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Geochemical signatures of metasedimentary rocks of high-pressure granulite facies and their relation with partial melting: Carvalhos Klippe, Southern Brasília Belt, Brazil

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High-grade metasedimentary rocks can preserve geochemical signatures of their sedimentary protolith if significant melt extraction did not occur. Retrograde reaction textures provide the main evidence for trapped melt in the rock fabrics. Carvalhos Klippe rocks in Southern Brasilia Orogen, Brazil, present a typical high-pressure granulite assemblage with evidence of mica breakdown partial melting (Ky + Grt + Kfs ± Bt ± Rt). The metamorphic peak temperatures obtained by Zr-in-Rt and ternary feldspar geothermometers are between 850 °C and 900 °C. The GASP baric peak pressure obtained using grossular rich garnet core is 16 kbar. Retrograde reaction textures in which the garnet crystals are partially to totally replaced by Bt + Qtz ± Fsp intergrowths are very common in the Carvalhos Klippe rocks. These reactions are interpreted as a result of interactions between residual phases and trapped melt during the retrograde path. In the present study the geochemical signatures of three groups of Carvalhos Klippe metasedimentary rocks are analysed. Despite the high metamorphic grade these three groups show well-defined geochemical features and their REE patterns are similar to average compositions of post-Archean sedimentary rocks (PAAS, NASC). The high-pressure granulite facies Grt-Bt-Pl gneisses with immature arenite (wacke, arkose or lithic-arenite) geochemical signatures present in the Carvalhos Klippe are compared to similar rocks in amphibolite facies from the same tectonic framework (Andrelândia Nappe System). The similar geochemical signatures between Grt-Bt-Pl gneisses metamorphosed in high-pressure granulite facies and Grt-Bt-Pl-Qtz schists from the Andrelândia and Liderdade Nappes, with minimal to absent melting conditions, are suggestive of low rates of melt extraction in these high-grade rocks. The rocks with pelitic compositions most likely had higher melt extraction and even under such circumstances nevertheless tend to show REE patterns similar to average compositions of post-Archean sedimentary rocks (PAAS, NASC).

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1. Introduction

Retrograde reaction textures such as partial pseudomorphs, coronae and symplectic coronae are relatively common features of granulite facies rocks and are among the more useful indicators of retrograde P-T evolution (White and Powell, 2011). Back-reaction textures may represent reactions between melt and residual phases (Ashworth, 1976; Waters, 1988, 2001; Kriegsman and Hensen, 1998), and their occurrence suggests that part of the melt produced was trapped within the system (Spear et al., 1999). As discussed in Kriegsman (2001), mesosomes of migmatic are a result of back reactions between restite and unsegregated melt. The leucosome represents crystallised segregated melt or melt products trapped in a drainage network (Sawyer, 1987; Barbay et al., 1996; Sawyer et al., 1999). Restitic mineral assemblages with little retrogression indicate nearly complete melt removal (Spear et al., 1999). The processes that control extraction of the melt from the system include segregation, connection and migration of the melt (Kriegsman, 2001; Sawyer, 2001). Migration is expected when the percentage of melt increases beyond 20–30% (van der Molen and Paterson, 1979; Vigneresse et al., 1996; Spear et al., 1999). If melt loss occurs, the bulk composition of the system may change. Therefore, the residual composition might be different from the protolith initial composition.

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The chemical record of the high-grade metasedimentary rocks of the Neoproterozoic belt south of São Francisco Craton, SE Brazil, was previously investigated to recognise the main features of the provenance area (Garcia et al., 2004). In the present study geochemical signatures of metasedimentary rocks from Carvalhos Klippe that contain typical high-pressure granulite mineral assemblages produced by mica dehydration melting reactions are analysed. The geochemical signatures of these rocks are compared with the average composition of post-Archean sediments (PAAS (Post-Archean average Australasian shale; Nance and Taylor, 1976) and NASC (North American shale composite; Haskin et al., 1968)) and with similar metasedimentary rocks that occur in the same tectonic framework (Andrelândia Nappe System) but that are of a lower metamorphic grade (amphibolite facies). The main goal of this comparison is to investigate the melt extraction from the system and the magma generation potential of the metasedimentary rocks from the Carvalhos Klippe.

2. Geological setting

The Neoproterozoic Brasília Orogen is located along the western, southwestern and southern margins of São Francisco Craton (Fock et al., 1994; Dardenne, 2000). The southern portion of the orogen consists of a succession of subhorizontal nappes within an orogenic wedge dipping to S-SW. Three different tectonic settings (from SW to NE) are represented within these nappes: (1) a magmatic arc domain, which was developed at the active continental margin of the Paranapanema Plate (Socorro-Guaxupé Nappe), (2) a subducted continental domain (the Andrelândia Nappe System) and (3) a passive continental margin/rift domain related to the Sanfranciscana Plate (the Carrancas and Lima Duarte nappe systems) (Fig. 1). These systems of nappes show a sub-horizontal detachment (Trouw et al., 2000) of at least 150 km towards E-NE (the upper nappes) to N-NE (the lower nappes) (Campos Neto and Caby, 1999, 2000).

The Andrelândia Nappe System (Campos Neto et al., 2007) presents an inverted metamorphic pattern that includes, from bottom to top, three main allochthons: (1) the lower Andrelândia Nappe that is mainly composed of metasedimentary rocks of lower to intermediate amphibolite facies; (2) the Liberdade Nappe that consists of schists of intermediate to upper amphibolite facies; and (3) the upper nappes in which high-pressure granulite facies metasedimentary rocks dominate (these include the Três Pontas-Varginha and Pouso Alto nappes and the Aiuruoca, Carvalhos and Serra da Natureza klippen). This study is focused on Carvalhos Klippe rocks (Trouw et al., 2000; Cioffi, 2009; Campos Neto et al., 2010) (Fig. 2), which is a basin-like structure with major axis of nearly 18 km in the NW-SE direction, that preserves high-pressure granulite facies rocks lying on intermediate to upper amphibolite facies rocks of Liberdade Nappe.

The Klippe is mainly composed of metasedimentary rocks with typical mineral assemblages of high-pressure granulate facies: Qtz + Ky + perthitic Kfs + Grt + Rt. The occurrence of mafic assemblages as centimetric to metric boudins with the Grt + Cpx + Pl + Qtz assemblage common. The high-pressure metamorphism took place at 617.7 ± 1.3 Ma (Campos Neto et al., 2010). The main lithotype from Carvalhos Klippe is a banded light-grey (Bt)-Ky-Grt-Kfs migmatitic granulite with predominantly medium- to coarse-grained inequigranular granoblastic texture with subordinated thin lepidoblastic layers rich in biotite. The banding of the migmatitic granulate is defined by centimetre- to metre-scale layers that contain different proportions of feldspar, quartz, garnet, kyanite and biotite. This banding is parallel to millimetre- to centimetre-scale leucosomes that are commonly boudined. These rocks are layered with centimetre- to decametre-scale (Ky)-Grt-Bt-Pl gneiss lenses. Finely-banded (Bt)-Grt gneiss also occurs in the central portion of the klippe.

3. Analytical methods

Optical petrography was conducted using a Zeiss Axioplan microscope. Chemical analyses were carried out at the ICP-MS and Chemistry Laboratory, Universidade de São Paulo. Un-weathered samples were crushed in a steel jaw crusher and subsequently in a disk mill of agate. Whole-rock major and trace element compositions were obtained by XRF spectrometry following analytical protocol of Mori et al. (1999) and four samples were analysed by ICP-OES.REE elements were measured by inductively coupled plasma mass spectroscopy (ICP-MS), using a Perkin Elmer Plasma Quadrupole MS ELAN 6100DRC, following analytical protocol of Navarro et al. (2002). Chemical analyses are presented in Table 1. Mineral chemical analyses were obtained at the Electron Microprobe Laboratory of the Universidade de São Paulo using a JEOL JXA-8600 Electron Probe Microanalyser. Garnet and feldspar analyses were run at 15 kV and 20 nA with a beam 5–10 μm in diameter. For rutile, analyses were run at 20 kV and 120 nA with a beam of 5 μm in diameter. The re-integration of ternary feldspar compositions was based on estimation of areal proportions between lamellae and host grains using backscattered images, which was then extrapolated to volume. This estimated volume was then converted to weight percentages using the mineral densities (2.67 g/cm³ for plagioclase and 2.57 g/cm³ for alkali feldspar; Smith, 1974). The chemical composition of both the lamellae and the host was obtained by electron microprobe analyses. Representative analyses of minerals are presented in Table 2. Mineral abbreviations follow Kretz (1983).

4. Sample descriptions

In the present study, samples from three different groups of the metasedimentary rocks of Carvalhos Klippe, which were divided according to petrographic criteria, have been analysed. Representative samples for analysis were selected from homogeneous portions of these migmatitic gneisses, which most likely represent the mesosomes. In these rocks the leucosomes are commonly thin (<1–5 cm) and boudined, and melanosome are not well-defined, making the identification and definition of leucosomes difficult. The few well-defined leucosomes are commonly coarse-grained and contain feldspar and/or garnet porphyroblasts, which make reliable and representative sampling difficult. However, it was possible to recognise rocks from Group 2 (as described in Section 4.2) in a single outcrop, from which a sample was taken from a thicker (5–10 cm) leucosome with a well-defined biotite melanosome. Generally, the mesosome samples analysed show evidence of partial melting, such as millimetre-scale leucosome lenses and pods. However, these melts have been trapped within the rock fabric and have not produced thicker leucosomes and/or large igneous bodies.

4.1. Group 1 (Ky-Grt-Kfs migmatitic granulite)

Banded bluish-grey kyanite-garnet-orthoclase migmatitic granulite with minor biotite and banding parallel to millimetre- to centimetre-scale leucosome lenses comprises Group 1 (Fig. 3a–b). The texture is predominantly granoblastic, medium- to coarse-grained with garnet porphyroblasts of approximately 2 cm that are rich in quartz, rutile and kyanite inclusions. The garnet crystals are commonly partially replaced by Bt + Qtz + Fsp intergrowths at the borders, along fractures and in pressure shadow zones. Biotite occurs in fine-grained lepidoblastic layers, surrounding garnet...
Fig. 1. A) Location of Southern Brasília Orogen in Brazil. B) Tectonic map of southeast Brazil, showing the São Francisco Craton and surrounding Neoproterozoic belts (from Campos Neto et al., 2010). C) Geological map of the Southern Brasilia Orogen (modified from Campos Neto et al., 2010) with the location of the study area.
crystals and defining a foliation. Kyanite crystals are submillimetric to centimetric in size and are partially replaced by local muscovite or Bt + Sil intergrowths. Orthoclase commonly exhibits perthitic lamellae exsolution and is locally partially replaced at the borders by myrmekite intergrowths. Rare plagioclase crystals occur only in small proportions. Typical accessory minerals are Fe-Ti oxides, rutile, tourmaline and zircon. The mineral proportions are: quartz (40-55%); garnet (10-20%); orthoclase (10-20%); kyanite/sillimanite (5-10%); biotite (5-10%); Fe-Ti oxides (1-3%); plagioclase (<1-1%); rutile (1%); tourmaline (<1-1%); and zircon (<<1%).

4.2. Group 2 (Grt-Bt-Pl gneiss)

Group 2 consists of foliated dark-grey garnet-biotite-plagioclase gneiss with less pronounced compositional banding than rocks from Group 1. Millimetric leucosome lenses are commonly discontinuous throughout the foliation. Thicker leucosomes (Fig. 3c) are rare and occur only locally. The texture is predominantly granoblastic, medium-grained, with abundant biotite-rich lepidoblastic lenses. Garnet crystals are submillimetric to 1.5 mm and are generally inclusion-free. Biotite occurs in small amounts (<5%) as discontinuous lepidoblastic lenses. Kyanite crystals are submillimetric. These rocks exhibit plagioclase (locally antiperthitic) and perthitic orthoclase. The main accessory mineral is rutile. The mineral proportions are: quartz (35%); plagioclase (25%); orthoclase (20%); garnet (5-10%); biotite (5-7%); kyanite (3-4%); rutile (1%); and muscovite (<1%).

4.3. Group 3 (Grt-Kfs-Pl gneiss)

Group 3 comprises finely-banded grey-colored garnet gneiss with minor biotite (Fig. 3d). The texture is granoblastic, fine- to medium-grained. Garnet crystals are submillimetric to 1.5 mm and are generally inclusion-free. Biotite occurs in small amounts (<5%) as discontinuous lepidoblastic lenses. Kyanite crystals are submillimetric. These rocks exhibit plagioclase (locally antiperthitic) and perthitic orthoclase. The main accessory mineral is rutile. The mineral proportions are: quartz (35%); plagioclase (25%); orthoclase (20%); garnet (5-10%); biotite (5-7%); kyanite (3-4%); rutile (1%); and muscovite (<1%).

5. Geochemistry

5.1. Major and trace elements

5.1.1. Group 1

Group 1 is characterised by a wide range of SiO₂, from 60.4 to 73.6 wt%, and higher Al₂O₃/SiO₂ ratios. It is low in Na₂O and CaO content, <0.5 wt% and <0.6 wt%, respectively (Fig. 4). TiO₂ contents are relatively higher than the other groups. The MgO values are similar to Group 3 and lower than those in Group 2. The Mg# varies between 21.3 and 28.9. In general, Group 1 shows slightly higher K₂O values when compared with Group 2, and the lowest MnO values. This group exhibits high A/CNK (3.23-4.49) and low N/K (0.02-0.22) ratios, which is typical of pelitic sediments. Fe₂O₃ contents of the three rock groups are widely ranging and P₂O₅ values are similar, therefore these elements do not represent good criteria to define the groups. Considering trace elements (Fig. 5), this group reveals the highest Zr (up to 479 ppm) and
## Table 1
Chemical analyses of metasedimentary rocks of the Carvalhos Klippe.

<table>
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<th>Sample</th>
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<th>Group 2</th>
<th>Leucosome</th>
<th>Group 3</th>
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lowest Sr values (55–129 ppm). V, Ni and Cr contents are, in general, intermediate compared with the other groups.

5.1.2. Group 2

This group is characterised by slight variation in SiO₂ contents (between 60.2 and 64.8 wt%) and by the highest values of MgO (3–3.9 wt%), Na₂O (2.4–3.8 wt%) and CaO (2.6–3.6 wt%). Mg# varies between 41.8 and 52.1. K₂O contents range between 1.11 and 1.21, and the N/K ratios vary markedly with values ranging from 1.47–2.01 and A/CNK ratios are between 1.12 and 1.34. Geochemically, Group 2 protoliths can be classified as immature arenites (wacke, arkose or lithic-arenite) (Pettijohn et al., 1972; Herron, 1988), though a more accurate classification is stymied by the lack of any textural evidence surviving from the sedimentary protolith. With regards to trace elements, this group shows the highest V, Ni and Cr contents. These rocks are characterised by relatively high SiO₂ contents (67.1–71.4 wt%), MgO values are similar to those of Group 1, although the Mg# is more variable, ranging between 22.0 and 40.8. Na₂O and CaO contents are intermediate in comparison with the other groups. Relatively high V, Ni and Cr contents were also observed.

5.1.3. Group 3

These rocks are characterised by relatively high SiO₂ contents (67.1–71.4 wt%), MgO values are similar to those of Group 1, although the Mg# is more variable, ranging between 22.0 and 40.8. Na₂O and CaO contents are intermediate in comparison with the other groups. Relatively high V, Ni and Cr contents were also observed.
5.2. REE patterns

Rocks samples from Groups 1 and 2 were analysed for rare earth elements (REE) (Fig. 6). The REE patterns of samples from Group 1 show a highly fractionated trend ($La_N/Yb_N = 10.7–11.1$) with light REE (LREE) enrichment compared with samples from Group 2 ($La_N/Yb_N = 4.6–5.9$). This overall fractionation results from the domination of LREE fractionation ($La_N/Sm_N$: Group 1 = 3.6–3.7; Group 2 = 2.3–3.0), considering that heavy REE (HREE) fractionation is less pronounced in both rock groups ($Gd_N/Yb_N$ Group 1 = 1.65–1.98 and $Gd_N/Yb_N$ Group 2 = 1.29–1.55). Negative Eu anomalies were detected in both groups and are stronger in Group 2 ($La/Sm$: Group 1 = 0.71–0.78). These REE patterns are similar to average patterns of post-Archean sedimentary rocks (Haskin et al., 1968; Nance and Taylor, 1976; Taylor and McLennan, 1985). Garcia et al. (2004) identified similar REE patterns in correlated high-grade metasedimentary rocks from the Três Pontas-Varginha Nappe, and these authors also acknowledged the similarity with REE patterns of post-Archean shales. The LREE enrichment in rock samples from Group 1 is apparently related to original compositions of the sedimentary protolith, considering that higher LREE contents in clays are expected when compared to the leucosomes which are commonly thin, coarse-grained and locally have garnet and feldspar porphyroblasts, making representative sampling difficult. In the Grt-Bt-Pl gneiss from Group 2 thicker leucosomes are also rare, but a sample of approximately 5–10 cm of thickness was taken parallel to the foliation in a selected outcrop (Fig. 3c). This leucosome shows medium- to coarse-grained granoblastic texture and is composed primarily of plagioclase and quartz with subordinated biotite. The melanosome consists predominantly of biotite. The REE pattern of this leucosome (Fig. 7) is depleted in total REE, is strongly depleted in heavy rare earth elements and has a well-pronounced positive Eu anomaly. Several authors (e.g. Sawyer, 1987; White and Chappell, 1990; Ellis and Obata, 1992) argue that leucosomes are likely to pass through differentiation processes and that those which are characterised by REE depletion and positive Eu anomalies may represent cumulates.

5.3. Comparison between Grt-Bt-Pl gneisses from Carvalhos Klippe (Group 2) and Grt-Bt-Pl-Qtz schists from the lower nappes

Grt-Bt-Pl-Qtz schist bodies with geochemical characteristics of immature arenites (wacke, arkose or lithic arenite) are recognised throughout the Andrelândia Nappe System (Troux et al., 1983; Campos Neto et al., 2007; Campos Neto et al., 2011). As in the Três Pontas-Varginha Nappe (Garcia et al., 2004), there are rocks with similar composition within the Carvalhos Klippe (Group 2), although showing a gneissic structure resulting from a higher metamorphic grade. This study compares granulite facies rocks from Group 2 and amphibolite to upper amphibolite facies Grt-Bt-Pl-Qtz schists from the lower nappes (Andrelândia and Liberdade nappes). The Harker diagrams (Fig. 8) show obvious geochemical similarities between the granulite facies Grt-Bt-Pl gneisses (Group 2) and the amphibolite to upper amphibolite facies Grt-Bt-Pl-Qtz schists (data from Teixeira, 2011). The geochemical similarity between Grt-Bt-Pl gneisses with evidence of partial melting and Grt-Bt-Pl-Qtz schists with melting conditions that are minimal to absent, suggests that there was not a significant extraction of melt from these higher grade rocks. Although millimetre-scale leucosomes and leucosome pods provide constraints to melt segregation, apparently there was no connection and extraction sufficient to considerably change the bulk rock composition. Comparison of REE-patterns (Fig. 9) between Group 2 rocks and Grt-Bt-Pl-Qtz schists from the Andrelândia and Liberdade nappes show marked similarity, although schists are slightly more fractionated, with $La_N/Yb_N$ ratios of 6.4–6.9, compared with the 4.6–5.9 $La_N/Yb_N$ ratios of Group 2. The negative Eu anomalies are slightly less pronounced in the schists, which show Eu/Eu* ratios of 0.68–0.75, contrasting with higher 0.71–0.78 Eu/Eu* ratios of Group 2. This similarity in REE patterns is also suggestive of low rates of melt extraction in these granulite facies rocks. The thicker Group 2 leucosome which was analysed in this study does not show K-feldspar and has low

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Fig. 3. Field aspects of metasedimentary rocks groups. (a–b) Group 1: Kyanite-garnet-orthoclase gneisses with banding parallel to millimetre- to centimetre-scale leucosomes. (c) Group 2: Garnet-biotite-plagioclase gneiss with rare thicker leucosome. (d) Group 3: Fine banded garnet gneiss.
Rb/Sr and high Sr/Ba ratios, characteristic of melting in the presence of a vapour phase (Harris and Inger, 1992). Most likely the rocks of Group 2 have not lost significant quantities of this type of melt, otherwise the rock compositions would be expected to change markedly, commensurate with the different REE patterns between this leucosome and the Group 2 rocks (Fig. 7).

6. Metamorphism

6.1. High-pressure granulite assemblage

The typical mineral assemblage of metasedimentary rocks of Carvalhos Klippe is Ky + Grt + perthitic Kfs + Qtz ± Pl ± Rt ± Bt.
Fig. 5. Harker diagrams of metasedimentary rocks from Carvalhos Klippe (trace elements). (a) Zr; (b) Sr; (c) Cr; (d) V.

Fig. 6. Rare earth element (REE) variation diagrams normalised to the chondrite values of Taylor and McLennan (1985). (a) Group 1; (b) Group 2; (c) NASC (North American shale composite; Haskin et al., 1968) and PAAS (Post-Archean average Australian shale; Nance and Taylor, 1976); (d) Comparison between REE patterns of metasedimentary rocks from the Carvalhos Klippe with PAAS REE pattern.
which corresponds to high-pressure granulite facies conditions. This assemblage suggests that reactions of muscovite and biotite breakdown were crossed (Vielzeuf and Holloway, 1988; Le Breton and Thompson, 1988; Patiño Douce and Beard, 1995) within the stability field of kyanite:

Fig. 7. Chondrite-normalised REE patterns of leucosome and mesosome of metasedimentary rock from group 2.

Fig. 8. Harker diagrams comparing the compositions of metasedimentary rocks from Carvalhos Klippe with Grt-Bt-Pl-Qtz schists from the lower nappes (data from Teixeira, 2011).
(a) Al₂O₃; (b) MgO; (c) CaO; (d) Na₂O; (e) TiO₂; (f) Zr.

Fig. 9. Comparison of chondrite-normalised (Taylor and McLennan, 1985) REE patterns between rocks from group 2 and Grt-Bt-Pl-Qtz schists from the lower nappes.
Ms + Qtz = Kfs + Ky + Bt + melt \hspace{1cm} (R1)

Bt + Ky + Qtz = Grt + Kfs + melt \hspace{1cm} (R2)

Biotite breakdown reactions producing orthopyroxene (Bt + Qtz = Kfs + Opx + melt) are not known to occur in migmatitic granulite from the klippe and may represent an upper temperature limit. The metamorphic peak temperatures obtained using Zr-in-rutile thermometry (Tomkins et al., 2007) are close to 850 °C, showing temperatures slightly higher than those described in Campos Neto et al. (2010). The highest temperatures were obtained in rutile inclusions in garnet porphyroblasts (Fig. 10). The temperatures obtained from the ternary feldspar re-integration (antiperthitic plagioclase) are close to 900 °C (Fig. 11). The baric peak of 16 kbar was obtained through GASP geobarometer (Newton and Haselton, 1981), using garnet porphyroblast core with comparatively higher grossular content (Fig. 12). Mafic rocks interlayered in migmatitic granulite contain the mineral assemblage Grt + Cpx + Pl + Qtz, which is compatible with high-pressure granulite facies conditions (Green and Ringwood, 1967; Ito and Kennedy, 1971; O’Brien and Rötzer, 2003). 6.2. Back reactions

Retrograde reaction textures are widespread in rocks from the Carvalhos Klippe. In the metasedimentary granulite facies rocks of the Carvalhos Klippe, the garnet crystals are partially replaced at the rims and fractures by skeletal and/or vermiciform intergrowths of Bt + Qtz = Fsp (Fig. 13a–c), which are the result of crossing R2 from high to low temperature during retrogression. Intergrowths of Bt + Sil + Qtz replacing garnet at the rims, fractures and garnet pressure shadows are common especially in the southeast portion of the klippe. Locally, kyanite grains are partially pseudomorphosed by muscovite (Fig. 13d), which is most likely equivalent to also crossing the muscovite breakdown back reaction (R1) from high to low temperature. These textures are interpreted as products from the interaction between melt and residual phases during the
retrograde path (Fig. 14). Therefore, these textures suggest that melt was present and trapped within the system during retrogression. If the melt was not present in the system during the retrogression, the rocks would be expected to have a restitic assemblage with little retrogression (Spear et al., 1999). This does not occur in the Carvalhos Klippe rocks, where retrograde reaction textures are extremely common. In later stages of retrogression, kyanite was locally replaced by sillimanite.

7. Discussion and conclusions

The metasedimentary rocks of the Carvalhos Klippe show the typical high-pressure granulite facies assemblage of Ky + Grt + perthitic Kfs + Qtz ± Rt ± Bt which suggests that muscovite breakdown reactions were crossed, reaching biotite dehydration melting reactions. The thermobarometric data demonstrate a thermal peak of 850 °C and a baric peak of 16 kbar. Partial replacement textures of garnet by Bt + Qtz + Fsp suggest reactions between melt and mineral phases during retrogression. In spite of the high metamorphic grade associated with partial melting, it is still possible to subdivide metasedimentary rocks groups with well-defined geochemical characteristics. Group 1 shows high A/CNK and low N/K ratios, which are characteristic of pelitic sedimentary rocks. Groups 2 and 3 have geochemical characteristics of immature arenites, with high feldspar contents (wacke, arkose or lithic arenite). Although rocks of the Carvalhos Klippe were metamorphosed in high-pressure granulite facies conditions with melting related to mica-breakdown reactions, the REE patterns of the metasedimentary rocks of the klippe are very similar to typical post-Archean sedimentary rocks.

The high-pressure granulite facies Grt-Bt-Pl gneisses present in the Carvalhos Klippe (corresponding to Group 2 in this study), show geochemical characteristics very similar to amphibolite to upper amphibolite facies Grt-Bt-Pl-Qtz schists from lower nappes (Andrelândia and Liberdade), despite the fact that these schists have been metamorphosed to lower grade with little or no partial melting. This similarity suggests that Grt-Bt-Pl gneisses of the Carvalhos Klippe from Group 2 did not experience substantial melt extraction. Rare larger leucosomes do not contain K-feldspar and have low Rb/Sr and high Sr/Ba ratios, suggesting that part of the melting occurred in the presence of a vapour phase and was not extensive. Extensive melt connection, migration and extraction does not appear to have occurred in these rocks; the compositions remained nearly unchanged. In rocks with the immature arenite signature, mica dehydration melting was not extensive, most likely because low muscovite contents and conditions of 850 °C to 16 kbar
did not allow for considerable biotite breakdown within this compositional range. Estimated proportions of melt for meta-
wackes under these metamorphic conditions would be less than 10% (Johnson et al., 2008), which does not allow for a connection between silicatic liquids and would not entail significant migration and extraction. Therefore, Grt-Bt-Pl gneisses with geochemical signatures of immature arenites (Group 2) most likely were not potential sources for the generation of igneous rocks plutons.

Most likely the metapelites (Group 1) were the main magma source inside the klippe because the high muscovite content within these sources allow for considerable melt generation through muscovite breakdown, at temperatures below 850 °C. Even among the metapelites, part of the generated melt was trapped within the system, as shown by several instances of reactions between the melt and mineral phases during retrogression. Even in these metamorphic rocks, REE patterns are very similar to REE patterns of post-Archean sedimentary rocks, showing that high metamorphic grade metasedimentary rocks with evidence of mica dehydration melting may still retain geochemical signatures of its sedimentary protolith.

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