Estudios Geológicos
Julio-diciembre 2014, 70(2), e014
ISSN-L: 0367-0449
doi: http://dx.doi.org/10.3989/egeol.41750.326

Petrographical and geochemical signatures of the Granja paragneisses (Médio Coreaú Domain, NW Ceará, Brasil)

Características petrográficas y geoquímicas de los paragneises de Granja (Dominio Medio Coreaú, NW Ceará, Brasil)

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ABSTRACT

The Granja Granulite Complex (GGC) exposed in the Médio Coreaú Domain (NW Ceará, Brasil) consists mainly of garnet and sillimanite migmatitic paragneisses enclosing discontinuous lenses of mafic granulites and enderbites. According to the published geochronological data, this high-grade metamorphic belt represents a segment of the Paleoproterozoic basement intensely reworked during the Brasiliano / Pan-African Orogeny in the Neoproterozoic (600 Ma).

The Granja paragneisses are strongly foliated rocks characterized by the alternance of dark garnet-biotite-sillimanite-rich layers and millimeter-thick leucocratic quartz-feldspathic bands, interpreted as indicative of incipient melting. As melt contents increase, layer-parallel leucosomes become thicker and a well-developed stromatic layering is defined. Both the gneissic and stromatic fabrics are strongly overprinted by a penetrative mylonitic foliation correlated to the last reactivation of the dextral NE-SW trending Granja Shear Zone (GCZ) that cuts across the studied area. Mineral assemblages and microstructures indicate that these rocks were affected by granulite-facies metamorphism and anatexis followed by decompression and cooling.

In order to constrain the protolith composition of the Granja paragneisses, twelve whole-rock samples from the parts of the migmatitic paragneisses that appear to have undergone little or no melt extraction were analysed for major and trace elements. In the classification diagram of Herron (1988), the samples plot in the transition between the greywacke and the pelite fields, suggesting that the pre-metamorphic sequence was dominantly composed by shales and immature clastic sediments (greywackes). Their chondrite normalized REE patterns show a moderate LREE enrichment ($La_N/Yb_N = 9.46–15.50$), flat HREE profiles and negative Eu anomalies ($Eu/Eu^* = 0.63–0.82$), closely resembling those of PAAS (Post-Archean average Australian Shale) and Early Proterozoic Greywackes. Geochemical data also suggest that the precursor sediments of the Granja paragneisses derived from source areas of felsic to intermediate composition and were deposited in a tectonically active continental margin / continental island arc setting.

Keywords: Brasiliano granulite metamorphism; migmatitic paragneisses; provenance

Recibido el 21 de abril de 2014 / Aceptado el 2 de octubre de 2014 / Publicado online el 11 de noviembre de 2014

Citation / Cómo citar este artículo: A.J.F. Silva et al. (2014). Petrographical and geochemical signatures of the Granja paragneisses (Médio Coreaú Domain, NW Ceará, Brasil). Estudios Geológicos 70(2): e014. http://dx.doi.org/10.3989/egeol.41750.326.

RESUMEN

El Complejo Granulítico de Granja (GGC), expuesto en el Dominio Medio Coreaú (NW del Estado de Ceará, Brasil), está constituido predominantemente por paragneises granatíferos con silimanita en cuyo seno se intercalan cuerpos lenticulares, discontinuos, de granulitas máficas y enderbitas. De acuerdo con los datos geocronológicos publicados, este terreno metamórfico de alto grado representa un segmento de un basamento Paleoproterozoico que fue intensamente retrabajado en el Neoproterozoico, durante la Orogénesis Brasiliense / Panafricana (600 Ma).

Los paragneises de Granja son rocas con una fuerte foliación, caracterizadas por la alternancia de niveles oscuros, ricos en granate-biotita-silimanita, y bandas milimétricas leucocráticas cuarzo-feldespáticas interpretadas como resultado de fusión incipiente. Con el incremento del componente fundido, aumenta el espesor de los leucosomas concordantes y las rocas adquieren un aspecto estromático. A estas estructuras se superpone una foliación milonítica asociada a la última reactivación de la Zona de Cizalla de Granja, un accidente con dirección NE-SW y movimiento dextral que atraviesa la zona estudiada. Las asociaciones minerales y las texturas de reacción indican que después de alcanzar las condiciones de fusión parcial en la facies granulítica, las rocas sufrieron descompresión y enfriamiento.

Con el fin de caracterizar la composición de los protolitos de los paragneises de Granja, se analizaron los elementos mayores y tierras raras de doce muestras de aquellas partes de los paragneises migmatíticos en los que la extracción de fundido parece haber sido nula o muy limitada. En el diagrama de clasificación de Herron (1988), las muestras se sitúan en la transición entre los campos de las grauvacas y pelitas, sugiriendo que en la secuencia pre-metamórfica dominaban sedimentos arcillosos y sedimentos clásticos poco maduros (grauvacas). Los patrones de tierras raras normalizados a condrita muestran un moderado enriquecimiento en las tierras raras ligeras (LaN/YbN = 9.46–15.50), perfiles planos en tierras raras pesadas y anomalías negativas de Eu (Eu/Eu* = 0.63–0.82), con pautas muy próximas tanto a las del PAAS (Post-Archean average Australian Shale) como a las del EP GREY (Early Proterozoic Greywackes). Los datos geoquímicos sugieren también que los sedimentos precursores de los paragneises de Granja tuvieron su origen en un área fuente con composición félsica a intermedia y fueron acumulados en un ambiente de margen continental activo / arco insular continental.

Palabras clave: Metamorfismo granulítico Brasiliense; paragneises migmatíticos; procedencia

Introduction

Granulite-facies metamorphic rocks provide crucial insights into the tectonothermal evolution of ancient orogens and deep crustal processes. Due to complex polyphase metamorphic and deformation overprinting, the chemical and textural characteristics of the original sedimentary and igneous precursors of granulite sequences are no longer preserved. Unravelling their previous geological history is a major goal of petrological investigation that can only be achieved by careful and comprehensive geochemical and isotope studies.

The main objective of this work is to summarize new and available petrographical and geochemical data for the kinzigitic gneisses exposed in the Médio Coreaú Domain in NE Brasil and use whole-rock geochemistry to discriminate their original protolith signatures and identify potential sediment source areas and the tectonic setting prevailing at the time of sedimentation.

Geological Setting

The Granja region is located in NW Ceará, NE Brasil, at latitudes between 02°47'S-03°22'S and longitudes between 40°20'W-41°24'W (Figs. 1 and 2). Geologically, the area is included within the Borborema Province (BP), which represents a segment of the Brasiliano / Pan-African orogenic belt developed by the collision of the Congo-São Francisco and São Luís-West African cratons during the amalgamation of West Gondwana, in the Late Neoproterozoic (ca. 600 Ma) (Almeida *et al.*, 1981; Cordani *et al.*, 2000). Covering an area of over 400,000 Km^2, the BP is divided into three main structural blocks: the Northern domain, the Transversal domain and the Southern domain, bounded by a system of sinuous and branched crustal scale shear zones (Caby, 1989).

Based on tectonostratigraphic and geochronological (U-Pb, Sm-Nd) evidence, the Northern block was further subdivided into the following major units, from north to south: the Médio Coreaú, the Ceará Central and the Rio Grande do Norte domains, bordered by the Patos, Senador Pompeu and Transbrasiliano shear zones (Santos *et al.*, 2008; Fig. 1).

As shown in Figures 1 and 2, the study area is situated within the Médio Coreaú Domain (MCD). The oldest rocks exposed in the MCD are Early Paleoproterozoic and span a wide spectrum of lithological types, ranging from orthogneisses with

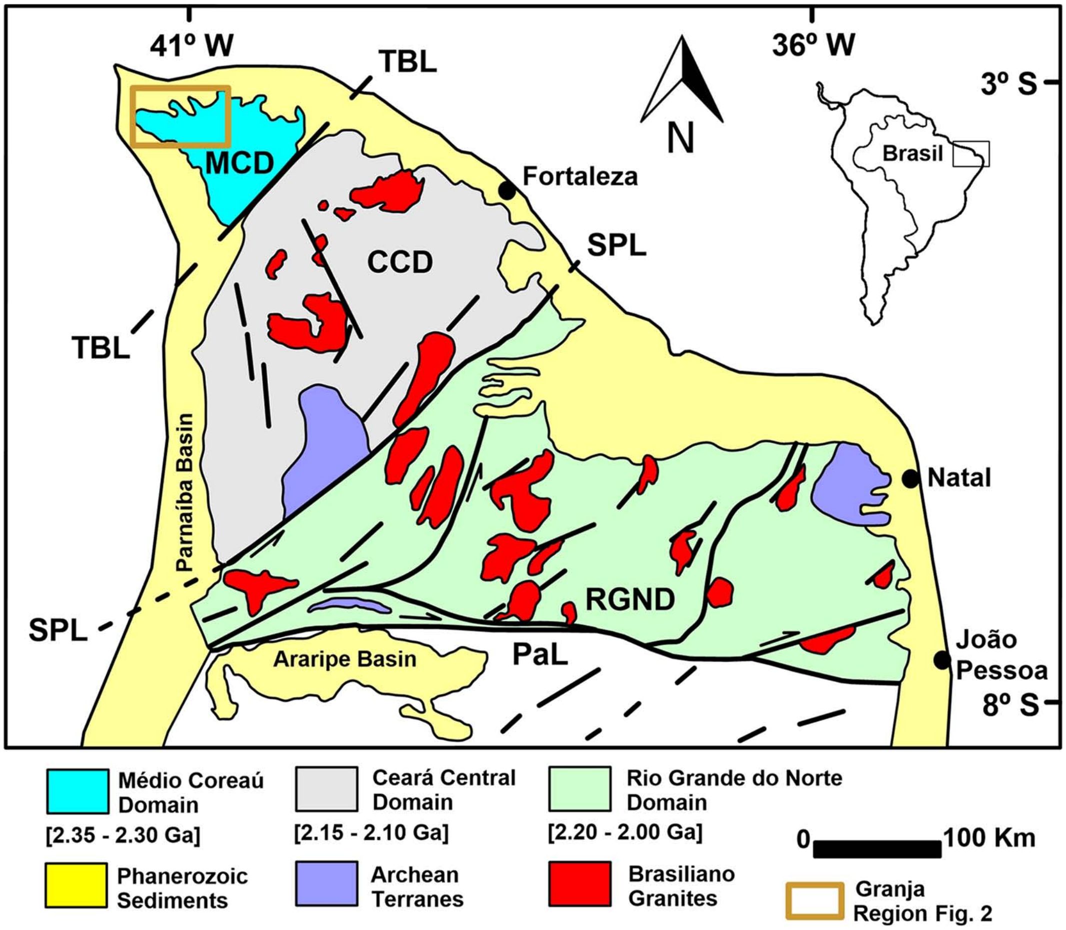

Fig. 1.—Geological map for the northern part of the Borborema Province, showing the location of the Médio Coreaú Domain (modified from Santos *et al*., 2008). TBL - Transbrasiliano Lineament; SPL; Senador Pompeu Lineament; PaL - Patos Lineament.

tonalite–trondhjemite–granodiorite (TTG) affinities to hornblende gneisses, amphibolites, mafic granulites, enderbites, kinzigites and khondalites (Santos *et al*., 2009; Amaral *et al*., 2012). U–Pb zircon ages obtained for the TTG orthogneisses (2.36–2.29 Ga) provide reliable time constraints for the crystallization age of their igneous protoliths, whilst the positive εNd_i values displayed by this rock suite point to a mantle-derived origin in an arc-type geodynamic setting (Fetter *et al.*, 2000; Nogueira Neto, 2000; Santos *et al.*, 2008, 2009; Amaral *et al.*, 2012; Praxedes *et al*., 2012). According to Fetter *et al.* (2000), the precursors of both the igneous-derived mafic granulites and enderbites and the granulitic paragneisses (kinzigites and khondalites) have also an Early Paleoproterozoic age.

During the Brasiliano / Pan-African Orogeny, all the MCD basement sequences were extensively affected by high-grade regional metamorphism and migmatization. Estimated peak metamorphic conditions vary between 7–10 kbar and 750–840°C for the mafic granulites and granulitic paragneisses and between 5–6 kbar and 600–700°C for the TTG orthogneisses (Nogueira Neto, 2000). The age of the Brasiliano migmatitic / granulitic metamorphic event is reasonably well constrained at ca. 600 Ma by U-Pb and Ar-Ar geochronological data (e.g. Monié *et al*., 1997; Fetter *et al*., 2000; Santos *et al*., 2008, 2009).

The MCD high-grade metamorphic complex is partially overlain by supracrustal volcanosedimentary and/or sedimentary successions belonging either to the Late Paleoproterozoic Saquinho sequence or to the Neoproterozoic Martinópole-Ubajara groups (e.g. Santos *et al*., 2008, 2009; Amaral *et al.*, 2012). Both the infra- and the supracrustal rock suites were

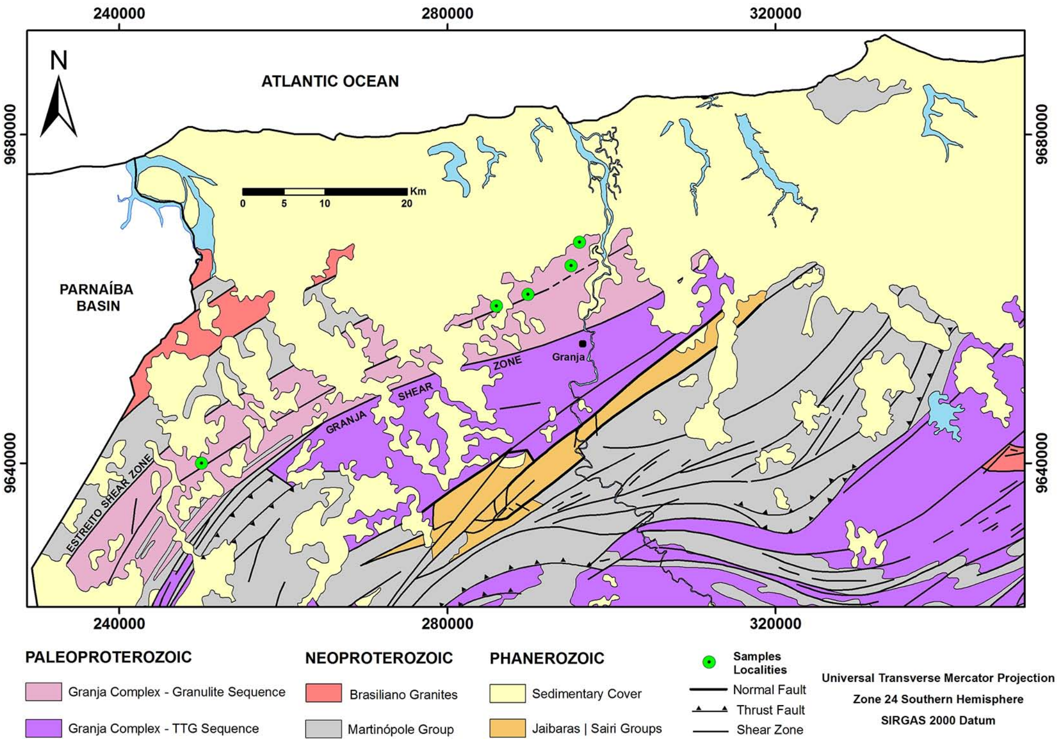

Fig. 2.—Simplified geological map for the Granja region, showing the location of the analysed samples (modified from Cavalcante *et al*., 2003).

intruded by syn- to post-tectonic Brasiliano granitoids with ages ranging between 590–532 Ma (Santos *et al.*, 2008). Finally, the Early Paleozoic sediments of the Jaibaras/Sairi troughs correspond to early molasse-type deposits post-dating the Brasiliano collage (Santos *et al.*, 2008).

The Granja Granulite Complex

The Granja Granulite Complex (GGC) constitutes a NE–SW-trending belt occupying the western sector of the MCD (Fig. 2). It contacts with the TTG migmatitic gneisses to the SE through the Granja dextral Shear Zone and with the supracrustal Martinópole sequence to the NW through the Estreito dextral Shear Zone (Fig. 2). The GGC is mainly composed of garnet–sillimanite migmatitic paragneisses enclosing distended lenses of mafic granulites, enderbites and enderbitic gneisses.

At outcrop scale, the high-grade garnet–sillimanite migmatitic paragneisses are well-foliated fine- to medium-grained grey rocks characterized by the alternance of dark garnet-biotite-sillimanite-rich layers and millimeter-thick leucocratic quartz-feldspathic bands, interpreted as indicative of incipient melting (Fig. 3a). For increasing melt fractions, the leucosomes grade into thicker concordant vein-type leucosomes producing a conspicuous NE-SW trending stromatic layering, plunging 50–60° to SE (Fig. 3b). Field evidence reveals that the migmatitic fabrics were developed during the second and third Brasiliano deformation phases (D_2 and D_3).

The metric to decametric bodies of mafic granulites and enderbites enclosed in the migmatitic paragneisses from the GGC consist of dark grey to dark greenish-grey coloured rocks with textures ranging from fine- to medium-grained granoblastic to slightly banded. A weak NE-SW trending S_{2+3} foliation can also be observed in these lithologies.

The S_{2+3} tectonic fabrics recorded in both sequences (paragneisses / mafic granulites + enderbites) were heterogeneously folded and overprinted by D_4. In the studied area, the last Brasiliano ductile deformation event (D_4) is related to the reactivation of the dextral Granja Shear Zone (GSZ) and produced a NE-SW striking foliation, steeply dipping towards

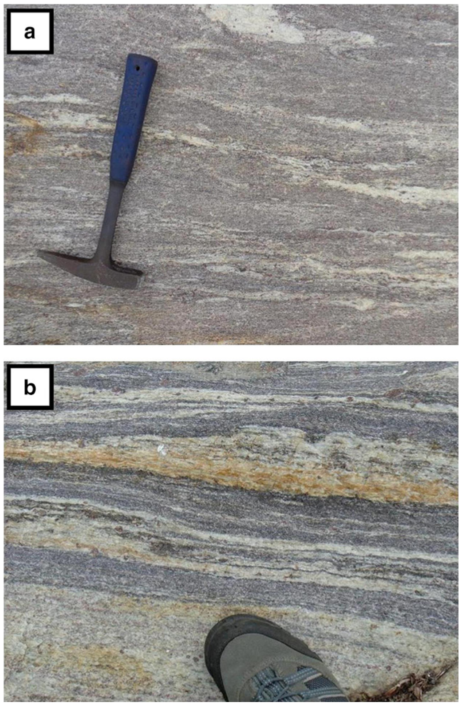

Fig. 3.—Field appearance of the Granja paragneisses: (a) mylonitic fabric in migmatitic paragneiss (b) Coarse garnet-bearing leucosomes in stromatic metatexite.

the SE (>70°). Mineral stretching lineations plunge gently towards northeast or southwest. In high-strain domains, a strong mylonitic / blastomylonitic fabric can be developed and the leucosomes are frequently boudinaged. Asymmetric S/C structures, when present, indicate a dominant dextral sense of movement.

Petrography

Petrographically, the garnet–sillimanite paragneisses display significant grain size reduction and strong S_4 mylonitic fabrics, obscuring their previous metamorphic textures. The high-grade mineral assemblage is dominated by garnet (Grt), sillimanite (Sil), biotite (Bt), quartz (Qz) and plagioclase (Plg) (Figs. 4a–b). K-feldspar (Kfs) and cordierite (Crd) are occasionally present. Accessory minerals include opaques (Opq), apatite (Ap), zircon (Zrn) and rutile (Rt).

In the paragneisses affected by incipient melting, the gneissic fabric is defined by the alternance of millimeter-thick biotite-sillimanite-rich and highly recrystallized quartz-feldspar layers. Garnet is abundant and may constitute large poikiloblasts (up to 2,5 cm) wrapped by the granolepidoblastic matrix (Fig. 4c) or smaller, rounded to subhedral, inclusion-free porphyroblasts. Cordierite is anhedral to subhedral and occurs in close spatial association with biotite and sillimanite but can also be found in contact with quartz and feldspars.

As melt contents increase, layer-parallel leucosomes become thicker (>5 cm up to 20 cm) and the migmatitic paragneisses grade into stromatic metatexites. The coarser stromatic leucosomes show also fine-grained mylonitic or blastomylonitic fabrics and are predominantly composed of quartz (30–40 vol.%), plagioclase (20 vol.%), K-feldspar (10–20 vol.%), garnet (5 vol.%) and minor proportions of biotite and fibrolitic sillimanite. Zircon, monazite, apatite and opaques are common accessory phases. Quartz is generally present as finely recrystallized elongate grains with undulose extinction, deformation bands and lobated edges or as ribbon-like aggregates. Plagioclase dominates over alkali feldspar and exhibits wedged and flexured twins (Fig. 4d). K-feldspar is perthitic orthoclase and may occur as small augen mantled by rims of fine grained quartz-feldspar aggregates (Fig. 4e) or as anhedral interstitial crystals in the matrix. Myrmekites are occasionally present. In these leucosomes, the garnet porphyroblasts are generally rounded to subhedral, highly fractured and devoid of inclusions (Fig. 4f). Biotite has a yellow-reddish to reddish-brown pleochroism and is frequently intergrown with fibrolitic sillimanite in very thin biotite-sillimanite selvages wrapping around the garnet neoblasts (Fig. 4f).

Evidence for the earlier S_1 fabric is only preserved as a discordant internal foliation (S_i) defined by inclusion trails of kyanite (rare), sillimanite, biotite, quartz, plagioclase, ilmenite and rutile within some garnet poikiloblasts. In low-strain domains, the S_{2+3} gneissic and stromatic banding constitute the main regional fabric observed in these rocks, being strongly transposed by a pervasive anastomosed S_4 foliation associated with dextral shearing in high-strain zones. Intense dynamic recrystallization of the leucosomes suggests that much of the D_4 deformation was imposed while the migmatites were subsolidus. Prismatic sillimanite and elongated ribbon-like quartz aggregates define a strong sub-horizontal lineation on the S_4 foliation planes.

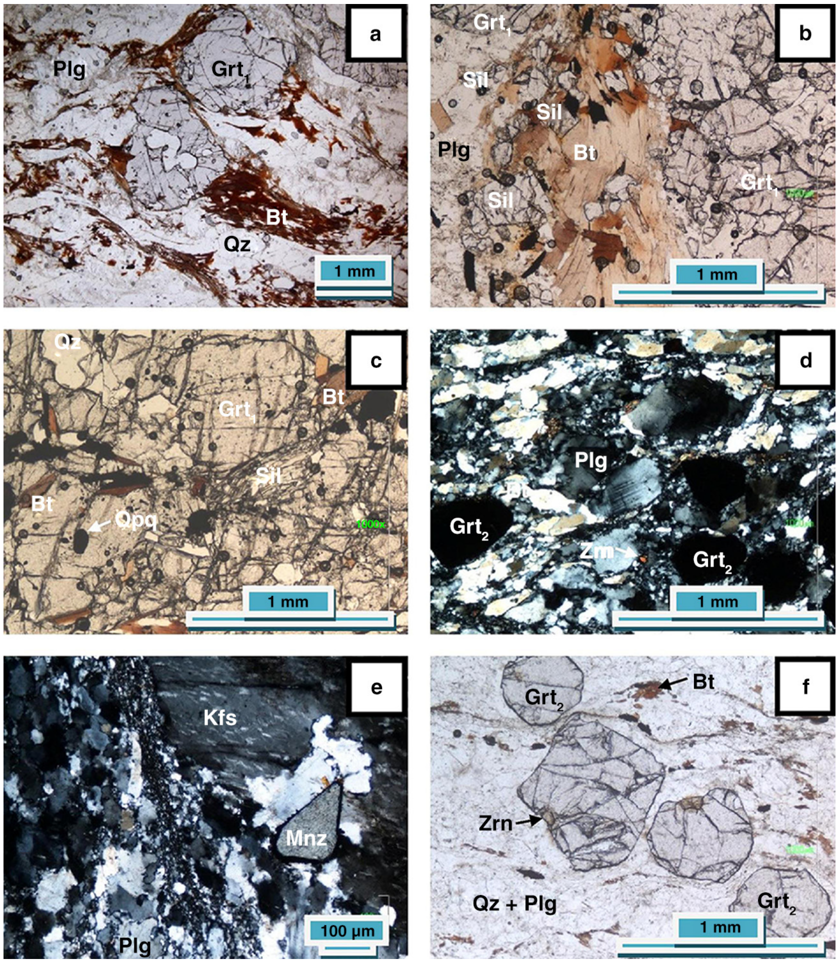

Fig. 4.—(a) High-grade metamorphic mineral assemblage in Granja paragneiss showing a strong S_4 mylonitic fabric, plane polarized light; (b) garnet poikiloblasts (Grt_1), prismatic silimanite and biotite in paragneiss, plane polarized light; (c) Garnet poikiloblasts (Grt_1) in paragneiss, plane polarized light; (d) Plagioclase with wedged and flexured twins in coarse leucosome, cross polarized light; (e) Augen of microperthitic K-feldspar mantled by finely recrystallized quartz-feldspar aggregates in coarse leucosome, cross polarized light; (f) Inclusion-free subhedral garnet porphyroblasts (Grt_2) in coarse leucosome, plane polarized light.

Metamorphic evolution

On the basis of microstructures and relations between mineral phases, it is possible to distinguish four main stages of metamorphism: a prograde metamorphic stage (M_1), a peak-metamorphic stage (M_2), a post-peak decompression stage (M_3) and a retrograde cooling stage (M_4).

The M_1 prograde assemblage is represented by inclusions of kyanite, sillimanite, biotite, quartz, plagioclase, ilmenite and rutile within M_2 garnet neoblasts (Grt_1). The occurrence of very thin leucosomes folded by D_2 suggests that partial melting conditions were probably reached during M_1 through the muscovite dehydration reaction (Pëto, 1976):

$$Ms + Plg + Qz \Rightarrow Al_2SiO_5\ (Sil) + Kfs + melt \quad (1)$$

Following the relict M_1 metamorphic event, a M_2 peak-metamorphic paragenesis composed of $Grt_1 + Sil + Bt + Qz + Plg + Kfs$ was developed involving the fluid-absent incongruent melting reaction of biotite (Le Breton & Thompson, 1988):

$$Bt + Sil + Plg + Qz \Rightarrow Grt_1 + Kfs + melt \quad (2)$$

The lack of primary muscovite in all the analysed rocks and the presence of millimetre- to centimetre-scale quartz-feldspar rich leucosomes parallel to S_2 foliation show that the biotite-dehydration melting reaction was crossed during this metamorphic event.

The M_3 metamorphic decompression stage is marked by the first appearance of cordierite, which forms relatively large grains of different shape in the rock matrix. This episode occurred in the sillimanite stability field and was controlled by the reaction (Spear *et al*., 1999):

$$Bt + Al_2SiO_5\ (Sil) \Rightarrow Grt_2 + Crd_1 + melt \qquad (3)$$

M_3 led to the production of additional melts and inclusion-free new garnet (Grt_2), preserved mainly in the leucosomes.

In the last metamorphic stage (M_4), the early-formed foliations were reworked by shearing and a strong S_4 mylonitic fabric was developed. Reaction textures appear to reflect a cooling history marked by the reversal of reactions 2 and 3 and the crystallization of biotite (Bt_2) + sillimanite (Sil_2). The presence of biotite and sillimanite along the rims of garnet neoblasts provides a strong argument in favour of retrogression by garnet consumption. Simultaneously, the melts crystallized and the water released during their solidification contributed to the retrograde reactions.

Analytical methods

Twelve representative samples of the Granja paragneisses were selected for purposes of geochemical characterization. Sampling strategy involved the collection of specimens that showed no evidence of any significant loss, or gain, of anatectic melts and could therefore provide the closest estimate of the original composition of the protolith. Only the paragneisses containing very thin leucosomes and a relatively homogeneous appearance were selected for chemical analysis. From these, 5–10 kg of rock-material was collected, crushed and split to obtain representative samples of ~250 g. Each sample was finally pulverized in an agate mill. Sample locations are shown in Figure 2.

Sample GR70 was recently collected and analysed for major (ICP-ES) and trace elements (ICP-MS) at ACME Labs (Vancouver, Canada), whilst the geochemical data for the remaining eleven samples were previously obtained by Gama Jr. (1992), Santos (1993) and Nogueira Neto (2000), using X-Ray Fluorescence spectrometry and ICP-MS at GEOSOL (Belo Horizonte, Brasil). Major and trace element compositions are presented in Tables 1 and 2.

Whole-rock geochemistry

As previously discussed, the Granja paragneisses experienced granulite facies metamorphism. Their compositions may therefore have been strongly modified by metamorphic overprint and anatexis. However, bulk-rock major and trace element geochemistry provide, in some cases, major constraints on both the nature and the provenance of the putative protoliths for high-grade metamorphic rocks (e.g. Bhatia & Crook, 1986; Roser & Korsch 1986, 1988; Otamendi & Patiño Douce, 2001; Augustsson & Bahlburg, 2003; Abu El-Enen, 2008, 2011).

The samples from the Granja paragneisses show a relatively wide compositional range with SiO_2 between 66.27 and 72.50% and Al_2O_3 between 11.91 and 15.94%. As illustrated in the P_2O_5/TiO_2 vs. MgO/CaO discrimination diagram proposed by Werner (1987), most of the analysed rocks display low P_2O_5/TiO_2 ratios coupled with slightly variable MgO/CaO values pointing to a sedimentary origin (Fig. 5). This strongly suggests that the migmatite samples selected for chemical analysis have undergone little or no melt extraction and may therefore have bulk major element compositions similar to those of their original protoliths.

In the log Fe_2O_3/K_2O vs. log SiO_2/Al_2O_3 classification diagram of Herron (1988), the investigated migmatitic gneisses plot mainly within the greywacke field or straddle the boundary between the greywacke and shale domains (Fig. 6). Conformable results are obtained using the Al/3-K vs. Al/3-Na (La Roche, 1968) and the Fe+Al+Ti vs. Ca+Mg (Moine & La Roche, 1968) millicationic diagrams (Figs. 7a–b). The low Ca and Mg contents observed in these rocks are consistent with the absence of a carbonate component in their precursor sediments.

The empirical discrimination ratio $100TiO_2/Zr$ (wt.%/ppm) based on transition metals (Ti) and HFSE (Zr), which are assumed to have an immobile behaviour during metamorphism, is lower than 0.4 in all the analysed paragneisses and points to a significant input of psammitic material to the original clastic sequence (Garcia *et al*., 1991; Abu El-Enen, 2011).

Table 1.—**Major element data and sample coordinates for the Granja paragneisses**

X - False Easting	296132	295171	296062	296065	289850	295085	285981	250067	250067	250067	295186	295205
Y - False Northing	9666860	9666562	9666549	9666489	9660481	9664004	9659105	9639725	9639725	9639725	9666972	9666950
Samples	Jn11	Jn12	Jn23-b	Jn23-c	Jn29-b	GR70	Jn02-c	209a	209b	209c	T-143	T-148
SiO_2	66.90	68.70	72.00	72.50	69.20	67.18	67.40	66.27	67.11	67.37	71.76	68.85
TiO_2	0.59	0.60	0.61	0.52	0.66	0.54	0.73	0.74	0.59	0.44	0.74	0.76
Al_2O_3	15.60	15.50	14.10	13.90	14.60	15.94	15.20	14.04	11.91	12.75	14.36	13.70
Fe_2O_3 (T)	6.23	5.66	5.00	4.68	6.17	6.12	7.46	5.76	8.36	8.58	5.09	6.80
MnO	0.12	0.11	0.01	0.11	0.11	0.10	0.09	0.09	0.07	0.08	0.06	0.05
MgO	2.10	1.60	1.40	1.30	2.10	1.80	2.10	2.69	1.54	1.35	0.71	1.46
CaO	1.80	0.96	1.60	2.00	2.10	2.43	1.70	2.29	1.71	1.71	2.09	1.90
Na_2O	2.60	1.60	2.20	2.70	2.30	2.87	1.90	2.75	2.50	2.23	2.87	2.48
K_2O	3.00	3.90	1.90	1.30	1.70	2.84	2.10	2.81	3.09	2.99	1.64	1.94
P_2O_5	0.08	0.08	0.07	0.07	0.05	0.07	0.12	0.16	0.08	0.08	0.07	0.07
LOI	0.01	0.38	0.13	0.07	0.07	−0.10	0.01	1.75	2.11	1.47	0.25	0.33
Total	99.03	99.09	99.01	99.15	99.06	99.79	98.81	99.35	99.07	99.05	99.64	98.34

Samples T-143 and T-148 are from Gama Jr. (1992); samples 209a-b-c are from Santos (1993); the other six samples (Jn11, 12, 23b-c, 29b, 02c) are from Nogueira Neto (2000).

Table 2.—**Trace element data for the Granja paragneisses. PAAS and EP GREY compositions are given in the last two columns**

Sample	Jn11	Jn12	Jn23-b	Jn23-c	Jn29-b	GR70	PAAS*	EP GREY*
Th	13.00	13.00	11.00	13.00	17.00	9.90	14.60	8.00
Sc	14.00	15.00	8.00	10.00	10.00	13.00	16.00	15.00
Zr	216.00	197.00	300.00	227.00	257.00	160.90	210.00	156.00
La	37.40	42.94	41.35	39.88	41.01	32.50	38.00	32.00
Ce	81.21	94.81	88.72	84.63	83.07	64.00	80.00	68.00
Pr	–	–	–	–	–	6.67	8.90	–
Nd	30.14	35.64	33.65	32.55	30.21	23.60	32.00	29.00
Sm	5.20	6.30	6.09	5.89	5.46	4.52	5.60	5.60
Eu	0.98	1.22	1.26	1.24	1.15	1.16	1.10	1.20
Gd	4.08	4.60	4.34	4.44	4.26	3.94	4.70	4.54
Tb	–	–	–	–	–	0.70	0.77	0.66
Dy	4.33	4.40	4.32	4.08	4.07	3.93	4.40	–
Ho	0.90	0.90	0.90	0.88	0.84	0.82	1.00	–
Er	2.56	2.50	2.56	2.66	2.42	2.30	2.90	–
Tm	–	–	–	–	–	0.36	0.40	–
Yb	2.06	2.18	2.08	2.22	1.79	2.32	2.80	1.80
Lu	0.31	0.33	0.32	0.35	0.28	0.34	0.43	0.29
∑REE	169.15	195.82	185.59	178.81	174.56	147.16	183.00	143.09
Eu/Eu*	0.63	0.66	0.72	0.71	0.70	0.82	0.64	0.71
La_N / Yb_N	12.27	13.28	13.40	12.11	15.50	9.46	9.16	12.00
Gd_N / Yb_N	1.60	1.70	1.68	1.61	1.93	1.37	1.36	2.04

* PAAS - Post-Archean average Australian Shale (Nance & Taylor, 1976); EP GREY - Average Chemical Composition of Early Proterozoic Greywackes (Condie, 1993).

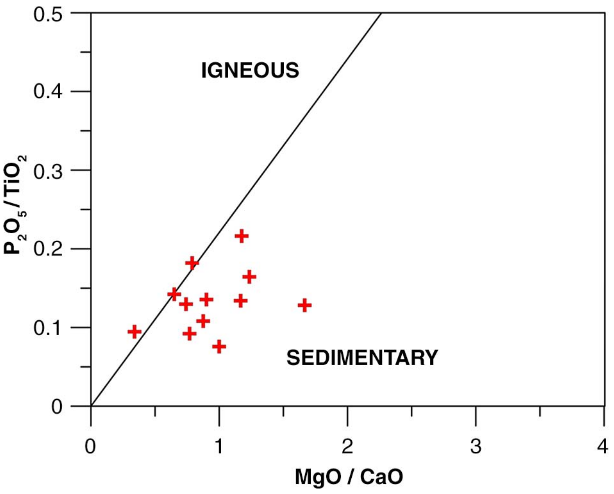

Fig. 5.—P_2O_5/TiO_2 versus MgO/CaO discrimination diagram (Werner, 1987) for the analysed Granja paragneisses (red symbols).

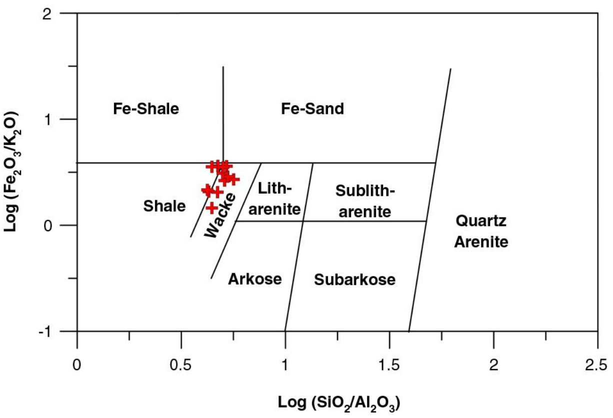

Fig. 6.—Log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) classification diagram of Herron (1988) showing the location of the studied samples (red symbols).

Six of the paragneiss samples have high K_2O/Na_2O ratios (>1), whilst the other six display K_2O/Na_2O values lower than 1, suggesting some diversity of protolith rock types (pelitic to semipelitic). In the A-CN-K ternary plot of Nesbitt & Young (1984), the samples define a trend between silt-clay and clay sediments consistent with a mixed greywacke-shale composition (Fig. 8).

Calculation of the chemical index of alteration (CIA; Nesbitt & Young 1982) gives CIA values of 53 to 65 indicative of low to moderate degrees of chemical weathering for the sediment parent rocks,

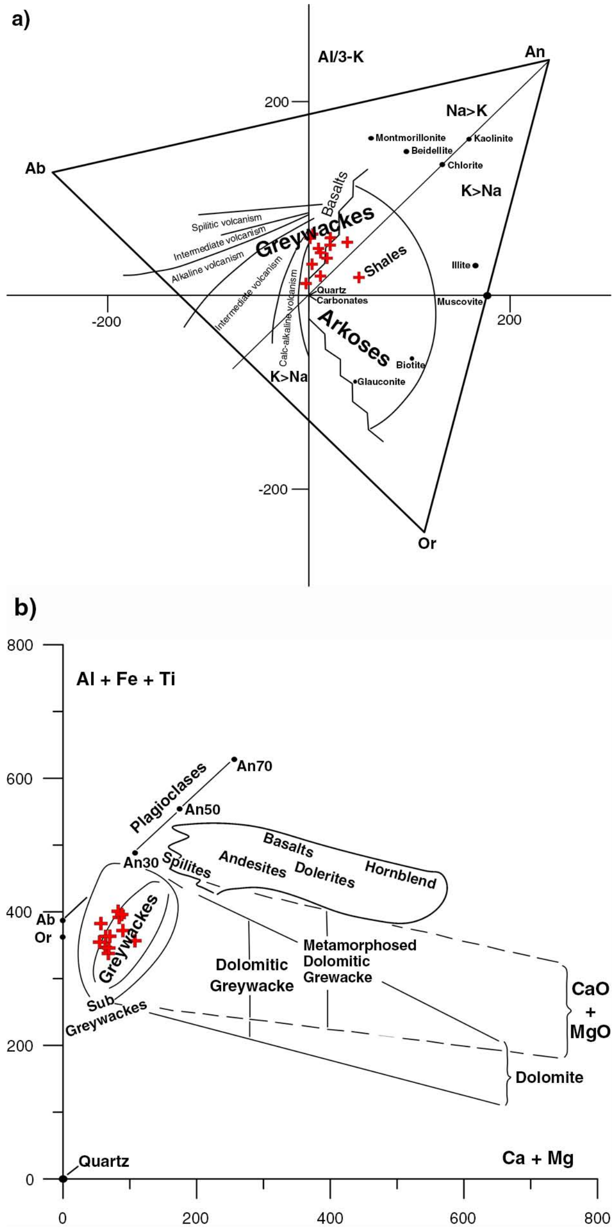

Fig. 7.—(a) Al/3-K versus Al/3-Na millicationic diagram (La Roche, 1968) and (b) Fe + Al + Ti versus Ca + Mg millicationic diagram (Moine & La Roche 1968) for the analysed paragneisses (red symbols).

supporting a provenance from igneous felsic to intermediate crustal sources.

Figure 9 illustrates the REE chondrite normalized patterns for six representative samples of the paragneiss suite. Overall, these patterns are characterized by: (a) moderate LREE / HREE fractionation ($La_N/Yb_N = 9.46–15.50$), (b) flat HREE

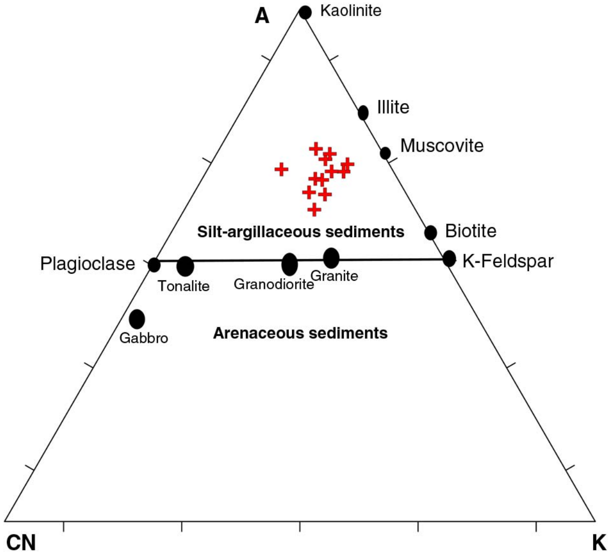

Fig. 8.—A-CN-K ternary plot of Nesbitt & Young (1984) showing the location of the analysed samples (red symbols). A = mol. Al_2O_3; CN = mol. CaO* + mol. Na_2O; K = mol. K_2O. CaO* = mol. CaO − 3.33 mol. P_2O_5.

profiles (Gd_N/Yb_N = 1.37–1.93) and (c) negative Eu anomalies of small amplitude (Eu/Eu* = 0.63–0.82). Their close similarities to Post-Archean average Australian Shale (PAAS, Nance & Taylor, 1976) and Early Proterozoic Greywackes (EP GREY, Condie, 1993) provide additional evidence for a pelitic to semipelitic derivation and reinforce the hypothesis that melt loss from these rocks has been negligible. The Eu/Eu* and Gd_N/Yb_N ratios are also within the range of values (Eu/Eu*<0.85; Gd_N/Yb_N<2.0) found in Post-Archean metasediments by McLennan & Taylor (1991) and McLennan *et al*. (1995) (Fig. 10).

Provenance and tectonic setting

Several attempts have been made to use major and trace elements as provenance indicators. In the F1-F2 diagram of Roser & Korsch (1988), the analysed samples plot within the fields of primary felsic or intermediate source rocks pointing to a major contribution of this type of igneous materials for the genesis of their precursor sediments (Fig. 11). Their Th/Sc and Zr/Sc ratios are similar to the upper continental crust (McLennan *et al.*, 1993) confirming their provenance from a felsic to intermediate source area (Fig. 12).

According to the K_2O/Na_2O vs. SiO_2 diagram of Roser & Korsch (1986), sediment deposition would have occurred at an active continental margin (Fig. 13). As shown in the ternary diagrams of Bhatia & Crook (1986), a continental island arc setting is

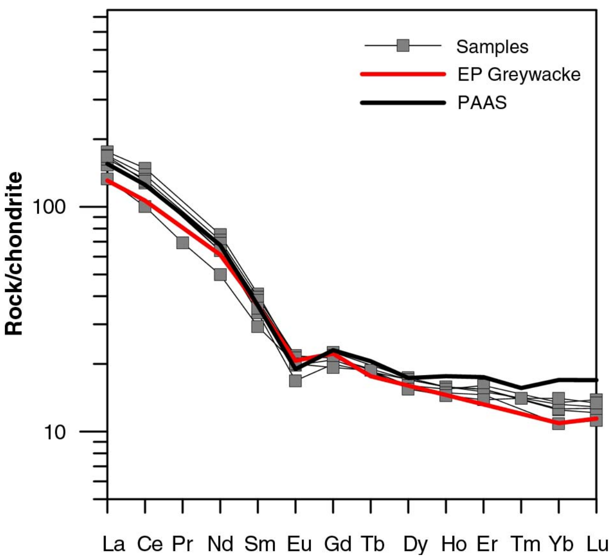

Fig. 9.—Chondrite normalized REE patterns for the Granja paragneisses (grey squares). Normalization constants from Evensen et al. (1978). Black line represents Post-Archean average Australian Shale (PAAS) and red line Early Proterozoic average Greywacke (EP GREY).

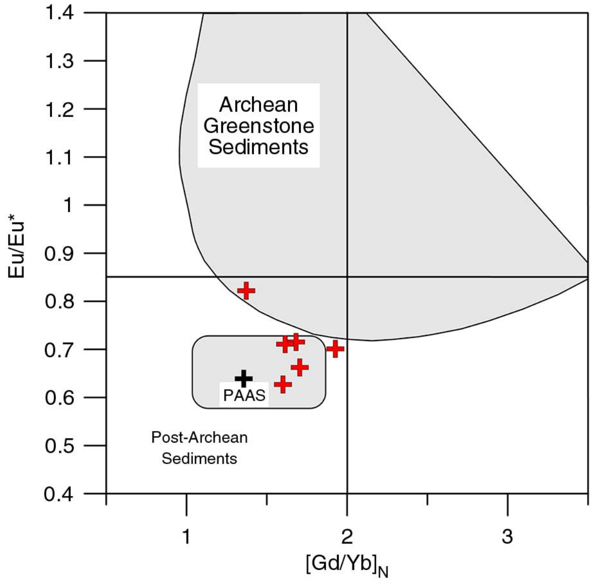

Fig. 10.—Eu/Eu* versus GdN/YbN diagram (McLennan & Taylor, 1991) for the analysed samples. Shadowed fields correspond to Post-Archean Sediments and Archean Greenstone Sediments (McLennan et al., 1995).

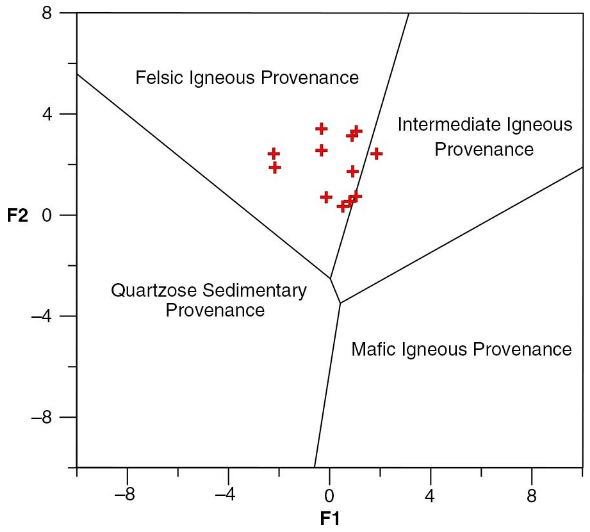

Fig. 11.—Classification of the analysed samples (red symbols) according to the provenance discrimination diagram proposed by Roser & Korsch (1988). $F1=(-1.773\ TiO_2+0.607\ Al_2O_3+0.76\ Fe_2O_3t-1.5\ MgO+0.616\ CaO+0.509\ Na_2O-1.224\ K_2O)-9.09$; $F2=(0.445\ TiO_2+0.07\ Al_2O_3-0.25\ Fe_2O_3t-1.142\ MgO+0.438\ CaO+1.475\ Na_2O+1.426\ K_2O)-6.861$.

indicated by the highly incompatible trace elements (La, Sc, Th, Zr) for the investigated paragneisses (Figs. 14a–b).

Finally, regional constraints suggest that the sedimentary protoliths of the Granja granulitic paragneisses could have resulted from erosion of intermediate to felsic igneous rocks similar to the TTG orthogneisses exposed in adjacent areas of the MCD (Fig. 2). This is

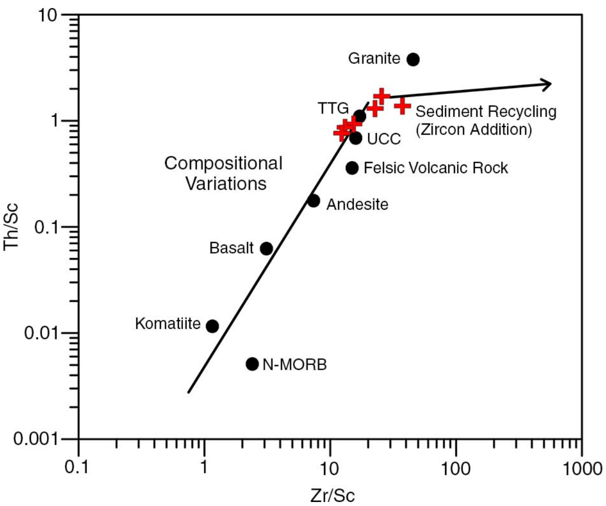

Fig. 12.—Th/Sc versus Zr/Sc diagram (McLennan et al., 1993) for the studied samples (red symbols).

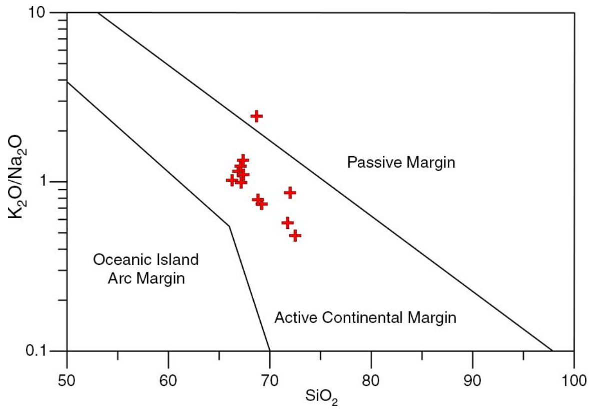

Fig. 13.—K_2O/Na_2O versus SiO_2 tectonic setting discrimination diagram of Roser & Korsch (1986) showing the location of the studied samples (red symbols).

further supported by the Early Proterozoic U-Pb ages obtained in detrital zircons from the paragneisses and the island arc tectonic setting inferred for the TTG sequence (Fetter *et al.*, 2000).

Conclusions

Based on the preliminary petrographical and geochemical data presented in this study, it is possible to draw the following conclusions:

The garnet-sillimanite migmatitic paragneisses exposed in the MCD experienced intense deformation and granulite facies metamorphism during the Brasiliano Orogeny. Microstructures and mineral assemblages in the Granja paragneisses reveal a metamorphic history involving four main stages: a prograde metamorphic stage (M_1), a peak-metamorphic stage (M_2), a post-peak decompression stage (M_3) and a retrograde cooling stage (M_4).

Partial melting conditions appear to have been reached during M_1, continued during the metamorphic peak (M_2) and persisted during most of the post-peak decompression stage (M_3). The retrograde cooling path (M_4) is coeval with D_4 shearing and was accompanied by intense dynamic recrystallization of the leucosomes suggesting that melt crystallization was completed before the end of the D_4 tectonic event.

Some of the migmatitic paragneisses from the Granja Granulite Complex appear to have undergone little or no melt extraction and provide the closest estimate for the composition of the original

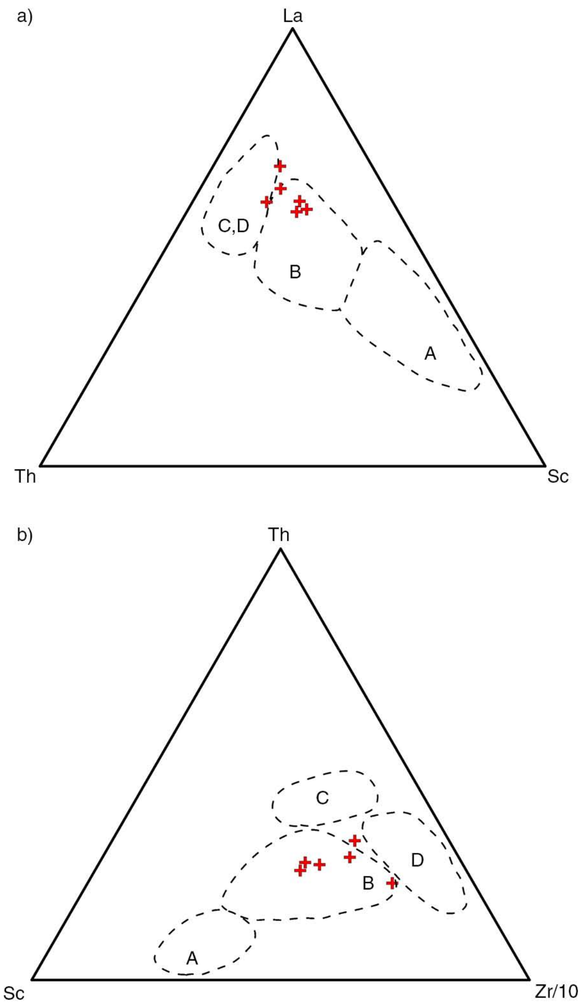

Fig. 14.—Tectonic setting ternary discrimination diagrams (Bhatia & Crook, 1986) for the analysed samples (red symbols). (a) La-Th-Sc, (b) Th-Sc-Zr/10. Dashed fields correspond to (A) Oceanic Island Arc, (B) Continental Island Arc, (C) Active Continental Margin and (D) Passive Margin.

protoliths. Whole-rock geochemical data for these rocks suggest that the precursor sediments had mixed greywacke-shale compositions and could have resulted from erosion of intermediate to felsic igneous rocks similar to the TTG orthogneisses. Sediment deposition would have occurred at an active continental marginal / continental island arc setting.

Given the evidence for the presence of melt in the samples analysed, the results obtained must be interpreted with caution and any inferences on the provenance of the Granja paragneisses require further support from isotopic and detrital zircon studies.

ACKNOWLEDGMENTS

This work was supported by the project Metamorphic Evolution of the Granja Complex & Metalogenetic Potential of the Central Ceará Pegmatites (SPU N° 11294909-6, FUNCAP, Brasil) and the GeoBioTec Research Unit (PEst-OE/CTE/UI4035/2014). The authors also thank the Department of Geology of the Federal University of Ceará (UFC), the Institute of Geosciences and Exact Sciences of the São Paulo State University (UNESP) and the Department of Geosciences of the University of Aveiro (UA). A.J.F. Silva benefits from a PhD grant (SFRH/BD/85292/2012) sponsored by FCT (Science and Technology Foundation, Portugal). Valuable comments on the original manuscript by C. Villaseca and an anonymous reviewer are greatly appreciated.

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