ARC-RELATED RAPAKIVI GRANITES FROM THE RIBEIRA FOLD BELT, SE BRAZIL.*

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ABSTRACT Arc-related late orogenic rapakivi granites from the Late Precambrian *Ribeira Fold Belt* (*RFB*) are presented and discussed. They occur intimately associated in space and time with Caledonian-type granites and appinites (mainly potassic diorites) and were emplaced during the *Post-collisional Crustal Identation and Uplift* stage of the *RFB.* The three rocks groups, together with shoshonitic and ultrapotassic ones, belong to the *Pluriserial Ribeira Magmatic System 590* (*PRMS-590*), with acted between 620 and 570 Ma ago during the *RFB* back-arc development.

Petrographic, geochemical and isotopic data define a high-K alkali-calcic nature and a lower crustal origin for the rapakivi granites. The crustal magmas may underwent or not further compositional changes either by mixing (up to 14 vol. %) with enriched mantle-derived appinitic magmas and/or by assimilation of fluid-rich upper crustal material. $\varepsilon_{Nd(585)}$ values for crust- and enriched mantle- derived rocks range between –12 and –16 & –7 and –10, respectively, and T_{DM} ages range between 2.4 and 1.8 Ga. & between (fictive) 1.4 and 1.6 Ga., respectively. With increasing participation of the appinitic component during mixing, the rapakivi granites became progressively more alkaline and their $\varepsilon_{Nd(585)}$ and T_{DM} values became less negative and lower, respectively.

Geochemical and isotopic data show that the rapakivi magmas are derived from calc-alkaline biotite and hornblende- bearing tonalitic/granodioritic sources by incongruent dehydration melting at low $\boldsymbol{P_t}$, high $\boldsymbol{T}$, and $\boldsymbol{f_{O2}}$ typical for high-K rocks. The development of the rapakivi texture is controlled mainly by physical conditions during magma ascent and cooling than by magma composition. Rapakivi plutons were emplaced under decompressional conditions during rapid orogenic uplift as shown by expressive rising and unroofing of their partly only slightly other calc-alkaline host-rocks. Due to their compositional and isotopic similarity, same age and close spatial association, the Ribeira rapakivi and Caledonian granites are considered as products derived from a same source under slightly variable melting conditions.

Keywords: Ribeira Fold Belt, Magmatic System, Rapakivi granites, Genesis, Evolution

INTRODUCTION The Late Precambrian *Ribeira Fold Belt* (*RFB*), about 2800 km long and with a mean width of around 200 km, runs parallel to the South American coast with a dominantly NE/SW strike from SE Brazil (northerly Vitória, Espírito Santo State) to Northern Argentina (Fig. 1). A synthesis, including structural organization, deformation phases, metamorphic events, magmatic episodes, was presented by Wernick (1998a).

During the *Postcollisional Crustal Identation and Uplift* (*PCIU*) evolutional stage of the *RFB*, between 620 and 570 Ma ago, the *Pluriserial Ribeira Magmatic System-590* (*PRMS-590*) (Wernick *1*998a, b) was developed comprising plenty isolated or clustered plutons beside minor flows and volcanoclastic deposits. Their emplacement is controlled either (subordinately) by arched structures linked to the last regional, open-waved, *RFB*-folding phase or (dominantly) by deep crustal weakness zones developed under transpressive and later on repeatedly reactivated under transtensional and tensional stress regimes during the post-collisional escape tectonics (Hackspacher and Godoy *1*999). The transcurrent fault phase promotes intensive horizontal crustal domains displacements as well as local and regional horst and graben structures. All rock types from the *PRMS-590*, independently of their origins and compositions, share same general features. These include a complex magmatic architecture comprising several magmatic phases and/or cycles. This aspect reflects several drainage and replenishments of magma chambers by successive reactivation of crustal weakness zones that control the dynamic of magma supply and magma chamber evolution. This processes also allows an intensive interaction between crust and mantle-derived magmas, magma mixing during chamber replenishments, strong fractionation and crustal assimilation (Wernick *et al*. 1993) as well as an important fluid role (Wernick and Teuppenhayn 1999, Wernick *et al*. 2000).

The *PRMS-590* comprises 7 high-K (calc-alkaline, shoshonitic, potassic, ultrapotassic) mantle- and crust- derived rock groups, all with arc-related chemical signatures (Wernick *et al*. 1997a, b, Wernick 1998a, b *1*999, Wernick and Menezes 2000a, Wernick *et al.* 2000). The aim of this paper is to present and discuss the *PRMS-590* rapakivi granites based on data from the Itu Province, State of São Paulo, SE Brazil. Fig. 2 shows its location in the frame of the *Ribeira Magmatic Arc* (*RMA*).

THE ITU PROVINCE The Late Precambrian Itu Rapakivi Province (Wernick 1992), surrounding the E/SE border of the Paraná Basin in the São Paulo State, SE Brazil, comprises about a dozen high-level emplaced intrusions from which the best known are shown in Fig. 3.

The most outstanding intrusions are the "S"-shaped Sorocaba body (150 km^2), the drop-like NE-SW trending São Francisco pluton (130 km^2) and the large (310 km^2) polycentred Itu complex, partially hidden by Paleozoic sediments, comprising four coalescent plutons (Salto, Cabreúva, Indaiatuba and Itupeva, the latter a Caledonian-type granite).

All major bodies show a rather complex magmatic history that starts with a restricted initial, often high-K dioritic, phase actually

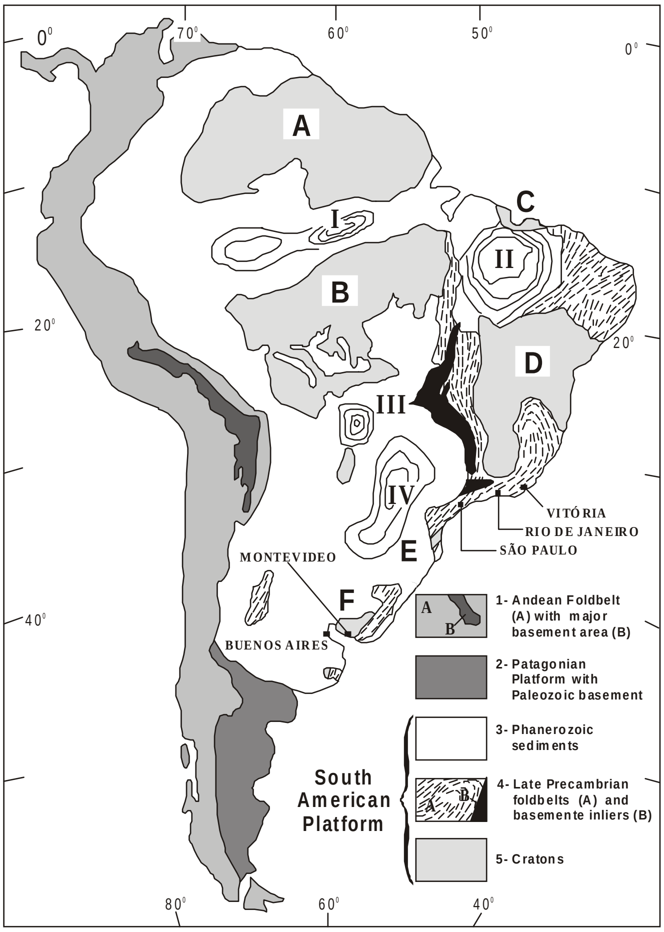

Figure 1-Simplified tectonic outline of South America. South America Platform: Larger Phanerozoic basins with depocentres: Amazonas (I), Maranhão (II), Alto Xingú (III) and Paraná (IV); Cratons: Guyana (A), Guaporé (B), São Luís (C), São Francisco (D), Luis Alves (E) and Plata (F).

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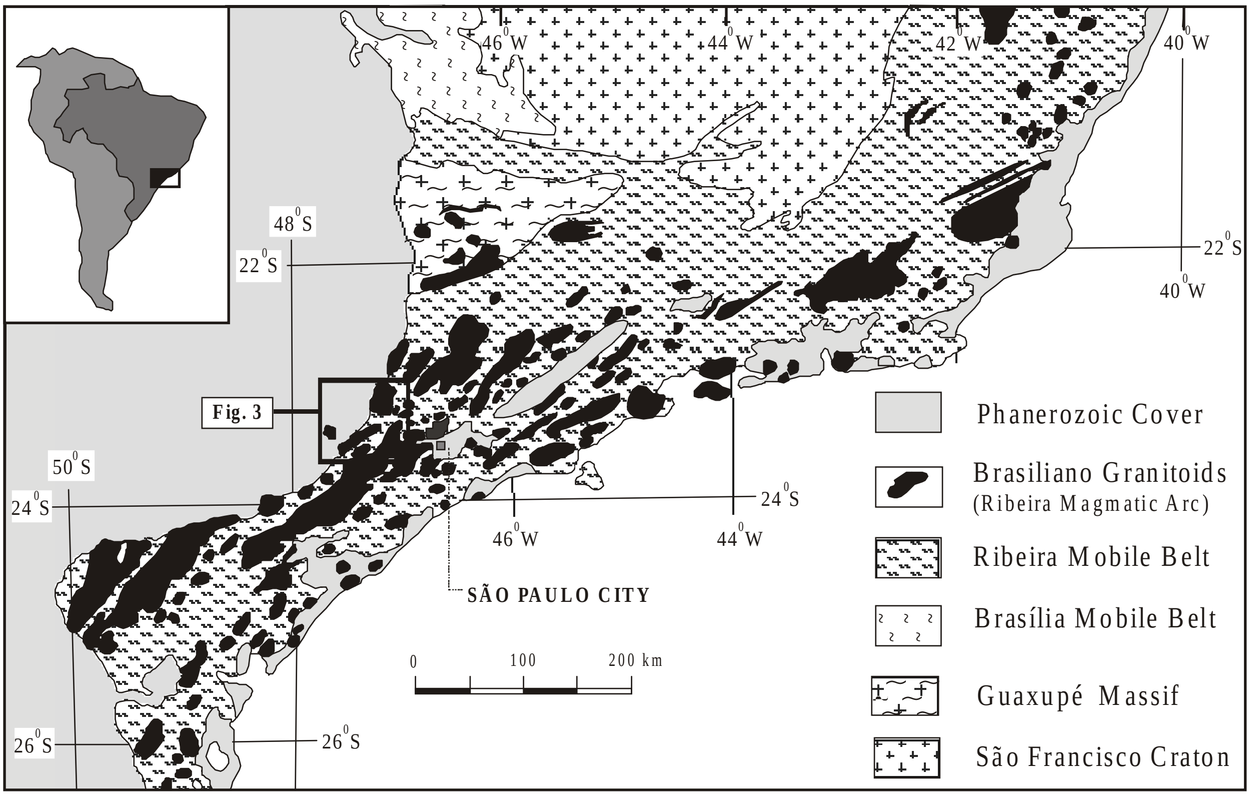

Figure 2-The Brasiliano (Late Precambrian) Ribeira Magmatic Arc in S/SE Brazil with location of the Itu Province (Fig. 3).

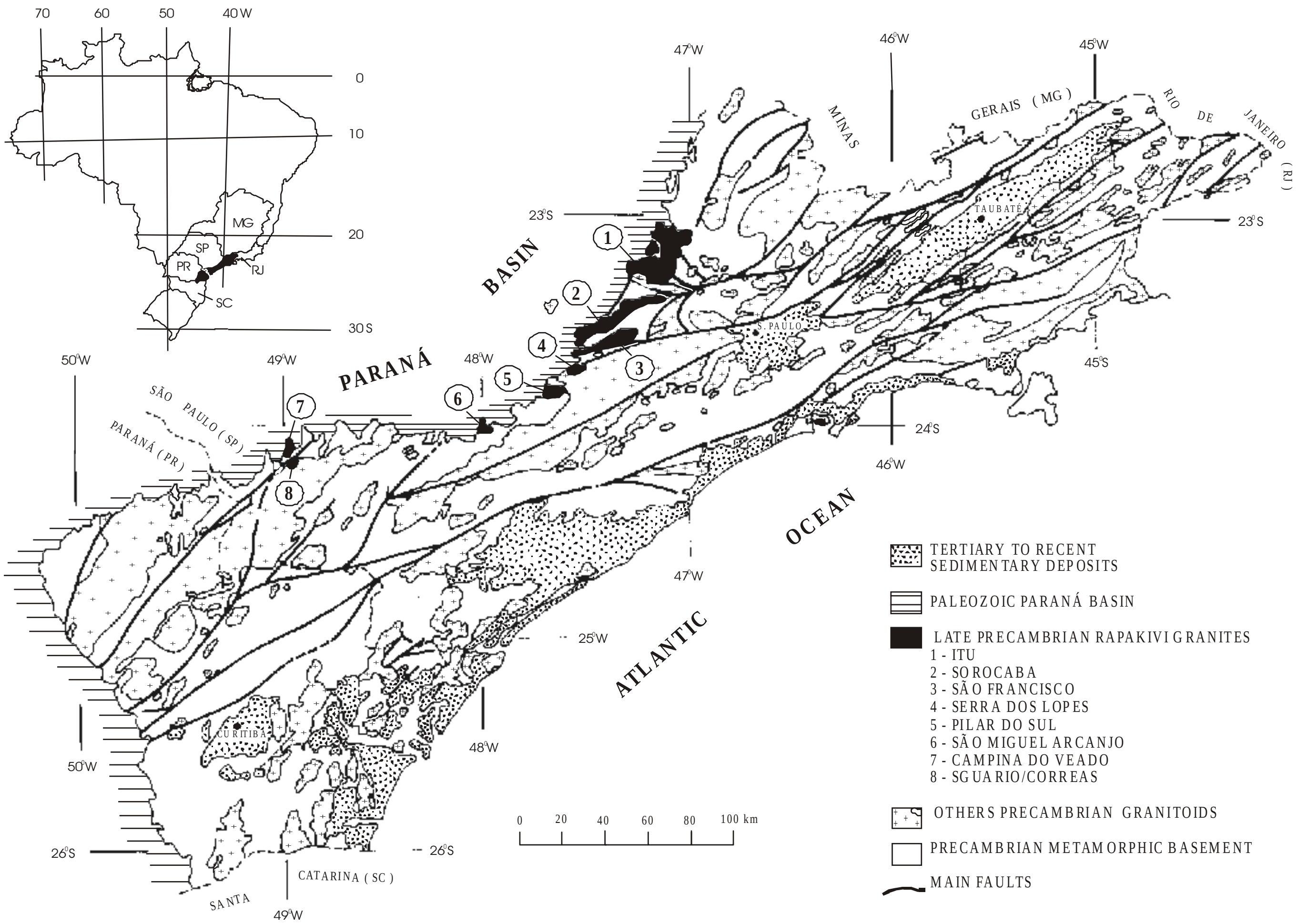

Figure 3-The Itu Rapakivi Province, São Paulo State, SE Brazil. After Wernick et al. 1997.

preserved as enclaves, mega-enclaves or even major continuous areas (as in the core of the Cabreúva and Itupeva plutons). It follows a main intrusive phase comprising several pulses of variable petrography (magma composition), textures (thermal history) and structures (magma rheology). The pulses are of small volume as observed in the "tectonic staircase" structure of the Sorocaba granite. The structure comprises three tectonic segments uplifted progressively from SE to NW along normal faults, thus allowing the observation of increasing lower levels of the pluton. The emplacements of stocks and bosses correspond to the third phase and the fourth (final) one is represented by the income of several types of dikes. As in all high-K groups of the *PRMS-590*, also the major rapakivi plutons comprise 2 or 3 magmatic cycles reflecting several drainage and replenishments of magma chambers by successive reactivation of faults which control their evolutional dynamic (Wernick 1998a, b, 1999; Wernick and Menezes 2000a; Wernick *et al.* 2000).

Host rocks include high- (Itapira and Amparo Groups) to low-grade (São Roque and Serra de Itaberaba Groups) metassedimentary/volcanic rocks beside high-K calc-alkaline batholiths. The São Francisco pluton which cuts phyllites from the São Roque Group developed an about 2 km wide contact aureole with rocks up to the sanidine facies. Contacts are intrusive, brecciated or tectonic (wrench and normal faults). For further details see Wernick *et al.* (1997a) and within listed references.

The petrography of the province is rather monotonous with the almost dominance of even-grained, porphyritic and megaporphyritic alkali-feldspar, syeno- and monzogranites with variable amounts of mantled feldspars. The coexistence of ovoid, rectangular, irregular and broken phenocrysts is a common feature. In some rather coarse even-grained rocks also fine albite/oligoclase rims surround the xenomorphic K-feldspar grains. Some monzogranites also display major amounts of antirapakivi megacrysts as well as phenocrysts with several alternating K-feldspar and oligoclase/albite rims the microscopic structure of the rapakivi texture is rather variable including all main types described in literature (Galembeck *1*997). Highly evolved rocks as magmatic topaz-bearing muscovite-albite granites occur in the Cabreúva, Pilar do Sul, Correas plutons. The fractionation process evolves to final fluid enrichment resulting in (Sn, W, Zn, Pb, Cu) -bearing pegmatites, quartz veins and exo/endogreisen, but only the Inhandjara wolframite-bearing exopegmatites from the Cabreúva pluton (Itu complex) were tentatively exploited during Second World War.

The main rapakivi mafic mineralogy comprises micas, ranging from the boundary between Mg- and Fe-biotite to the upper Mg-boundary of the lepidomelane field, beside rare amphiboles of Mg-hornblende/edenite to Fe-edenite compositions. Very rare augite occurs as badly preserved cores in some amphiboles. Magnetite, zircon, apatite, xenotime, allanite, pyrite and fluorite are conspicuous accessories. Wernick *et al.* (1997a), Galembeck (1997) and Galembeck *et al.* (1997) discuss geochemical data for rocks and minerals.

$(Rb/Sr)_{WR}$ and $(U/Pb)_z$ data from Tassinari (1988) and Töpfner (1996) for the Cabreúva intrusion (Itu complex) result in ages of 586 ± 10 and 583 ± 20 Ma, $(^{87}Sr/^{86}Sr)_i$ values of 0.7066 and 0.7081, respectively, and a concordia age of 582 ± 6.4 Ma. For the same rocks Zielenski (1993) got high $\delta^{18}O$ values (+ 9.5 ‰ ± 0.2). $\varepsilon_{Nd(585)}$ values (Wernick *et al*., in preparation) ranges between –16.6 and –7.45 and T_{DM} ages between 2.1 and 1.56 Ga.

The chemical data chosen for this paper are from the Itu complex (Köhler 1990, Ruf 1990, Galembeck 1991, 1997, Zielenski 1993, Töpfner 1996) as well as from the Sguario and Correa plutons (Rothmaier 1994). The analyses were performed by XRF and ICP at the Mineralogisch-Petrographisches Institut und Museum, University of Kiel, Germany, and at the Institut für Allgemeine und Angewandte Geologie, University of München, Germany. Analytical errors for major and trace elements are between 3-5% and 2-3%, respectively.

TECTONIC SETTING Fig. 4 shows the data for the rapakivi granites in several high-K rocks tectonic discrimination diagrams. In almost all diagrams the rapakivi granites plot in the continental arc, post-collisional arc and late orogenic granites fields. For detailed geochemical data see Wernick *et al*. (2000) with plenty comparative geochemical diagrams for Ribeira rapakivi and Caledonian-type granites.

DISCUSSION Up to now rapakivi granites have been considered as a specific type of anorogenic A-type magmatism. In Finland, the home of the classic rapakivi granites, their emplacement associated with basic and alkaline dikes and/or plutons post-dated in more than 200 Ma the last typical arc-related magmatism (Rämö and Haapala 1995).

Based on our studies in the Late Precambrian *Itu Province*, São Paulo State, SE Brazil, belonging to the *Ribeira Magmatic Arc*, a new type of rapakivi granite, clearly arc-related, is proposed. This type of rapakivi granite shows following main characteristics:

1 – They were emplaced mainly 585 ± 15 Ma. ago during the *Postcollisional Crustal Identation and Uplift Stage* of the *Ribeira Fold Belt.*

2 – They occur intimately associated in space and time with high-K calc-alkaline Cordilleran and high-K alkali-calcic Caledonian batholiths and plutons in addition to appinitic rocks. In the former case the rapakivi granites cut or surround the Cordilleran-type batholiths. In the latter case they occur associated with Caledonian-type plutons and appinitic stocks, pods and dikes either in polycentred complexes or along expressive lineaments. Together with shoshonitic and ultrapotassic rocks from the

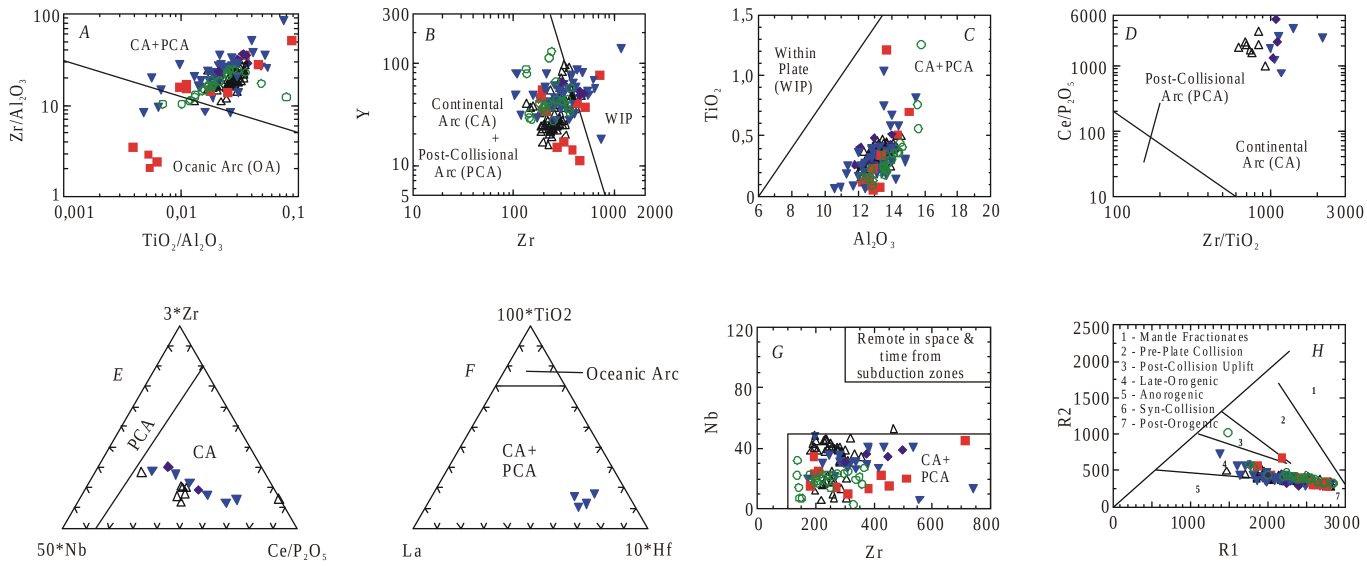

Figure 4-Plots for rapakivi rocks from the Itu Province, São Paulo State, SE Brazil, in several high-K rocks tectonic environment discrimination diagrams. Internal division of A-F after Müller et al (1992); G after Thompson and Fowler (1986); H after Batchelor and Bowden (1985). Rapakivi plutons: Campina do Veado (■); Sguario (○); Cabreúva (&); Salto (+); Indaiatuba (◆).

PRMS-590 they define a typical high-K arc-related rock association emplaced during the *RFB* back-arc development (Wernick and Menezes 2000b).

3 - Modeling of mixing between crustal magmas extracted from meta-quartz dioritic/granodioritic sources and high-K dioritic magmas, employing for the latter the mean composition of the Piracaia pluton, São Paulo State, (Wernick *et al*. 1997a, Wernick and Menezes 2000a), indicates a participation of the latter up to 14 vol. %. For the hybrid Jaala-Iitti ring-dike at the NW border of the Wiborg batholith Salonsaari (1995) determined a mixture between crustal and mantle magmas with a mafic mass fraction up to 0.3. However, this model has only an indicative character as the hybrid Itu magma underwent later fluid-rich upper crust assimilation. This is suggested by almost flat Upper Crust normalized REE patterns with values close to 1 (Wernick *et al*. 2000). Mixing and assimilation, beside fractional crystallization, characterize an open mantle-crust system (Kerr and Fryer 1993, Salonsaari 1995, Poitrasson *et al*. 1995) and ACF processes. Isotopes confirm the mixing as crust- and enriched mantle-derived rocks show contrasting Sm/Nd features. The latter have $\varepsilon_{Nd(585)}$ values between –10 and –7 and (fictive) T_{DM} ages between 1.4 and 1.6 Ga. (corrected T_{DM} ages around 2.0 Ga.), whereas the former have $\varepsilon_{Nd(585)}$ values between –16 and –12 and T_{DM} ages between 2.4 and 1.8 Ga., indicating for uncontaminated crustal rapakivi magmas an Early Proterozoic lower crustal source. (Vlach 1993; Janasi 1999; Wernick *et al*., in preparation). Increasing mixing between crustal and appinitic magmas results in progressively more alkaline rapakivi granites with $\varepsilon_{Nd(585)}$ values as low as –7.5 and T_{DM} ages as low as 1.56 (Wernick *et al.* in preparation).

4 - The larger rapakivi bodies and polycentred complexes comprise several magma cycles and plutons of variable alkalinity, respectively. In the Sorocaba granite the first (oldest) cycle, without rapakivi textures, is near calc-alkaline whereas the following two are alkali-calcic and with variable amounts of rapakivi textures. In the Itu complex all three rapakivi plutons are alkali-calcic but zircon typology and mica composition define increasing alkalinity along the sequence Indaiatuba → Salto → Cabreúva (Galembeck 1997, Galembeck and Wernick 1998). The subvolcanic Salto intrusion, is the richest in porphyritic rapakivi textures and in coarse even-grained rocks fine albitic rims surround the xenomorphic K-feldspars grains. In the Cabreúva pluton, comprising almost entirely fine to coarse even-grained rocks, this feature is missing. This indicates that the development of rapakivi texture is more controlled by physical conditions during magma ascent and cooling than by specific magma composition (Nekvasil 1991).

5 - The generation of (high-K) calc-alkaline I-, alkali-calcic I- and metaluminous A-type granitic magmas by incongruent dehydration melting of relatively dry calc-alkaline biotite and hornblende bearing tonalitic/granodioritic and orthogneisses was proposed by several authors (Anderson 1983, Carroll and Wyllie 1990, Creaser *et al*. 1991, Rämö 1991, Haapala and Rämö 1992, Weaver *et al*. 1992, Skjerlie and Johnston 1993, Roberts and Clemens 1993, Patiño Douce 1997). This model is confirmed for the Itu Province by isotopic [$\delta^{18}O$, Sm/Nd and $(Sr)_i$] and geochemical data (Wernick *et al*. 2000). The amount of melt got by this process is constrained either by the composition of the protolith, including its water content, besides melting temperatures and pressures. For incongruent dehydration melting of mafic to intermediate calc-alkaline orthogneisses with 0.7 to 1.6 wt.% H_2O at 900 - 950ºC and 5 – 10 kbar, Clemens and Vielzeuf (1987) and Johannes and Holz (1991) predicted melt volumes between 30 – 60 vol. %. These data agree with the volumes obtained experimentally by Skjerlie and Johnston (1993) and Patiño Douce (1997) melting hornblende and biotite bearing tonalites and granodiorites at 950ºC and 4 - 10 kb. The melts are metaluminous and water undersaturated, and in all cases higher and lower melting pressures resulted in magmas with more I- and A-type affinities, respectively.

6 - For the subvolcanic Salto and the somewhat deeper Cabreúva plutons from the Itu complex, Galembeck (1997) got amphibole crystallization pressures of 1.7 and 2.4 - 2.9 kb, respectively. For appinitic (quartz)(monzo)diorites, Vlach (1993) achieved pressures between 2.3 – 2.7 and 1.3 – 1.7 for fine/medium- and coarse-grained rocks, respectively. These values agrees with those (3.0 – 3.1 kb) obtained by Salonsaari (1995), for matrix hornblende from the hybrid Jaala-litti ring-dike at the NW border of the Wiborg batholith which matrix hornblende have slightly higher crystallization pressures (3.6-3.9 kb). All data refer to the Johnson and Rutherford (1989) calibration and very low pressures (less than 2 kb) are explained by subsolidus exchanges. Thus the overall hornblende crystallization pressures in rapakivi granites and associated appinites are comparable to the 4 kb experimental conditions of Patiño Douce (1997). Also and the Ab:Or:An system the mean value for the rapakivi rocks plots near the anhydrous 4 kb experimental data (Wernick *et al.* 2000).

7 - Crystallization temperatures for rapakivi and associated Caledonian granites from the Itu complex, using zircon typology thermometry (Pupin 1980), are between 900-950ºC and 850-900ºC, respectively (Galembeck 1997, Galembeck *et al*. 1999), approaching the experimental conditions of Skjerlie and Johnston (1993) and Patiño Douce (1997).

8 - Based on mica compositions from the Itu complex, a f_{O2} in the NNO-HM range was determined (Galembeck 1997; Galembeck *et al*. 1997), typical for many high-K granitoids (Speer 1984, Rowins *et al*. 1991). The Jaala-Iitti mixing occurred under f_{O2} conditions at or slightly below the QFM buffer (Salonsaari 1995).

9 - The substantial melting (> 20 vol. %) of the source under high temperatures (900-950ºC) and low pressures (4-6 kbar) requires strong thermal income. This is provided mainly through (1) income of basic (appinitic) magmas approaching the Earth's surface and derived from an enriched convecting mantle (Wernick *et al*. 1997b, Wernick and Menezes 1999, 2000) and (2) fast orogenic uplift (rapid decompression) following crustal thickening. This first aspect is supported by mixing between crust and mantle derived magmas at high crustal level. The second is indicated by the "rising and unroofing" of the rapakivi calc-alkaline batholithic host-rocks which age differences with respect to the cutting plutons are in some cases very small (Wernick 1998a). Thus, the geologic aspects support effective heat transfer. This explains the genesis of the Ribeira rapakivi granites having as source the roots or deeper intrusions of high-K calc-alkaline granitoids they cut or surround.

10 – The Ribeira rapakivi granites define a chemical continuum ranging from metaluminous high-K alkali-calcic to high-K near alkaline (Wernick *et al.* 2000).

11 - The associated Caledonian granites overlap in their petrography, geochemistry, metallogeny and isotopy the rapakivi ones. Thus, both are considered as melting products of a same protolith under slightly variable conditions. This feature is also observed in the "Post-Svecofennian" Transscandinavian Igneous Belt (*TIB*) comprising late- to post-orogenic granites roughly emplaced between 1.8 and 1.6 Ga. ago. Among the late-orogenic granites two different types are discernible. One (e.g. Järna granite) compare better with the older late-orogenic high-K Smöland-Värmeland I-type granites whereas the other (Garberg and Siljan granites) shows close geochemical, petrographic and metallogenic similarities with rapakivi granites (Ahl *et al*. 1997, and within listed references). As in the *PRMS-590* successively reactivated zones of crustal weakness control the pluton emplacement, rapakivi and Caledonian granites may occur associated either along a same tectonic lineament or clustered in polycentred complexes.

CONCLUSIONS A new type of rapakivi granite, late orogenic and clearly arc-related, is defined. This type developed during the *Postcollisional Identation and Crustal Uplift* stage of fold belts, as in the Late Precambrian Ribeira Belt. Arc-related rapakivi granites occur intimately associated with Caledonian-type granites and K-lamprophyric kersantitic/appinitic rocks in space and time. The rapakivi magmas result from incongruent dehydration melting of older, slightly younger or even about isochronous biotite and hornblende bearing calc-alkaline tonalites and granodiorites under low pressure and high temperature. The rapakivi texture reflects particular physical conditions during magma ascent and crystallization rather than specific chemical compositions. Due to their overall similarity, rapakivi and Caledonian-type magmas are considered as different products of a same source melting under slightly variable conditions. The magmas underwent or not further compositional changes either by mixing with the coeval alkaline transitional, mainly dioritic, K-lamprophyric magmas and/or assimilation of upper crustal material.

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