÁ M AND ANDREIS RR. 2000. The Central Segment of the Ribeira Belt. In: CORDANI UG, MILANI EJ, THOMAZ FILHO A AND CAMPOS DA (Eds), *Tectonic Evolution of South America*, p. 287–310.
- VASCONCELOS CS, DEHLER NM, YAMATO A AND LOPES JR I. 1999. Projeto Jacupiranga-Rio Guaraú (escala: 1: 50.000), relatório final, CPRM/Secretaria de Energia, São Paulo, 233 p.
- VASCONCELOS PM, ONOE AT, KAWASHITA K, SOARES AJ AND TEIXEIRA W. 2002. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology at the Instituto de Geociências, USP: instrumentation, analytical procedures, and calibration. *An Acad Bras Cienc* 74: 297–342.
- WHEELER J AND BUTLER RWH. 1993. Evidence for extension in the western Alpine orogen: the contact between the oceanic Piemonte and overlying continental Sesia units. *Earth Planet Sci Lett* 117: 457–474.
- WINKLER HGJ. 1967. *Petrogenesis of metamorphic rocks*. 2nd ed., New York: Springer Verlag.