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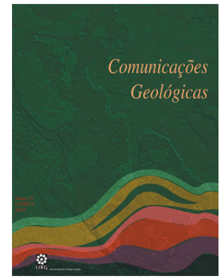
Geodynamic evolution of the Ribeira Fold Belt (SE Brazil): preliminary geochronological and geochemical evidence for diachronic collision, slab break-off and underplating



Evolução geodinâmica da Faixa Ribeira (SE do Brasil): evidências geocronológicas e geoquímicas preliminares para colisão diacrónica, *slab break-off* e *underplating*

T. Bento dos Santos[1,2*], C. Tassinari[3], P. E. Fonseca[2], J. Munhá[2]

Artigo Curto
Short Article

Abstract: Integrated geochronological and geochemical data for the entire Ribeira Fold Belt (SE Brazil) reveal that: a) pre-, syn- and post-orogenic periods are perfectly individualized within each geographic segment and are consecutively coeval with the intrusion of 3 distinct large magmatic series that evolved from: i) calc-alkaline, arc-related magmatism; ii) syn-orogenic, anatectic magmatism coeval with the metamorphic climax; iii) calc-alkaline/alkaline magmatism with significant lower-crust/mantle contribution; b) progressively younger ages from south to north, implying that the different geographic sectors were, from south to north, diachronically amalgamated into Ribeira Fold Belt. Results provide important evidence for the existence of a single diachronic collision event at 630-590 Ma, followed by the thermal climax at 615-560 Ma, slab break-off, asthenospheric upwelling and mantle underplating that sustained long-term high heat flux conditions until 540-490 Ma, when post-tectonic calc-alkaline/alkaline granitoids intruded the middle/low-crust during the final stages of thermal and orogenic collapse of Ribeira Fold Belt.

Keywords: Gondwana, Continental collision, Orogenic collapse, U-Pb geochronology, Neoproterozoic.

Resumo: A integração de dados geocronológicos e geoquímicos para toda a Faixa Ribeira (SE do Brasil) revela: a) os períodos pré-, sin- e pós-orogénicos estão perfeitamente individualizados em cada sector geográfico e são consecutivamente simultâneos com a intrusão de 3 grandes séries magmáticas distintas que evoluíram de: i) magmatismo calco-alcalino de arco magmático; ii) magmatismo anatéctico sin-orogénico, síncrono com o clímax metamórfico; iii) magmatismo calco-alcalino/alcalino com importante contribuição da crosta inferior e manto; b) idades progressivamente mais jovens de sul para norte, implicando que os diferentes segmentos geográficos foram, de sul para norte, diacronicamente amalgamados à Faixa Ribeira. Os resultados evidenciam a existência de uma única colisão diacrónica a 630-590 Ma, seguida do clímax térmico a 615-560 Ma, *slab break-off*, *upwelling* astenosférico e *underplating* mantélico que manteve condições prolongadas de elevado fluxo térmico até 540-490 Ma, quando granitóides pós-tectónicos calco-alcalinos/alcalinos intruíram a crosta média/inferior durante os estágios finais de colapso térmico e orogénico da Faixa Ribeira.

Palavras-chave: Gondwana, Colisão continental, Colapso orogénico, Geocronologia U-Pb, Neoproterozóico.

[1]LNEG – Laboratório Nacional de Energia e Geologia, Apartado 7586, 2720-866 Amadora, Portugal.
[2]IDL/CeGUL – Instituto Dom Luiz/Centro de Geologia, Universidade de Lisboa, 1749-016 Lisboa, Portugal.
[3]IEE-USP – Instituto de Energia e Ambiente, Universidade de São Paulo, Rua do Lago, 562, CEP: 05508-080, São Paulo, Brazil.
* Corresponding author / Autor correspondente: telmo.santos@lneg.pt

1. Introduction

The Ribeira Fold Belt (RFB) is a NE-SW to NNE-SSW trending Neoproterozoic mobile belt that extends along the SE and S coast of Brazil and Uruguay (Cordani *et al*., 1973). The RFB is a complex orogenic belt formed during the Pan-African assembly of the Gondwana Supercontinent (Trouw *et al*., 2000). Western Gondwana was formed in several steps between 700 and 450 Ma that included the convergence of different cratonic blocks, such as the Amazonian – Rio de la Plata – Paranapanema – São Francisco Cratonic Block (in the South American part of Gondwana) and the Congo/Kalahari Cratons (in the African part of Gondwana), and the Ediacaran – Cambro-Ordovician closure of the Adamastor Ocean to form the RFB (Trouw *et al*., 2000; Pedrosa-Soares *et. al*., 2001; Heilbron & Machado, 2003; Basei *et al*., 2010; Schmitt *et al*., 2012).

The recent widespread use of *in situ* high-resolution dating of zircon by SHRIMP/SIMS and HR-LA-ICP-MS has allowed several conceptual breakthroughs, but also the proposal of various conflicting models for the geodynamic evolution of the RFB. For instance, Campos Neto & Figueiredo (1995) and Heilbron & Machado (2003) suggested the possibility of having multiple collision events of distinct microplates during the Brasiliano Orogeny, with collision between the São Francisco Craton and the Oriental Terrane, a magmatic island arc, occurring at ~ 580 Ma, whereas the large continental collision between the Congo Craton with the São Francisco Craton (and the aggregated Oriental Terrane) would only have happened at ~ 525 Ma, during the so-called Búzios Orogeny (Schmitt *et al*., 2004). Alternatively, Pedrosa-

Soares *et al*. (2001) and Bento dos Santos *et al*. (2010) propose a geodynamic model with a single orogenic scenario, where after the early collision event between the São Francisco Craton and the Congo Craton at 610-590 Ma, the syn-orogenic period, coeval with peak granulitic metamorphism and lower crust partial melting, occurred at 575-560 Ma. High temperature conditions and low cooling rates (~ 1ºC/Ma) were sustained at mid/lower crust levels for ≥ 80 Ma (Bento dos Santos *et al*., 2010) with post-orogenic magmatic intrusions occurring at 520-480 Ma during the tectonic collapse of RFB.

This work presents a compilation and a preliminary reinterpretation of a large set of geochronological and geochemical data for the entire RFB (Table 1; Fig. 1) and discusses it with the objective of providing an integrated geodynamic model for the evolution of the RFB. Therefore, this work will try to answer 3 fundamental questions: a) what were the duration and rates of the different stages of magmatism and metamorphism in the different sectors of the RFB?; b) were these stages synchronous or diachronic?; c) was the RFB formed by successive collision events during the Brasiliano cycle (as proposed by Campos Neto & Figueiredo, 1995; Heilbron & Machado, 2003) or is the RFB the result of a single Brasiliano orogenic event (as in Pedrosa-Soares *et al*., 2001; Bento dos Santos *et al*., 2010)?

Table 1 Summary of the geochemical data for the Ribeira Fold Belt.

Tabela 1. Resumo dos dados de geoquímica para a Faixa Ribeira.

	Magmatic Series I	Magmatic Series II	Magmatic Series III
Geochemistry	Arc-related calc-alkaline magmatism Metaluminous to slightly peraluminous I-type	Convergent tectonics sub-alkalic magmatism Peraluminous Mostly S-type (with minor I-type)	Thermal relaxation calc-alkaline/alkaline magmatism Metaluminous I-type (with occasional A-type affinity) Lower crust with mantle contribution
Rock types	Granitoids (s.l.), tonalites, gabbros and shoshonites	Low-temperature granites and leucogranites	Granitoids (s.l.), gabbros, diorites and shoshonites
Tectonic setting	Convergent volcanic/magmatic arc	Anatectic complexes	Orogenic collapse
Orogenic Period	Pre-orogenic	Syn-orogenic	Post-orogenic

2. Results and Discussion

The compiled geochronological data (Fig. 1) is indicative of: a) magmatic events are coeval with results interpreted as metamorphic overprinting of previous rocks. The RFB has widespread granulite formation with temperatures achieving T > 900ºC (Bento dos Santos *et al*., 2011) which implies abnormal geothermal gradients as high as 45-60ºC/km and requests an orogenic process capable of heating large sections of the crust, both causing metamorphism in existing rocks and melting to produce new magmatic occurrences; b) although with an important time range that can be > 25 Ma, each area shows a clear separation of 3 main orogenic events that essentially do not overlap; c) there is a clear shift to progressively younger ages from south to north, irrespective of the orogenic period considered.

Table 1 summarizes the geochemical evolution of the RFB, showing a progression of the geochemical features of the various magmatic occurrences as evolving from: a) Magmatic Series I, mostly composed of arc-related, calk-alkaline, I-type, metaluminous to slightly peraluminous granitoids; to b) Magmatic Series II, dominantly composed of anatectic, sub-alkalic, S-type, peraluminous granitoids; to c) Magmatic Series III, mostly composed of calc-alkaline to alkaline, I-type, metaluminous, high-K granitoids.

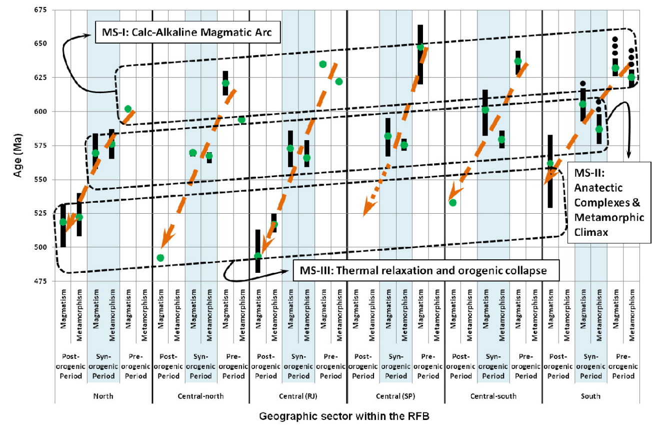


Fig. 1. Integration of the geochronological and geochemical datasets. Dashed boxes show range of geochronological results for each Magmatic Series (MS) in each geographic sector.

Fig. 1. Integração dos dados geocronológicos e geoquímicos. As caixas a tracejado mostram a variação dos resultados geocronológicos para cada Série Magmática (MS) em cada sector geográfico.

Integration of the geochronological results and geochemical data for the entire belt (Fig. 1) shows that the pre-orogenic, syn-orogenic and post-orogenic events are coeval with the emplacement of Magmatic Series I, II and III, respectively. These three major magmatic periods can be related with the long-term evolution of the RFB from 670 to 530 Ma in southern RFB and from 630 to 480 Ma in northern RFB. The results for the syn-orogenic periods in each geographic segment also show that the ages are progressively younger from south to north, implying that the different geographic sectors of the RFB must have been diachronically amalgamated into the Western Gondwana Supercontinent. Closure of the Adamastor Ocean must have occurred at ≥ 630 Ma in southern RFB and at ~ 590 Ma in northern RFB (Fig. 2).

3. Geodynamic Model

The previous data and interpretations show that throughout the RFB, the syn-orogenic period was 15-30 Ma prior to the onset of the post-orogenic period. The syn-orogenic event is very well constrained by the intrusion of anatectic, S-type, peraluminous granitoids, whereas the post-orogenic period is mostly characterized by the intrusion of late calc-alkaline/alkaline, I-type, metaluminous granitoids (and shoshonitic rocks) that were considered by Pedrosa-Soares *et al*. (2001) as "originated in the lowermost continental crust with important mantle contribution". This suggests that the first period is related with the main orogenic event, coeval with the metamorphic peak (Bento dos Santos *et al*., 2010), whereas the latter is related with the stabilization of the orogenic landmasses and late intrusion of lower-crust/mantle-derived or hybrid granitoids, considerably different from those created during the thermal climax in the RFB.

The compiled data clearly shows that the vast majority of ages related with the main orogenic event, even considering a diachronic collision, is concentrated between ~ 615 and 560 Ma (60% of the entire geochronological dataset), whereas the 540-490 Ma time period represents only 25% of the entire dataset. This evidence suggest that the large-scale collision between the Amazonian – Rio de la Plata – Paranapanema – São Francisco Cratonic Block and the Congo/Kalahari Cratons must have happened shortly before the syn-orogenic period, i.e.: before 615-560 Ma, considering the diachronic evolution of RFB.

Heating of the middle/low-crust capable of producing zircon growth can be caused by orogenic events, namely crustal thickening, but also by other types of processes related with the evolution of an orogenic belt after the collision period, such as granitoid intrusion, radioactive decay of high heat-producing elements, upwelling of asthenospheric mantle, magma underplating, etc. The 540-490 Ma thermal evidence (granitoid production and associated metamorphism) probably reflects mountain range breakdown through orogenic collapse and late intrusion of post-orogenic, metaluminous, I-type granitoids and shoshonites. This very late period of magmatic emplacement is coeval with the period of very fast cooling constrained by Bento dos Santos *et al*. (2010) at 500-480 Ma in the central and north segments of the RFB. These authors concluded that the very fast cooling experienced by large portions of the middle/low-crust was due to exhumation during orogenic collapse, which might have triggered the closure of the U-Pb isotopic systems of magmatic and metamorphic rocks that had been maintained at higher temperatures until that period.

An external heat source capable of originating and maintaining a long-term high heat flux in the middle/low-crust of the RFB (as indicated by Bento dos Santos *et al*., 2010) is supported by recent geodynamic models proposed for continental collision orogenic belts. Slab break-off or detachment (e.g.: Davies & Blanckenburg, 1995), shortly after the collision event, followed by asthenospheric upwelling through the slab window has been suggested as a distinctive feature during the post-collision evolution of prolonged hot orogenic belts. Thermal upwelling in the resultant slab window and magma underplating beneath the crust (Henk *et al*., 1997) could provide both the crustal thermal anomaly (with geothermal gradients as high as 45-60ºC/km; Bento dos Santos *et al*., 2011) and the long-lived (>100 Ma) magmatic activity. Minor production of lower-crust/mantle hybridized granitoids coeval or shortly following the dominant S-type, peraluminous granitoids and leucogranites emplaced during the thermal climax (*e.g.*: Pedrosa-Soares *et al*., 2001; Heilbron & Machado, 2003) could also be explained with this process.

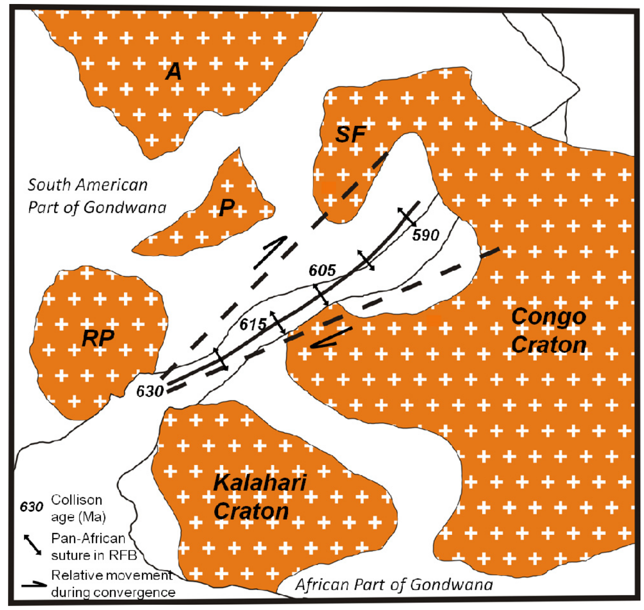


Fig. 2. Diachronic collision of the cratonic blocks involving the RFB starting at 630 and lasting until 590 Ma. Arrows show palinspatic dextral oblique relative movement due to diagonal convergence related to the Euler's rotation poles at 630 – 590 Ma. Cratons: A – Amazonian; SF – São Francisco; P – Paranapanema; RP – Rio de la Plata.

Fig. 2. Colisão diacrónica dos blocos cratónicos que envolvem a Faixa Ribeira entre 630 e 590 Ma. As setas evidenciam movimento relativo palinspático dextro devido a convergência diagonal relacionada com a rotação dos pólos eulerianos a 630 – 590 Ma. Cratões: A – Amazónico; SF – São Francisco; P – Paranapanema; RP – Rio de la Plata.

Therefore, and considering the central RFB as an example, the presented results suggest a geodynamic model for the RFB with the following stages: a) continental rifting, break-up and dismembering of the Rodinia Supercontinent at ~ 1.0-0.9 Ga (Brito Neves *et al*., 1999); b) oceanization stage with ocean-floor spreading and formation of the Adamastor Ocean at ≥ 800 Ma in a passive-margin setting (Pedrosa-Soares *et al*., 2001); c) active-margin setting with subduction of oceanic crust and pre-orogenic arc-related magmatism with formation of the cordilleran-type Rio Negro Magmatic Arc from ca. 790-610 Ma (Tupinambá *et al*., 2012); d) main collision event between the Amazonian – Rio de la Plata – Paranapanema – São Francisco Cratonic Block and the Congo/Kalahari Cratons at 610-590 Ma (Fig. 2), followed by the syn-orogenic period with metamorphic climax and intrusion of large peraluminous granitoid plutons at 590-565 Ma; e) slab break-off and asthenospheric upwelling at 580-555 Ma; f) transpressive tectonics with the formation of large dextral shear zones and long-term sustaining of high-thermal flux due to mantle underplating from 570 to 520 Ma; g) post-orogenic calc-alkaline/alkaline (with minor slab melting/hybridization) magmatic intrusions at middle/low-crust level during orogenic collapse from 525 to 490 Ma, followed by thermal relaxation and crust stabilization from 510 to 475 Ma.

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