CONSTRAINS ON THE TERMOCHRONOLOGICAL EVOLUTION OF RIBEIRA FOLD BELT, SE BRASIL: EVIDENCE FOR LONG-TERM ELEVATED GEOTHERMAL GRADIENT OF NEOPROTEROZOIC OROGENIES

Tassinari, C.C.G.[1],. Munhá, J.M.U.[2]; Dias Neto, C.[1], Santos, T.[2]; Cordani, U.G.[1], Nutman, A.P.[3], Fonseca, P.[4]

1 Instituto de Geociências da Universidade de São Paulo, CNPq, ccgtassi@usp.br
2 Departamento/Centro de Geologia, Faculdade de Ciências, Universidade de Lisboa, jmunha@fc.ul.pt
3 Australian National University, allen.nutman@anu.edu.au
4 Departamento Geologia/LATTEX, Faculdade de Ciências, Universidade de Lisboa

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INTRODUCTION

The Ribeira Fold Belt in southeastern Brazil is one of the better studied orogenic belts on western Gondwana. During the last decade several papers have proposed different hypothesis on the orogenic evolution of the Neoproproterozoic Ribeira Fold Belt (Campos Neto & Figueiredo, 1995, Hackspacker et. al., 2000, Tupinambá, 1999, Schmitt 2000 and others). Because of the overwhelming amount of information and contrasting interpretations, some basic questions still remain in order to characterize the complete tectonometamorphic evolution of the Ribeira Belt. Does it indeed reflect a poly-orogenic belt, produced by the activity of a large number of collisional processes originating a orogenic collage as defined by Helwig's (1974); on the other hand, could the Ribeira Fold Belt result from a long term single orogeny? To unravel some of these questions it is important to characterize tectonometamorphic P-T conditions, as well as the thermochrnology of burial, heating, cooling and uplift stages during the development of the Neoproterozoic Ribeira Fold Belt.

The main objective of this paper is to integrate new thermochronological data obtained for selected key areas, in order to contribute to a better understanding of the geodynamic evolution of the Ribeira Fold Belt. The selected areas are: Costeiro and Embú Complexes in São Paulo State, São Fidelis - Santo António de Pádua Charnockite/Migmatitic Complex in Rio de Janeiro State and the Migmatitic - Gneissic Complex of Araçuaí Belt in Espírito Santo State.

GEOLOGICAL SETTING

The Neoproterozoic Ribeira Fold Belt (Almeida, 1977) extends along the southeastern Brazil, over 1,500 km from southern Bahia, through Espírito Santo, Rio de Janeiro, Minas Gerais, São Paulo and Paraná States. Within the Western-Gondwana Supercontinent context, the Ribeira Belt, together with the Damara, West Congo and Kaoko Belts in Africa, comprises a Neoproterozoic orogenic system, that borders the São Francisco and Congo Cratons, as well as, an inferred cratonic block, that actually occur under the Paleozoic sedimentary rocks of the Paraná Basin (Brito Neves and Cordani, 1991). The Ribeira Fold Belt constitutes a very complex orogenic zone composed of several geological units (separated by major tectonic lineaments), that can be grouped in four major lithological associations (Trouw et. a.l., 2000); a) reworked Archean-Paleoproterozoic basement rocks; b) deformed meta-sedimentary sequences, c) molassic sedimentary basins and d) extensive granitoid intrusive bodies. Tectonometamorphic activity is characterized NE trending transpressive shear deformation associated with long-term HT/LP metamorphism that occurred during Brasiliano (Pan-African) Orogenic Cycle, comprising the time-period of 670-480 Ma (Trouw et. a.l., 2000).

The reworked basement rocks contain predominantly metavolcano-sedimentary sequences, granodioritic to tonalitic (± migmatitic) orthogneiss (Valadares et. al., 1997) and intermediate/basic granulites (Heilbron et. al. 1998). The deformed meta-sedimentary sequences are composed mainly by pelitic schists and high-grade ky/sill migmatitic paragneisses, containing quartzite, marble, calc-silicate, meta-cherts and amphibolite intercalations (Trouw et. a.l., 2000). Granitoid rocks are widespread along entire fold belt, and display variable geochemistry which has been related to different tectonic settings, from pre- to post-collisional stages of the Brasiliano orogenic system (Campos Neto & Figueiredo, 1995, Trouw et. a.l., 2000 and Pedrosa Soares & Wiedmann-Leonardos., 2000). A notorious feature of the Ribeira Fold Belt is the widespread occurrence of Neoproterozoic charnockites; they include syn-/late metamorphic intrusions of tonalitic-enderbitic composition occurring over large areas (massif type igneous charnockites), massive metamorphic charnockites, to variable sized patches and (pegmatitic) veins (incipient charnockites), representing in-situ formation of granulites. Associated with these charnockites is a suite of porphyrytic granites and gneisses and aplites.

Various tectonic models have been proposed for the geodynamic development of the Neoproterozoic Ribeira Fold Belt (Trompette 1994, Campos Neto & Figueiredo, 1995; Machado et al., 1996; Tassinari & Campos Neto, 1988, Trow et al., 2000; Heilbron & Machado 2003;

Campos Neto, 2000 and Schmitt 2000). A dominant ensialic evolution with important crustal reworking has been favored, although subordinated oceanic crust subduction and continental accretion have also been considered.

According Campos Neto & Figueiredo (1995) the Ribeira Fold Belt in southeastern Brazil includes disctint terranes and micro-plates, which were amalgamated during Neoproterozoic and Eopaleozoic times. Within the Serra do Mar microplate, which include the Costeiro Complex, the Rio Doce Orogeny was active from 590 Ma to 570 Ma, involving calc-alkaline arc magmatism, followed by collision (560 – 530 Ma) of the microplate against the continent. Post-collisional magmatism, (520 – 480 Ma), was characterized by the emplacement of alkali-calcic plutons and dikes.

Within the central part of the belt (Rio de Janeiro state), Machado et. al., (1996) characterized four lithologic/tectonic units (Andrelandia, Juiz de Fora, Paraiba and Costeiro domains), separated by deep dextral shear zones. Despite the identification of scattered older ages (~620 Ma), the main regional tectono-thermal event occurred at 590 – 565 Ma, involving reworking and partial melting of older continental basement rocks, with emplacement of several granitoid bodies. In some domains a younger orogenic episode was identified at 535 – 520 Ma, followed by late thermal-tectonic activity at 503 - 492 Ma. The younger orogenic event (the so-called Buzios orogeny; Schmitt 2000) was defined in the Cabo Frio Terrane (Throw et al., 2000). Peak metamorphic conditions during the Buzios Orogeny ($P \geq$ 9Kb e $T \geq 780°$ C) were reached at 525 – 520 Ma and estimated cooling rates averaged about 10 ºC/Ma until 480 Ma, decreasing afterwards to ~5 ºC/Ma (Schmitt 2000).

In the northern part of the Ribeira Fold belt (Araçuaí Belt) a 625 – 595 Ma calc-alkaline magmatic arc was developed in a continental active margin; this was followed by a collisional stage (595 – 575 Ma) during which fragmented slices of oceanic crust were obducted upon the epineritic sedimentary sequences. Long term, intensive granitic magmatism characterized late- to post-collisional times, from 575 to 490 Ma (Pedrosa Soares & Wiedmann-Leonardos, 2000).

According to the poly-orogenic hypothesis, the older orogeny of the Ribeira fold belt corresponds to the 630 – 610 Ma Rio Negro Orogeny (Tupinambá 1999; Campos Neto, 2000); this was followed by the 580 – 540 Ma Araçuaí Orogeny (Pedrosa Soares & Wiedmann-Leonardos, 2000) and by the late ~520 Ma Buzios orogeny (Schmitt 2000) in the Cabo Frio terrane.

RESULTS AND DISCUSSION

New U/Pb, Sm/Nd, Rb/Sr and K-Ar isotopic analyses on whole rock and mineral separates (zircon, garnet, pyroxene, biotite and feldspar) from igneous and metamorphic rocks of the Ribeira Fold Belt have been obtained during this study; together with pre-existing results this new data was used to unravel thermal peak metamorphic ages and cooling rates of selected areas within the Ribeira Belt.

The first studied area is located near São Sebastião, within the Costeiro Complex. The analyzed samples correspond to amphibolites, migmatized garnet-sillimanite-biotite gneisses (kinzigites), and pegmatitic veins, derived from partial melting of their host rocks. Metamorphic recrystallization was contemporaneous with extensive shearing during transpressive deformation, reaching granulite facies peak conditions of 750 ± 30ºC, 5 ± 0.5 kbar. Rb-Sr whole-rock (WR) geochronological data on regional granitoids indicate that basement rocks underwent extensive reworking/partial melting with development of an almost continuous granitic magmatism, from syn-collisional, catazonal, batholith emplacement (~630-600 Ma) to late-/post-tectonic epizonal "stock-like" intrusions at 540 –500 Ma. Zircon U-Pb ages of thin metamorphic overgrowths in kinzigitic migmatites indicate that thermal peak metamorphic conditions were reached at 571±10 Ma, which was coeval with regional aplitic intrusions and associated development of incipient charnockitization of their orthogneisssic host rocks. Garnet-WR Sm/Nd (560 - 530 Ma), plagioclase-WR Rb/Sr (518 – 484 Ma), plagioclase-muscovite Rb/Sr (509 – 481 Ma), plagioclase-biotite Rb/Sr (488 - 464 Ma) and K/Ar muscovite/biotite (490 – 470 Ma) thermochronology indicate that after reaching peak P-T conditions, the Costeiro metamorphic complex underwent a very slow cooling rate, ~3 ºC/Ma, from 570 to 480 Ma; afterwards, cooling was much faster, as indicated by FK K-Ar ages around 470 Ma, implying higher exhumation rates.

Moving northwards along the Ribeira Fold Belt, the second studied site focused on the Quirino orthogneisses that belong to the Embu Complex in the Bananal area. In order to characterize the termochronological evolution of this segment we have used previous U-Pb zircon and titanite ages (Valadares et. al. 1997), together with new U-Pb SHRIMP, Sm-Nd and Rb-Sr isotopic data. U-Pb SHRIMP zircon ages of 622±17 Ma, 605±3 Ma and 571±3 Ma indicate multiple re-crystallization events and suggest that the studied rocks sustained high temperature conditions (high heat flow) from ~620 to ~570 Ma. Cooling ages of titanite (U-Pb - 535±2 Ma; Valadares et al., 1997), plagioclase-WR and plagioclase-biotite (Sm-Nd - ~520 to ~500 Ma), coupled with plagioclase-biotite Rb-Sr closure at 446±10Ma, suggests that the Bananal area underwent initial relatively slow cooling (~5 ºC/Ma) until ~500 Ma, followed afterwards by faster cooling rates.

The third studied area is located near the southeastern boundary of the Além Paraíba – Santo António de Pádua megashear, within the São Fidelis – Santo António de Pádua (northern Rio de Janeiro state) sector of the Ribeira Fold Belt. The area underwent complex polyphase, ductile, deformation (early thrusting, dominantly, towards ESE, followed by NNE-SSW sub-horizontal dextral shearing), associated with generalized granulite facies metamorphism, that reached T-P conditions, up to 800 – 900 ºC at 8 – 9 kb (Santos et al., 2005). Intensive migmatization, partial melting of dominant paragneisse lithologies is characteristic, being related to the emplacement of a variety of granitoid and aplitic bodies; locally, diatexitic migmatites still preserve (metric/decametric) xenoliths of (meta-) gabbroic to pyroxenitic cumulates that probably represent dismembered fragments of early mantle derived magma chambers. Both massive type metamorphic charnockites - granulites and incipient charnockitization are widespread features in the area; the latter is often related with mesoscopic shear zones and pegmatitic veins that cut across the regional penetrative fabrics of orthogneisses, being associated with graphite deposits. Our new zircon U-Pb (SHRIMP and conventional TIMS) geochronological data on migmatitic gneiss (555±8 Ma), massive charnockites (JC24A: 575±15 Ma; JC45: 571±7 Ma) and orthogneiss (560±13 Ma) yield identical dates (within error); thus, regional peak metamorphic conditions occur at about 563±15 Ma, being coeval with the emplacement of garnet-bearing aplitic veins (JC24B zircon U-Pb SHRIMP age 561±17 Ma) into massive charnockites. Garnet-whole rock Sm-Nd dating of two migmatitic gneisses (JC28B: 553±4Ma; JC13: 524±4 Ma), and the garnet-bearing aplite (JC24B: 513±4 Ma) suggest, either differential early exhumation of high grade rocks (during HT transpressive deformation), or variable garnet closure temperatures for the distinct analyzed lithologies. Feldspar-biotite Rb-Sr dating of two charnockites (several km apart) gave similar ages of (JC24A) 456±4 Ma and (JC45) 459±4 Ma, whereas K/Ar dating of biotites in migmatitic gneisses provide cooling ages typically within the range of 488±8 Ma (JC27) to 463±4 Ma (JC12); however, K/Ar ages obtained in charnockite biotites, ranging from 576±10 to 492±10 Ma, are much older than equivalent Rb-Sr dates, suggesting that biotite in charnockites are affected by excess ^{40}Ar and must have been open to argon diffusion (uptake) during metamorphism. In addition, an allanite-bearing granite, that cross-cut the massive charnockite JC24A, yielded a weighted mean ^{206}Pb/^{238}U SHRIMP, age of 491±14 Ma and a biotite-whole rock Rb-Sr age of 455± 4 Ma, consistent with its biotite K-Ar date of 462 ± 9 Ma. The available geological and thermochrnological data suggests that, despite estimated relatively rapid initial cooling rates (~20 ºC/Ma), most of the São Fidelis high grade rocks have sustained a long period (~20 to ~50 Ma) at high temperatures after reaching their metamorphic peak. After this, exhumation rates progressively decreased and rapid uplift/erosion had ceased as the rocks passed bellow 600 – 400 ºC at 500 – 470 Ma ago.

The north segment of the Ribeira Fold belt, also named Araçuaí Fold Belt (Espirito Santo State) is characterized by widespread masiif type igneous charnockites and migmatitic gneisses, which experienced granulite facies metamorphism (820 ± 20 °C; 6.5 ± 0.5 kbar) during the late stages of the Brasiliano Orogeny. Charnockite magmatic activity ranges from 560 to 500 Ma (Medeiros et al. 2003), whereas migmatitic gneisses have remained at conditions close to peak metamorphism for a long period (~530 Ma to ~480 Ma), promoting muscovite + biotite partial melting, followed by retrograde reactions that produced late cordierite + biotite and garnet reabsorption. Fe-Mg garnet-biotite diffusion modeling and Sm-Nd, Rb-Sr and Ar-Ar geochronology on garnet, plagioclase, biotite, K feldspar and WR yielded consistent results, indicating a short period (<10 Ma) of rapid cooling (≥ 60 ºC/Ma) at about 480 Ma, followed by a longer period of slow cooling rates close to 2ºC/Ma (Munhá et al., 2005). The initial rapid cooling is interpreted as due to the thrusting of the migmatitic gneisses onto cooler basement rocks, reflecting gravitational collapse of the orogen.

Considering the available petrological and termochronological data it is clear that in general for the studied segments of the Ribeira Fold Belt intermediate pressure granulite facies peak metamorphic conditions are typical (≥750 ºC; 5-9 kb). The timing of peak metamorphism and lower crustal partial melting is mostly within the range 630 – 570 Ma. At least in some of the studied sites, peak metamorphism was followed by slow cooling rates until 480 – 470 Ma; after this cooling rates increased by thrusting of the rocks onto cooler basement and/or rapid exhumation, which is associated with post-orogenic fault tectonics, probably related with the initial stages of Paraná basin-type sedimentary infilling. The thermochronological evolution for all studied areas suggests a significant period of high temperatures at lower continental crust, which imply a long term elevated geothermal gradient relative to a stable continental geotherm. Indeed, active mountain building should have been followed by gravitational collapse of the orogen, caused by thermal erosion and progressive thinning of the lithosphere (caused by heating from the mantle and by internal heating of the previously thickened crust itself); this induced upwelling of asthenospheric mantle and magma underplating which sustained the long term thermal anomaly. These conditions promoted sustainable lower crustal melting and widespread charnockite-granulite development at different stages of the Ribeira Fold Belt orogenic evolution. Thus, crystallization of new zircon at different times could become possible in different areas, reflecting the same orogeny. Clearly, variable regional thermal regimes and cooling rates could produce the closure of isotopic systems at different times along the Ribeira Fold Belt, producing different geochronological ages.

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REFERENCES

Almeida, F. F. M., 1977, O Craton do São Francisco, Ver. Brás. De Geoc., 7 (4), 349 – 364.

Brito Neves, B.B.; CordaniI, U.G. (1991) Tectonic evolution of South America during Late Proterozoic. Precambrian Research, v. 33, p. 23-40.

Campos Neto, M.C.; Figueiredo, M.C.H. (1995) The Rio Doce orogeny, Southeastern Brazil. Journal and South American Earth Sciences, v. 8, n. 2, p. 143-162.

Campos Neto, M.C. (2000) Orogenic Systems from Southwestern-Gondwana: na approch to Brasiliano - Pan-Africano Cycle and collage in southeastern Brazil. In: CordaniI, U.G.; MilaniI, E.J.; Thomaz-Filho, A.; Campos, D.A (eds.). Tectonic Evolution of South América. Rio de Janeiro, p. 335-365.

Hackspacher, P.; Dantas, E.l.; Spoladore, A.; Fetter, A.H.; Oliveira, M.A.F. (2000) Evidence of Neoproterozoic backarc basin developement in the Central Ribeira Belt, Southeastern Brazil: New geochronological and geochemical constrains from the São Roque – Açungui Group. Revista Brasileira de Geociências, v. 30, nº 1, pp.110-114.

Heilbron M. & Machado, N., (2003). "Timing of Terrane Accretion in the Neoproterozoic-Eopaleozoic Ribeira Orogen (SE Brazil)". Precambrian Research, 125, pp. 87-112.

Machado, N.; Valladares, C.; Heilbron, M.; Valeriano, C. (1996) U-Pb geochronology of the central Ribeira belt (Brazil) ans implications for the evolution of the Brazilian Orogeny. Precambrian Research, v. 79, p. 347-361.

Medeiros, S.R;Mendes, J.C.; McReath, I.; and Wiedemann, C.M., 2003, U-Pb and Rb-Sr dating and isotopic signature of the charnockitic rocks from Várzea Alegre Intrusive complex, Espirito Santo, Br.. Short papers of IV South American Symposium on Isotope Geology, 609-612.

Munhá, J.M.U., Cordani, U.G.; Tassinari, C.C.G and Palácios, T., 2005, Petrologia e Termocronologia de gnaisses migmatíticos da Faixa de Dobramentos Araçuaí (Espírito Santo, Brasil). Revista Brasileira de Geociências, 35 (1), 123-134.

Pedrosa-Soares, A. C. & Wiedmann-Leonardos, C., - 2000 – Evolution of the Araçuaí belt and its connection to the Ribeira Belt, eastern Brazil. In: CORDANI, U.G.; MILANI, E.J.; THOMAZ-FILHO, A; CAMPOS, D.A. (eds.). Tectonic evolution of South America. p. 287-310.

Santos, T.B., Munhá J., Tassinari C.C.G., Dias Neto C., 2005, Geotermobarometria de rochas metamórficas na região de São Fidelis, SE, Brasil. Actas do VIII Cong. De Geoq. Dos Paises de língua portuguesa, 1, 95 –100.

Schmitt, R.S., 2000, Um evento tectono-metamórficoCambro-Ordoviciano caracterizado no domínio tectônico Cabo Frio, Faixa ribeira, sudeste do Brasil, Rio de janeiro, IG-UFRJ, tese de Doutoramento, 273 p.

TassinariI, C.C.G.; Campos Neto, M.C. (1988) Precambrian continental crust evolution of sotheastern São Paulo State-Brazil: based on isotopic evidences. Geochimica Brasiliensis, v. 2, n. 2, p. 175-183.

Trompette, R. (1994) Geology of western Gondwana (2000-500 Ma) Balkema, Rotterdam, 350p.

Trouw, R.A.J.; Heilbron, M.; Ribeiro, A.; Pacciullo, F.; ValerianoO, C.; Almeida, J.C.H.; Tupinambá, M.; Andreis, R.R. - 2000 - The central segment of Ribeira belt. In: Cordani, U.G.; Milani, E.J.; Thomaz-Filho, A; Campos, D.A. (eds.). Tectonic evolution of South America. p. 287-310.

Tupinambá, M. (1999) Evolução tectônica e magmática da Faixa Ribeira na região serrana do Estado do Rio de Janeiro; Tese de Doutoramento - Instituto de Geociências da Universidade de São Paulo: IGc-USP São Paulo; 221p.

Valladares, C.S. (1996) Evolução Geológica do Complexo Paraíba do Sul, no segmento central da Faixa Ribeira, com base em estudos de geoquímica e geocronologia U-Pb. Tese de Doutoramento, Instituto de Geociências USP, 147p.

RESUMO

O objetivo deste trabalho é obter novos dados termocronológicos para a compreensão da evolução geodinâmica da Faixa de Dobramentos Ribeira, caracterizando se esta Faixa foi poli-ororgênica ou foi resultado uma única orogênese. Novos dados U-Pb, Sm-Nd, Rb-Sr e K-Ar em rocha total e em minerais separados (zircão, granada, biotita, piroxênio e feldspatos) de rochas ígneas e metamórficas foram obtidos e com os dados pré-existentes permitiu caracterizar as idades dos picos metamórficos e as taxas de resfriamento de áreas selecionadas. Os dados petrológicos e geocronológicos indicaram condições de T e P do pico metamórfico em fácies granulito de ≥750 ºC; 5-9 kb no período de 630 – 570 Ma. O pico metamórfico foi seguido por taxa de resfriamento lenta até 480 - 470 Ma, após isto a taxa de resfriamento foi rápida por cavalgamento destas rochas sobre um embasamento mais frio ou uma exumação rápida da orogenia. A evolução termocronológica observada sugere um período significante de temperaturas elevadas na crosta inferior, implicando em um longo período com elevado gradiente geotermal. A construção da cadeia de montanhas foi seguida por um colapso gravitacional do orógeno, e um adelgaçamento progressivo da litosfera, induzindo a ascenção da astenosfera, o que sustentou por longo tempo a anomalia termal. Tal fato nos permite concluir que a Faixa de Dobramentos Ribeira é constituída de uma única orogênese, com elevado fluxo térmico por longo tempo. Variações locais nos regimes termais, podem produzir o fechamento dos sistemas isotópicos em tempos distintos, produzindo diferentes idades, no período com elevado gradiente geotérmico.