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Cadomian magmatism and metamorphism at the Ossa Morena/Central Iberian
zone boundary, Iberian Massif, Central Portugal: geochemistry and *P-T*
constraints of the Sardao Complex

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Abstract: A well preserved Cadomian basement is exposed in the Iberian Massif, Central
Portugal, at the Ossa Morena/Central Iberian zone boundary, which allows the determination
of reliable geochemical data. A sequence of Cadomian and Variscan magmatic and
tectonometamorphic events has been already described for this area and are documented in
other areas of the Avalonian-Cadomian orogen. However, the geochemical information
concerning the Cadomian basement for this area is still limited. We present whole rock
geochemical and oxygen isotopic information to characterize the igneous protoliths of the
Sardao Complex, located within the Tomar-Badajoz-Córdoba Shear Zone, and indentify their
tectonic setting. We use detailed petrography, mineral chemistry and *P-T* data to characterize
the final Cadomian tectonometamorphic event. The Sardao Complex contains orthogneiss

and amphibolite units. The protoliths of the orthogneiss are calc-alkaline magmas of acid composition and peraluminous character that were generated in an active continental margin in three different stages (*ca.* 692 Ma, *ca.* 569 Ma and *ca.* 548 Ma). The most significant processes in their petrogenesis are the partial melting of old metasedimentary and meta-igneous crust at different crustal levels and the crystal fractionation of plagioclase, alkali feldspars, apatite, zircon and Fe-Ti oxides. The protoliths of the amphibolite, older than *ca.* 540 Ma, are tholeiitic and calc-alkaline magmas of basic composition that display N-, T- and E-MORB affinities. They were generated in an active continental margin. Crustal contamination and fractional crystallization of hornblende and diopside were involved in their petrogenesis. However, the fractional crystallization was not significant. The magmatic activity recorded in the Sardoal Complex indicates the existence of a long-lived continental arc (*ca.* 692-540 Ma) with coeval felsic and mafic magmatism. The final stage of the Cadomian metamorphism is usually represented in other areas of the Cadomian basement as a LP-HT metamorphic event. However, the *P-T* data obtained by thermodynamic modelling indicates medium pressure/high temperature conditions at *ca.* 540 Ma. These data suggest that the Sardoal Complex represents a deeper level of the exhumed Cadomian basement where the final stage of the Cadomian metamorphism was recorded.

Keywords: North Gondwana, Continental arc, Geochemistry, Petrogenesis, Oxygen isotopes

1. Introduction

A linear belt of Andean type generated by the Avalonian-Cadomian orogeny was active from the Late Proterozoic to the early Paleozoic at the Northern edge of Gondwana. Its fragments are preserved in the Avalonian and Cadomian terranes of north-eastern North America and

Western Europe (e.g. Nance et al., 1991). Cadomian terranes of Western Europe are recognized in the northern Armorican Massif (e.g. D'Lemos et al., 1990), the Bohemian Massif (e.g. Linnemann et al., 2008a) and the Iberian Massif (e.g. Eguíluz et al., 2000 and references therein; Ordoñez-Casado, 1998 and references therein; Ribeiro et al., 2009 and references therein). In the Iberian Massif, the Cadomian basement crops out at the Ossa Morena/Central Iberian zone boundary, in the Tomar-Badajoz-Córdoba Shear Zone (Fig. 1a) (e.g. Eguíluz et al., 2000; Henriques et al., 2015; Ribeiro et al., 1990, 2009) and at the Olivenza-Monesterio Antiform (e.g. Ordoñez-Casado, 1998 and references therein). However, information on the geochemical and *P-T* conditions of these rocks is limited due to intense Cadomian and Variscan polymetamorphism (e.g. Dallmeyer and Quesada, 1992; Henriques et al., 2015; Ordoñez-Casado, 1998) and alteration.

In Central Portugal, near the Abrantes area (Fig.1a), a well preserved Cadomian basement occurs, which allows the determination of a reliable set of geochemical data. A sequence of Cadomian events was established for this area: island arc magmatism accompanied by deposition of fine-grained sediments in a Neoproterozoic basin; early continental arc magmatism (*ca.* 692 Ma); generation of igneous protoliths with isotopic signature of old crustal sources (*ca.* 569 Ma) the final phase of the arc magmatism that involved mainly partial melting of continental crust (*ca.* 548–544 Ma); continental arc accretion of the Ossa Morena Zone with the Iberian Autochthon passive margin (future Central Iberian Zone) at *ca.* 540 Ma (U-Pb, ID-TIMS method; Henriques et al., 2015). In this paper, we use detailed petrography, mineral chemistry and *P-T* data to characterize the Cadomian metamorphism recorded in the Sardoal Complex. Geochemical and isotopic ($\delta^{18}\text{O}$) data of representative samples from the different magmatic stages are also presented, in order to understand the evolution of the Cadomian arc. This study aims to contribute to the understanding of the magmatic and metamorphic processes involved in the assembly of North Gondwana.

2. Geological setting

The Iberian Massif, is considered the westernmost segment of the European Variscides (e.g. (Burg and Matte, 1978; Dallmeyer and García, 1990) and it has been subdivided into different tectonostratigraphic units broadly from NE to SW: (1) the Iberian Terrane (including the Cantabrian Zone (CZ), the West Asturian–Leonese Zone (WALZ), the Central Iberian Zone (CIZ), the Parautochthonous with CIZ affinities, the Basal Complex with Ossa Morena Zone (OMZ) affinities and the Ossa Morena Zone (OMZ); (2) the South Portuguese Terrane (SPT); (3) the Exotic Terranes (NW: the Continental Allochthonous Terrane (CAT) and the NW Ophiolite Terrane; SW: the SW Ophiolite Terrane and the Finisterra Terrane) (Fig. 1a; e.g. Julivert et al., 1972; Lotze, 1945; Ribeiro, 2013).

The study area is located in the Iberian Massif, at the Ossa Morena/Central Iberian zone boundary, within the Tomar-Badajoz-Córdoba Shear Zone, in the Abrantes-Tomar sector (Fig. 1a). The accretion of the Ossa Morena Zone and the Central Iberian Zone has been subject of considerable debate and two models have been proposed for the Tomar-Badajoz-Córdoba Shear Zone: i) it was originally active during the Cadomian orogeny and subsequently reactivated during the Variscan (e.g. Eguíluz et al., 2000; Ribeiro et al., 2009); ii) it was solely a Variscan intra-continental shear zone (e.g. Pereira et al., 2012; Simancas et al., 2005). However, the recognition of solely Variscan metamorphism and deformation in some areas of the shear zone is the result of the stronger Variscan overprint. In areas preserved from Variscan overprint it is agreed that the metamorphic conditions during the Cadomian Orogeny are well-preserved (e.g. Álvaro et al., 2014). New results constrained significantly the timing of the continental collision at *ca.* 540 Ma and extended the timing of the continental arc at *ca.* 692–540 Ma (Henriques et al., 2015), previously established in the

103 Ossa Morena Zone at *ca.* 600–544 Ma (e.g. Oschner, 1993; Ordoñez-Casado, 1998). The
104 Central Iberian Zone is considered as a continental fragment of the Iberian Autochthon (e.g.
105 Sánchez-García et al., 2008 and references therein). Late Neoproterozoic reconstructions
106 place the Ossa Morena Zone adjacent to the West African craton (e.g. Nance et al., 2008;
107 Pereira 2015 and references therein). Several locations have been suggested for the Central
108 Iberian Zone: near Amazonia (e.g. Gutiérrez-Alonso et al., 2003; Fernández-Suárez et al.,
109 2000) and Saharan metacraton and the Arabian–Nubian Shield (e.g. Bea et al., 2010; Teixeira
110 et al., 2011).

111 Previous work on the local geology includes geological sketch maps (Conde, 1984; Pereira et
112 al., 1998; Pereira et al., 2010; Ribeiro et al., 2013; Romão et al., 2014; Gonçalves in Teixeira,
113 1981) and 1: 50 000 geological maps (Romão and Esperancinha, 2000; Romão, 2006;
114 Zbyszewski et al., 1981, 1983). Recently, a new tectonostratigraphic sequence of the area has
115 been established and three major units with Ossa Morena affinities were distinguished, from
116 base to top: the Série Negra, the Sardoal Complex and the Mouriscas Complex (Fig. 1b)
117 (Henriques et al., 2015).

118 In the studied area, the Série Negra comprises metavolcanic rocks, metavolcaniclastic rocks,
119 metagreywacke, phyllite, quartz-phyllite, schists (micaschist, quartz-mica schist, quartzo-
120 feldspathic schist) with interbedded black chert, greenschist and amphibolite and rhyodacite
121 intrusions (Fig. 1b). The Série Negra Unit is a volcano-sedimentary succession, deformed and
122 metamorphosed under variable P-T conditions (Alía, 1963; Carvalhosa, 1965; Eguíluz et al.,
123 2000). It is recognized in southern Portugal and Spain (e.g. Eguíluz et al., 2000; Pereira et al.,
124 2006) and it has an equivalent in the Bohemian Massif (Linnemann et al., 2008a). It is
125 considered to have been deposited in a back arc basin of Ediacaran age (*ca.* 590–550 Ma) (e.g.
126 Linnemann et al., 2008a and references therein). In the study area, the protoliths of the
127 amphibolite have a tholeiitic character with island arc affinity and transitional-alkalic

character with an intra-plate signature (Henriques, 2013). Island arc magmatism was recognized in the Série Negra in other areas of the Ossa Morena Zone (Ribeiro et al., 2003; Sánchez Lorda et al., 2014; Sánchez Lorda et al., 2016). It is represented by metabasites with an igneous age of *ca.* 645-580 Ma (Sánchez Lorda et al., 2014; Sánchez Lorda et al., 2016).

The Sardoal Complex consists of deformed metamorphic rocks mainly of igneous origin, intruded by Late Variscan rhyodacites of Carboniferous age (308 ± 1 Ma; Henriques et al., 2016; Fig. 1b). The metamorphic rocks comprise: quartzo-feldspathic schist, orthogneiss, migmatite, gneissic granite, amphibolite and amphibolitic gneiss (Fig. 1b). Detailed mapping, petrography, ID-TIMS U-Pb geochronology and whole rock isotopic (Rb–Sr, Sm–Nd) data were presented for the quartzo-feldspathic schist, orthogneiss and amphibolite (Henriques et al., 2015). The main characteristics of orthogneiss and amphibolite are summarized in Appendix 1. Four units of orthogneiss were recognized and important distinctions concerning igneous crystallization age, occurrence, textural features and mineral assemblage were observed (Appendix 1): Souto orthogneiss (692^{+77}_{-60} Ma), Carvalhal orthogneiss (569 ± 3 Ma), Sardoal orthogneiss (548 ± 4 Ma) and Olalhas orthogneiss (unknown age). The igneous crystallization age of 692^{+77}_{-60} Ma of the quartzo-feldspathic schist was assumed for the Souto orthogneiss, based on the identical features and close spatial association. This age is the oldest found in the Ossa Morena Zone, so far, and is related to the early arc magmatism (Henriques et al., 2015). The Sr and Nd initial isotopic signatures of the orthogneiss, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7057$ to 0.7117 and $\epsilon\text{Nd}_t = -5.2$ to -8.1 , indicate partial melting of metasedimentary and meta-igneous crust in different crustal levels and they were considered hybrid rocks (Appendix 1). The range of ϵNd_t isotopic signatures (-5.2 to -8.1) and T_{DM} model ages (1.53 to 1.69 Ga) reflect the involvement of old crustal sources, which is characteristic of Cadomian type-terrane (Henriques et al., 2015 and references therein).

Elongated metre-size bodies of amphibolite intrude the Souto and Olalhas orthogneiss:

Cabeço da Moura and Vila Nova amphibolite. Their metamorphic age indicates an igneous crystallization age older than 539 ± 3 Ma (Appendix 1). Cabeço da Moura amphibolite is fine-grained, while Vila Nova amphibolite presents an incipient gneissic banding. Different compositions of the mineral content are observed (Appendix 1) and the occurrence of metamorphic zircon is restricted to Cabeço da Moura amphibolite. A metamorphic age of *ca.* 540 Ma is recorded in metamorphic monazite from Souto and Carvalhal orthogneiss and metamorphic zircon (multi-faceted «soccer-ball» zircon) in amphibolite (Appendix 1). The age of metamorphic titanite in amphibolite (*ca.* 529 Ma; Appendix 1) was interpreted as the age of cooling through the blocking temperature for titanite after the *ca.* 540 Ma peak of metamorphism (Henriques et al., 2015). The metamorphic age of *ca.* 540 Ma was interpreted to represent the continental collision of the Ossa Morena Zone with the Iberian Autochthon passive margin (future Central Iberian Zone). This event generated major medium/high grade metamorphism ($P=7-8$ kbar and $T=640-660^{\circ}\text{C}$) registered in the Cabeço da Moura amphibolite and correspond to the maximum $P-T$ conditions attained in the area (Henriques et al., 2015).

The Mouriscas Complex is a deformed and metamorphosed predominantly mafic igneous complex of Ediacaran and Ordovician age, that consists of amphibolite, protomylonite trondhjemitic, garnet amphibolite, metatexite and diatexite (Fig. 1b; Henriques et al., 2015).

3. Analytical methods

Most mineral analyses were performed on a CAMECA SX-100, at the Scientific-Technological Centre of the University of Oviedo, Spain. The operating conditions for silicates and oxides were 5 μm beam diameter, 15 kV accelerating voltage, and 15 nA beam current, but for sulfides were: 1 μm beam diameter, 20 kV accelerating voltage and 20 nA

beam current. The peak counting times were 10 s for most elements except for V (20 s), Co and Ni (5 s). Some of the mineral analyses were carried out on a Jeol 8500-F at LNEG, Portugal, with identical operating conditions for silicates, oxides and sulfides. The peak counting times were 15 s. Precision is better than 2%.

Whole rock major and trace elements analyses were obtained for 35 samples at Activation Laboratories – ACTLABS (Canada). The major elements abundances were determined by ICP-AES and the trace elements abundances, including the REE, were determined by ICP-MS (with the exception of Sc, V, Sr and Ba, which were determined by ICP-AES). The detection limits are 0.001 wt.% for MnO and TiO₂ and 0.01 wt.% for the remaining oxides and lower than 1 ppm for most trace elements, except for Sr (2 ppm), Ba (3 ppm), V (5 ppm), Cu (10 ppm), Cr and Ni (20 ppm) and Zn (30 ppm). The precision for major elements is better than 4% and better than 10% for trace elements. Whole rock FeO contents were determined by titration with a standardized potassium permanganate solution with an accuracy of $\pm 1\%$, at the Geosciences Center of University of Coimbra, Portugal.

The whole rock oxygen isotope values were obtained for 13 samples at the Laboratory for Stable Isotope Science of University of Western Ontario, Canada. The procedure follows that of Clayton and Mayeda (1963) as modified by Borthwick and Harmon (1982) for use with ClF₃. The accuracy is $\pm 0.2\%$ for homogenous samples and was checked by using NBS-30, NBS-28, an internal laboratory quartz and kaolinite standard, respectively, both calibrated to their accepted values. An oxygen-isotope, CO₂–H₂O fractionation factor of 1.0412 at 25 °C was used to calibrate the mass-spectrometric reference gas. The oxygen-isotope data are presented in the normal δ -notation relative to Vienna Standard Mean Ocean Water (VSMOW).

4. Petrography and mineral chemistry

A petrographic description has been previously presented (Henriques et al., 2015) and is summarized in Appendix 1. Additional information is provided below. Representative electron microprobe analyses of minerals are given in supplementary material.

4.1. Orthogneiss

The orthogneiss is composed of quartz, plagioclase, K-feldspar, biotite and muscovite and the content of subordinate minerals is variable (Appendix 1). Although, relict igneous texture is preserved (Appendix 2), all units show textural features of intensive deformation (Appendix 1).

4.1.1. Feldspar

Feldspar occurs as porphyroclasts and in the matrix. It exhibits fracturing, marginal recrystallization and twinning deformation. In some samples, feldspar porphyroclasts shows fish microstructure with small aspect ratios. In the relict igneous textures feldspar shows elongated forms characteristic of igneous origin (Appendix 2).

Plagioclase has dimensions of up to 4 mm, shows lobate boundaries with quartz and myrmekite. It contains inclusions of quartz, muscovite, biotite and zircon. Plagioclase corresponds to oligoclase and rarely andesine (Fig. 2). The anorthite content is usually higher in porphyroclasts than in the matrix (Fig. 2; Table 1a), suggesting that its composition was not significantly affected by the metamorphism. However, there is some overlap in the range of values (Fig. 2; Table 1a).

K-feldspar is present in Carvalhal and Sardoal orthogneiss and is rare in Souto and Olalhas orthogneiss (Table 1a). Porphyroclasts of K-feldspar have dimensions of up to 4 mm, are partially replaced by myrmekite and exhibit flame perthite. K-feldspar occurs as orthoclase and microcline. Orthoclase is twinned on the Carlsbad law and microcline displays crosshatch twinning. It contains inclusions of biotite, quartz and scarce ilmenite. K-feldspar porphyroclasts show orthoclase content identical to the matrix or lower (Table 1a). BaO content is higher in K-feldspar porphyroclasts than in the matrix (Table 1a), which is in agreement with the magmatic origin of the protoliths (Long and Luth, 1986). The analysed feldspar is unzoned.

4.1.2. Micas

Biotite and muscovite occur as porphyroclasts and in the matrix (Appendix 3a, 3b). Muscovite porphyroclasts attain dimensions of 7 mm and biotite only of 3 mm. They show lenticular mica fish and mica fish with small aspect ratios. Biotite and muscovite contain inclusions of sillimanite, zircon, apatite, ilmenite and monazite. Biotite is pleochroic from γ - and β - reddish brown to α - pale yellow or colourless. Muscovite and biotite are intergrown in the Sardoal orthogneiss.

Representative electron microprobe analyses of biotite and muscovite are given in Appendix 3a, 3b and chemical compositions are summarized on Table 1a. Biotite and muscovite are unzoned. Biotite has Al^{VI} contents of 0.242–0.620 (apfu) and $Fe_t/(Fe_t+Mg)$ ratios of 0.491–0.614, that plot in the biotite field in the diagram of Deer et al. (1966) (Table 1a). The composition of biotite is mainly ferriferous ($Mg:Fe$ ratio < 1 ; Foster, 1960) but magnesian compositions ($Mg:Fe$ ratio > 1 ; Foster, 1960) are observed (Table 1a). The X_{Mg} [$Mg/(Mg+Fe^{2+})$] range of the biotite porphyroclasts (0.42–0.53) is identical to the matrix

(0.39–0.52) (Table 1a), which is interpreted as metamorphic re-equilibration (Lefebvre et al., 2005). The X_{Mg} content of the biotite included in garnet is lower than the X_{Mg} content observed in the porphyroclasts and matrix (Table 1a). Low X_{Mg} content is characteristic of retrograde biotite replacing garnet (e.g. Taylor et al., 2010). Muscovite shows low FeO, MgO and Na₂O and high K₂O and Al₂O₃ (Appendix 3b). Porphyroclasts have higher F and LiO₂ contents than the matrix suggesting that their growth took place after the matrix (Appendix 3b).

4.1.3. Other Minerals

Garnet occurs as irregular porphyroclasts in Souto and Olalhas orthogneiss and in the matrix in Souto orthogneiss (Appendix 3c). The porphyroclasts have dimensions of up to 2 mm, are generally fractured and the fractures are filled by biotite. The porphyroclasts contain inclusions of quartz, biotite, muscovite, oligoclase and ilmenite (Fig. 3a). Garnet is almandine rich with the following composition: Alm₆₃₋₆₈Sps₁₄₋₂₁Prp₈₋₁₁Grs₅₋₈Adr₀₋₁ (Souto orthogneiss) and Alm₇₆₋₇₉Prp₁₀₋₁₄Sps₆₋₁₁Grs₁₋₃Adr₀₋₂ (Olalhas orthogneiss) (Appendix 3c; Table 1a). The almandine and pyrope components are higher in Olalhas porphyroclasts, while grossular and spessartine components are higher in Souto porphyroclasts (Table 1a). There is no significant distinction between the composition of porphyroclasts and matrix of the Souto orthogneiss, suggesting a metamorphic re-equilibration of garnet (Appendix 3c; Table 1a). Sillimanite is present in all orthogneiss units except for the Carvalhal. Fibrolitic sillimanite occurs mostly enclosed in biotite, muscovite, plagioclase, quartz and tourmaline. Prismatic sillimanite is observed only in Olalhas orthogneiss (Fig. 3b). Staurolite occurs in Olalhas orthogneiss, as small porphyroclasts and in the matrix. Staurolite porphyroclasts occur associated with fibrolitic sillimanite and muscovite (Fig. 3c). The

staurolite has a Fe-rich composition ($X_{Mg} = 0.16\text{--}0.22$) and there is no chemical distinction between porphyroclasts and matrix, indicating a metamorphic re-equilibration (Appendix 3d; Table 1a).

Apatite occurs included in other minerals and in the matrix where can be up to 1 mm in size. In the most deformed rocks the apatite from the matrix is fractured. The apatite is classified as fluorapatite according to the nomenclature of Pasero et al. 2010 (Appendix 3e; Table, 1a).

Ilmenite and magnetite occur enclosed on biotite and plagioclase and dispersed in the matrix. Ilmenite is the most abundant oxide and is present in all orthogneisses. MnO content of ilmenite is highest in Sardoal (3.51–4.72 wt.%) and the lowest in Olalhas orthogneiss (0.85–1.34 wt.%) (Appendix 3f). Ilmenite from rocks rich in garnet (Olalhas) tends to be poorer in MnO than ilmenite from garnet-absent rocks (Sardoal) (Frost, 1991). Mn strongly favours garnet over ilmenite with K_d ranging from 6 to 10 (Tracy, 1982 in Frost, 1991). Magnetite is observed in Carvalhal and Sardoal orthogneiss (Appendix 3f). Rutile occurs dispersed in the matrix and is only observed in Olalhas orthogneiss (Appendix 3f). Sulphides (arsenopyrite, pyrite, and pyrrhotite) occur isolated or filling veins and fractures. They are present in all orthogneiss units except for the Souto (Appendix 3f).

4.2. Amphibolite

The amphibolite units are characterized by the mineral assemblage of: amphibole, plagioclase, clinopyroxene and subordinate minerals (Table 1b). The texture is fine-grained and granoblastic to nematoblastic (Fig. 3d; Appendix 1). The gneissic banding, presented by the Vila Nova amphibolite, consists of layers of amphibole, alternating with layers of plagioclase, epidote, titanite and carbonates.

4.2.1. Amphibole

Amphibole from Cabeço da Moura amphibolite consists of magnesiohornblende and minor ferrohornblende and actinolite in the nomenclature of Leake et al. (1997) (Appendix 4a; Fig. 4a; Table 1b). Magnesiohornblende is the most common amphibole and does not show significant zoning (Appendix 4a). Actinolite partially replaces magnesiohornblende and diopside (Fig. 3e). Amphibole from Vila Nova amphibolite consists of magnesiohornblende and minor pargasite, ferropargasite and edenite in the nomenclature of Leake et al. (1997) (Appendix 4a; Fig. 4a; Table 1b). Magnesiohornblende is usually unzoned. Pargasite is rimmed by ferropargasite, which is stable under lower temperatures than pargasite (Gilbert et al., 1982) and is probably a retrograde phase.

4.2.2. Plagioclase

Plagioclase ranges from andesine to anorthite in Cabeço da Moura amphibolite (An₃₇₋₉₂) (Fig. 4b; Table 1b). Anorthite was only observed in one sample (Fig. 4b). Plagioclase from Cabeço da Moura amphibolite shows homogeneous compositions, normal zoning with decrease of anorthite content towards the rim by up to 18 mol% (An₅₅₋₃₇; Fig. 3e) and reverse zoning with increase of anorthite content towards the rim by up to 13 mol% (An₆₂₋₇₅). Examples of normal zoning are anorthite (An₉₂) rimmed by bytownite (An₈₈), labradorite (An₅₅) rimmed by andesine (An₃₇₋₄₈) and andesine (An₃₁₋₃₈) rimmed by oligoclase (An₂₅₋₂₉). Plagioclase from Vila Nova amphibolite displays a narrower range of composition (Fig. 4b; Table 1b), from andesine to labradorite (An₄₇₋₆₁), homogeneous compositions and normal zoned patterns as labradorite (An₆₄) rimmed by andesine (An₄₉), where the decrease of anorthite content towards the rim is up to 15 mol %.

4.2.3. Clinopyroxene

Following the nomenclature of Morimoto et al. (1988), the clinopyroxene from Cabeço da Moura amphibolite is classified as diopside ($\text{Wo}_{46-49}\text{En}_{34-38}\text{Fs}_{14-19}$), hedenbergite ($\text{Wo}_{47-50}\text{En}_{23-27}\text{Fs}_{25-29}$) and augite ($\text{Wo}_{28-41}\text{En}_{36-38}\text{Fs}_{22-34}$) (Appendix 4b; Fig. 4c; Table 1b). In Vila Nova amphibolite the clinopyroxene is only classified as diopside ($\text{Wo}_{48-50}\text{En}_{29-36}\text{Fs}_{14-21}$) (Appendix 4b; Fig. 4c; Table 1b). Diopside from Cabeço da Moura amphibole contains higher TiO_2 and Al_2O_3 and lower CaO than diopside from Vila Nova amphibolite (Fig. 4d). The X_{Mg} range of diopside is similar in Cabeço da Moura amphibolite ($X_{\text{Mg}}=0.65-0.74$; Table 1b) and in Vila Nova amphibolite ($X_{\text{Mg}}=0.62-0.75$; Table 1b). No significant zoning is observed in the clinopyroxene.

4.2.4. Other Minerals

Epidote appears chiefly as elongated prisms and needles. Prisms contain inclusions of magnesiohornblende, titanite and ilmenite. According to the nomenclature of Armbruster et al. (2006) all the epidote group minerals are classified as clinozoisite (Appendix 4c). The clinozoisite shows a narrow compositional range and no zoning. X_{Fe} ($\text{Fe}^{3+}/\text{Al}^{3+}$) is higher in Cabeço da Moura amphibolite ($X_{\text{Fe}}=0.14-0.17$; Table 1b) than in Vila Nova amphibolite ($X_{\text{Fe}}=0.11-0.13$; Table 1b). The decrease of anorthite content in plagioclase towards the rim and the presence of inclusions of magnesiohornblende, titanite and ilmenite in the clinozoisite prisms suggest the following reaction: anorthite + hornblende + titanite + H_2O $\leftrightarrow$ Al-epidote + actinolite + ilmenite (Deer et al., 1997).

351 Titanite appears as dispersed small grains and as rims surrounding ilmenite (Fig. 3f). Based
 352 on X_{Al} values $[Al/(Al+Ti+Fe^{3+})]$ all the titanite is low-Al with $X_{Al} = 0.03\text{--}0.06$ ($X_{Al} < 0.25$;
 353 Oberti et al., 1991; Appendix 4d; Table 1b). In order to identify possible secondary grains of
 354 titanite, the analysed compositions were plotted on a F vs. $Al+Fe^{3+}$ diagram (Enami et al.,
 355 1993) together with metasomatic titanite from Gieré (1992) (Fig. 5a). Enrichment of titanite
 356 in Al and F is characteristic from hydrothermal titanite (Gieré, 1992; Morad et al., 2009). The
 357 analysed titanite shows distinct compositions from the metasomatic titanite, supporting their
 358 metamorphic origin (Fig. 5a). There are no significant compositional differences between
 359 Cabeço da Moura and Vila Nova titanite (Appendix 4d). Small grains show a higher range of
 360 values in F and Fe_2O_{3t} contents ($F = 0.00\text{--}0.28$ wt.%; $Fe_2O_{3t} = 0.18\text{--}0.62$ wt.%; Table 1b)
 361 than rims surrounding ilmenite ($F = 0.00\text{--}0.20$ wt.%; $Fe_2O_{3t} = 0.11\text{--}0.26$ wt.%; Table 1b).
 362 The substitution of Al and Fe^{3+} for Ti $[(Ti+O \leftrightarrow (Al, Fe^{3+}) + (OH, F))$; e.g. Franz and Spear,
 363 1985] is more important on titanite surrounding ilmenite, as shown on Fig. 5b.
 364 Reactions rims of titanite on ilmenite are in contact with amphibole, plagioclase and quartz
 365 (Fig. 3f). The mineral assemblages also include clinopyroxene and sometimes epidote. The
 366 reaction rims of titanite on ilmenite are likely to be due to the following hydration reaction:
 367 clinopyroxene+ilmenite+quartz+ H_2O = amphibole+titanite (Harlov et al., 2006).
 368 Apatite forms dispersed small grains and is classified as fluorapatite (Pasero et al., 2010;
 369 Appendix 4e; Table 1b).
 370 Ilmenite forms disseminated grains and inclusions in amphibole, clinopyroxene and titanite
 371 (Fig. 3d; Appendix 4f). The dispersed grains are unzoned. The highest MnO contents are
 372 observed in ilmenite enclosed in titanite (1.42–1.84 wt.%; Appendix 4f). Sulphides are
 373 pyrrhotite, pyrite and chalcopyrite (Appendix 4f). They are dispersed and their compositions
 374 do not show any significant zoning.

375

5. Whole rock geochemistry

Major and trace element contents from orthogneiss and amphibolite samples from the Sardoa Complex are given in Tables 2 and 3. Considering the deformation and polymetamorphism of these rocks, some mobility of major elements (especially alkali elements) and LILE (Sr, K, Rb, Ba) is to be expected (e.g. Gómez-Pugnaire et al., 2003; Will et al., 2010). Meta-shear zones contain higher values of K, Rb and Ba that were metasomatically introduced via fluids penetrating the shear zones during low amphibolite facies metamorphism (Floyd and Winchester, 1983). Post-magmatic alteration results in mobilisation of many elements including LREE and Th (Polat and Hofmann, 2003). MREE, HREE and HFSE (Ta, Nb, Zr, Hf, Ti and Y) have a relatively immobile behaviour during metamorphism and weathering (e.g. Shatsky et al., 1990; Tang et al., 2007; Will et al., 2010 and references therein). Some of the transition metals (Cr, Ni, Sc and V) are thought to be relatively immobile (Ayuso and Till, 2014 and references therein). In these conditions, care should be taken when using mobile elements. In order to minimize the mobility problem, only unaltered and less deformed samples were selected for analyses. The analysed samples have LOI values in the range of 0.53 to 3.16 wt.%. Most of the orthogneiss units have LOI < 3 wt.% (Table 2) and amphibolite have LOI < 2 wt.% (Table 3), suggesting that they are relatively unaltered (e.g. Le Roex et al., 2010; Polat et al., 2002). The method of Cann (1970) has been used to evaluate the mobility of elements in rocks of basic and intermediate compositions (e.g. Hastie et al., 2007; Polat and Hofmann, 2003). This method is based on the construction of bivariate diagrams with an immobile element on the x-axis (e.g. Nb, Zr) and the evaluated element on the y-axis. If both elements are immobile and incompatible and the samples cogenetic, the degree of correlation should be close to one (Hastie et al., 2007) and not lower than 0.75 (Polat and Hofmann, 2003). For the amphibolite (rocks of basic composition) we have tested

elements of interest that can be mobilised: Sr, Ba, Th and Ce. For comparison, Ta usually considered immobile, is also plotted (Fig. 6). High degree of correlation (R^2) is observed for Ta, Th and Ce and lower for Sr and Ba (Fig.6). Some mobilization of Sr and Ba occurred, particularly in Ba from Vila Nova amphibolite, while Ta, Th and Ce behave as immobile elements.

5.1 Orthogneiss

The orthogneiss units show a granitic to granodioritic composition (Fig. 7a) with SiO_2 contents that range from 63.47 to 70.72 wt.% (Table 2). They are calc-alkaline (Fig. 7b) and peraluminous (Fig. 7c). In the Ta–Yb tectonic setting discrimination diagram of Pearce et al. 1984, all the samples plot in the volcanic arc granite field (Fig. 7d). In the Th/Ta–Yb tectonic setting discrimination diagram of Gorton and Schandl (2000), all the samples plot in the active continental margins field (Fig. 7e).

The chondrite-normalized REE diagram shows subparallel patterns with considerable overlapping (Fig. 8a). The REE contents are 5.33 to 210.55 times chondrite abundances (Table 4). The higher values are shown by Souto orthogneiss, while the lowest values are observed in Olalhas orthogneiss (Table 4). The chondrite-normalized REE patterns show enrichment of LREE relative to MREE $[(\text{La}/\text{Sm})_N=2.85\text{--}4.99]$ and to HREE $[(\text{La}/\text{Yb})_N=5.12\text{--}16.63]$ and of MREE compared to HREE $[(\text{Sm}/\text{Yb})_N=1.69\text{--}4.04]$ (Fig. 8a, Table 4). A negative Eu anomaly is present in all orthogneiss patterns ($\text{Eu}/\text{Eu}^*=0.33\text{--}0.8$) and is controlled by the crystal fractionation of feldspar, particularly plagioclase (Rollinson, 1993; McKay, 1989). The fractionation of LREE is attributed to monazite formation during metamorphism from the breakdown of pre-existing apatite (Villasca et al., 2003), while the igneous zircon retains the HREE (Bea, 1996).

The MORB-normalized spider diagram displays enrichments of LILE, Ce and Sm compared to HFSE (Fig. 8b). The depletion of Sr, Ba, P and Ti may be explained by the fractionation of respectively plagioclase, alkali feldspars, apatite and Fe-Ti oxides (Brown et al., 1984). The MORB-normalized patterns of the orthogneiss are subparallel and overlapped (Fig. 8b). Souto orthogneiss shows the lowest contents of P and highest of Sm, Y and Yb, while Sardoa orthogneiss displays the highest contents of P (Fig. 8b).

5.2 Amphibolite

The amphibolite protoliths have basic compositions ($\text{SiO}_2=45.69\text{--}50.55$ wt.%), are low-Ti ($\text{TiO}_2=0.69\text{--}1.51$ wt.%) and are classified as subalkaline basalt and as andesite/basalt (Table 3, Fig. 9a). In the Th/Yb vs. Ta/Yb diagram of Pearce (1983), adapted by Wilson (1989), the samples fall in MORB and depleted mantle source fields with the influence of a subduction and within-plate components (Fig. 9b). Most of the samples have tholeiitic affinity and two are calc-alkaline but close to the tholeiitic field (Fig. 9b). In order to make an accurate distinction between the possible tectonic settings we used the Th-Hf/3-Ta tectonic setting discrimination diagram of Wood (1980) and the Zr-Ti/100-3Y diagram of Pearce and Cann (1973) (Figs. 9c, 9d). In the first plot, the samples are projected in N-MORB, T- and E-MORB and WPT fields (Fig. 9c). In the second plot, the WPB setting is excluded (Fig. 9d). The Cabeço da Moura amphibolite displays N-, T- and E-MORB affinities, while the Vila Nova amphibolite shows only E-MORB affinities (Fig. 9c).

The chondrite-normalized REE diagram shows subparallel patterns, contents that are 6.13 to 26.67 times chondrite abundances and the Eu anomalies are almost inexistent ($\text{Eu}/\text{Eu}^*=0.93\text{--}1.25$) (Figs. 10a, 10b, Table 4). The Cabeço da Moura amphibolite presents two groups of samples: one group with chondrite-normalized REE patterns subparallel,

identical to E-MORB, with $(\text{La/Sm})_N > 1$ and identical to Vila Nova amphibolite (Fig. 10a, Table 4); a second group with chondrite-normalized REE patterns subparallel, similar to that of N-MORB (Fig. 10b), with $(\text{La/Sm})_N < 1$ and an enrichment of MREE compared to HREE $[(\text{Sm/Yb})_N = 1.09\text{--}1.22]$, attributed to diopside and hornblende fractionation (Reitan et al., 1980; Rollinson, 1993) (Table 4). The Vila Nova amphibolite generally shows chondrite-normalized REE subparallel patterns similar to that of E-MORB (Fig. 10a), low enrichment of LREE relative to MREE $[(\text{La/Sm})_N = 0.77\text{--}1.28]$ and HREE $[(\text{La/Yb})_N = 0.64\text{--}1.73]$ (Table 4).

The MORB-normalized spider diagram shows an enrichment in LILE compared to HFSE and a pattern of HFSE (except for Th, Ta, Nb and Ce) parallel to MORB but at lower level (Figs. 10c, 10d).

6. Whole rock oxygen isotopic data

Whole rock oxygen isotopic data and SiO_2 content of analysed samples are presented in Table 5. Souto orthogneiss, (*ca.* 692 Ma), displays distinct values of $\delta^{18}\text{O}$ (6.74 ‰ and 11.52 ‰), characteristic of mantle and supracrustal sources respectively (Whalen et al., 2006 and references therein). However, previous Rb-Sr and Sm-Nd data support the involvement of metasedimentary and metagneous lower crust (Henriques et al., 2015). In these conditions, it is likely that the low value of $\delta^{18}\text{O} = 6.74$ ‰ results from alteration (e.g. Owen et al., 2003). Most of the orthogneiss units show a narrow range of $\delta^{18}\text{O}$ compositions: Carvalhal (*ca.* 569 Ma; $\delta^{18}\text{O} = 11.67\text{--}11.98$ ‰), Sardoal (*ca.* 548 Ma; $\delta^{18}\text{O} = 10.59\text{--}11.84$ ‰) and Olalhas ($\delta^{18}\text{O} = 11.41\text{--}11.96$ ‰). The values higher than 10 ‰ are indicative of supracrustal sources (Whalen et al., 2006 and references therein).

Sardoal Complex amphibolite shows a wide range of $\delta^{18}\text{O}$ values (5.58–9.85 ‰). The lowest value falls within the MORB range ($\delta^{18}\text{O} = 5\text{--}7$ ‰; Eiler, 2001 and references therein). The increase of $\delta^{18}\text{O}$ with increase of SiO_2 (Table 5) suggests that the samples with higher values of $\delta^{18}\text{O}$ were affected by crustal contamination (e.g. Wilson, 1989 and references therein).

7. Thermodynamic modelling

The phase equilibria modelling was performed on representative samples of orthogneiss units. The P - T diagrams were computed using the Perple_X program (Connolly, 2009) and the thermodynamic dataset of Holland and Powell (1998, revised 2003). The bulk rock compositions used for the calculations are given in mol% in the P - T diagrams (Figs. 11, 12). The following solution models were used: biotite (Tajcmanova et al., 2009), cordierite, staurolite, chlorite and garnet (Holland and Powell, 1998), muscovite (Coggon and Holland, 2002), plagioclase (Newton et al., 1980) and sanidine (Waldbaum and Thompson, 1968). An ideal model was used to account for the Mn and Mg solution in ilmenite. Quartz and sillimanite were considered as pure phases. The representative chemical system may differ for each sample depending on the importance of additional minor components assumed (see details below). The effect of Fe^{3+} was neglected because, although potentially important, no magnetite was present in the samples and the amount of Fe^{3+} present in biotite was assumed to be insignificant. Representative electron microprobe analyses of minerals from selected samples are listed in Appendixes 5a and 5b.

7.1 Souto orthogneiss

Sample 311-53 is fine- to coarse-grained with a porphyroclastic texture. It is characterized by garnet + plagioclase + biotite + muscovite + ilmenite + quartz + chlorite assemblage. Chlorite is a retrogression phase. Plagioclase shows X_{An} content of 0.25–0.27, biotite X_{Mg} ($Mg/(Mg+Fe^{2+})$) of 0.42–0.50 and garnet X_{Mg} of 0.10–0.12. The calculation was made for MnNCKFMASHT (MnO-Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂) chemical system with water in excess. The P - T conditions were estimated based on the compositional isopleths of X_{An} in plagioclase, X_{Mg} in biotite and X_{Mg} in garnet for the observed stability field (Bt-Chl-Pl-Ms-Ilm-Grt-Qtz) at 7–5.5 kbar and 550–560°C (Fig. 11).

7.2 Olalhas orthogneiss

Sample 311-30 is fine- to medium-grained reflecting a transition from a porphyroclastic to mylonitic texture. It is characterized by staurolite + plagioclase + biotite + sillimanite + muscovite + quartz + zircon + pyrite assemblage. Plagioclase shows X_{An} content of 0.12–0.14, biotite X_{Mg} of 0.50–0.52 and staurolite X_{Mg} of 0.16–0.22. Calculations were made for NCKFMASH (Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O) chemical system with water in excess. MnO was not considered in the calculation because when involved it led to a larger stability field of garnet and to modal proportions of phases which were not in agreement with the natural observations. The P - T conditions were estimated based on the pressure dependent compositional isopleths of X_{Mg} in staurolite in the stability field with the observed mineral assemblage (Bt-St-Pl-Ms-Sil-Qtz) at 6.4 kbar and 650 °C (Fig. 12).

8. Discussion

8.1. Petrogenesis of orthogneiss

524

525 The three magmatic pulses that occurred in the range of ca. 692–548 Ma (Henriques et al.,
526 2015) produced calc-alkaline magmas of granitic to granodioritic composition and
527 peraluminous character (Figs. 7a, 7b, 7c). The protoliths of the orthogneiss units were
528 generated in an active continental margin setting as suggested by the tectonic discrimination
529 diagrams of Pearce et al. (1984) and Gorton and Schandl (2000) (Figs. 7d, 7e). This is in
530 agreement with the trace element abundances that show an enrichment of LILE, Ce and Sm
531 compared to HFSE (Fig. 8b), which is a characteristic of subduction-related magmas. The
532 enriched elements are transferred to the mantle wedge by partial melt or fluid-transfer
533 processes associated with the dehydration of the subducted slab (Wilson, 1989 and references
534 therein). Chondrite-normalized REE and MORB-normalized diagrams display subparallel
535 patterns with considerable overlapping for different orthogneiss units (Figs. 8a, 8b). These
536 data suggest that magmas generated in different stages of the Cadomian arc activity (*ca.*
537 692–548 Ma) have identical major and trace element compositions. The MORB-normalized
538 patterns of the orthogneiss units are similar to the pattern of the bulk continental crust (Fig.
539 8b). This is consistent with the Sr and Nd isotopic signature that indicates partial melting of
540 old metasedimentary and meta-igneous crust at different crustal levels (Henriques et al., 2015)
541 and with the $\delta^{18}\text{O}$ values (10.59–11.98) indicative of supracrustal sources. Fractional
542 crystallization of plagioclase, alkali feldspars, apatite, zircon and Fe-Ti oxides was an
543 important process in the petrogenesis of the protoliths of the orthogneiss units as shown by
544 chondrite-normalized REE and MORB-normalized diagrams (Figs. 8a, 8b).

545

546 **8.2. Petrogenesis of amphibolite**

547

Most of the protoliths of the amphibolite are low-Ti, tholeiitic basalts and only two have a calc-alkaline signature (Figs. 9a, 9b). They have N-, T- and E-MORB affinities, displayed by tectonic discrimination diagrams of Pearce and Cann (1973) and Wood (1980) (Figs. 9c, 9d). This is in agreement with the ratios of $(La/Sm)_N$ (Table 4). The chondrite-normalized REE and MORB-normalized diagrams show subparallel patterns for the N- and E-MORB groups, suggesting a common source (Fig. 10). It corresponds to a depleted mantle source with the influence of a subduction and within-plate components (Fig. 9b). Crustal contamination is also suggested by the higher values of the $\delta^{18}O$ range (5.58–9.85 ‰) and by the increase of $\delta^{18}O$ with increase of SiO_2 (Table 5; e.g. Wilson, 1989 and references therein). Although, MORB-normalized diagrams show some identical features to the modern island arcs (Figs. 10c, 10d), the enrichments of Ta and Nb relative to MORB and the high concentrations of Ta and Nb relative to Zr and Hf are characteristic of active continental margin setting (Pearce, 1983). Fractional crystallization of diopside and hornblende is observed only in the N-MORB group and the low ratio of $(Sm/Yb)_N$ (Table 4) suggests that it was not significant in their petrogenesis. This might explain the depletion observed in some of the HFSE elements.

8.3. Metamorphism

The *P-T* conditions of the Cabeço da Moura amphibolite indicate metamorphism under amphibolite facies near the transition to the granulite facies at *ca.* 540 Ma ($P=7\text{--}8$ kbar and $T=640\text{--}660^\circ\text{C}$; Henriques et al., 2015). The *P-T* conditions of Souto and Olalhas orthogneiss units ($7\text{--}5.5$ kbar and $550\text{--}560^\circ\text{C}$; 6.4 kbar and 650°C ; Figs. 11, 12) indicate metamorphism under amphibolite facies conditions, at *ca.* 540 Ma. The magmatic origin of the protoliths from the Sardaoal Complex orthogneiss units is indicated by relict igneous textures,

plagioclase composition (porphyroclasts usually display higher anorthite content than the matrix) and K-feldspar composition (porphyroclasts usually show higher BaO content than the matrix). Plagioclase and K-feldspar compositions were not significantly affected by the metamorphism. The compositions of biotite, garnet and staurolite suggest the occurrence of metamorphic re-equilibration.

The *P-T* conditions for the Variscan metamorphic event were not determined. However, the Variscan metamorphic event is not high enough to significantly reset the Cadomian metamorphic ages of zircon, monazite or titanite. One piece of evidence is that the titanite is concordant at ca. 529 Ma (Henriques et al., 2015), and it would be re-set in a strong Variscan metamorphism of upper amphibolite grade or higher. The best interpretation is that the Variscan event here is greenschist grade or lower amphibolite. Greenschists facies retrogression is observed in Cabeço da Moura and Vila Nova amphibolite. This retrogression is represented by hydration reactions that led to partial replacement of diopside by actinolite, development of titanite rims on ilmenite and formation of clinozoisite. The timing of the greenschists facies retrogression is not yet geochronologically constrained. However, the Paleozoic cover exposed within the Tomar-Badajoz-Córdoba Shear Zone is re-crystallized under low-*P* amphibolite to greenschist facies (Ribeiro et al., 2010 and references therein), suggesting that the greenschists facies metamorphism occurred during the Variscan orogeny.

9. Summary and conclusions

The magmatic activity of the Cadomian arc recorded in the Sardaoal Complex indicates a long-lived continental arc (ca. 692-540 Ma), that generated mostly calc-alkaline magmas of acid composition. The most significant processes in their petrogenesis are the partial melting of old metasedimentary and meta-igneous crust at different crustal levels and the fractional

598 crystallization. The protoliths of the orthogneiss units show trace element contents identical to
599 the bulk continental crust, which is consistent with a mature continental arc (e.g. Ducea et al.,
600 2015 and references therein). A modern example of a long-lived continental arc is represented
601 by the Andes, where five episodes of igneous activity were recognized (ca. 248-21 Ma;
602 McCourt et al., 1984). In the Sardoal Complex three magmatic events of acid composition
603 were identified at ca. 692 Ma, ca. 569 Ma and ca. 548 Ma and coeval magmatism is observed
604 in several areas of the Avalonian-Cadomian belt (Henriques et al., 2015 and references
605 therein). However, the Sardoal Complex represents a particular case where the multistage of
606 Cadomian magmatism is observed.

607 Coeval felsic and mafic magmatism is commonly observed in active continental margin
608 setting (e.g. Wilson, 1989). Basic magmatism with an active continental margin signature is
609 represented by the protoliths of the amphibolite. Their igneous crystallization age is unknown,
610 but their metamorphic age allows us to establish it prior to ca. 540 Ma. The protoliths of the
611 amphibolite show a tholeiitic signature that prevails over the calc-alkaline signature and N-,
612 T- and E-MORB affinities. They were generated from a depleted mantle source with the
613 influence of a subduction and within-plate components.

614 In other areas of the Ossa Morena Zone two major phases of Cadomian deformation and
615 metamorphism were recognized (e.g. Eguíluz and Ábalos, 1992). The Sardoal Complex is a
616 tectonostratigraphic unit, bounded by NW-SE thrust faults and was metamorphosed under
617 medium pressure/high temperature conditions at ca. 540 Ma, the final stage of the Cadomian
618 metamorphism. This stage is represented in other areas of the Cadomian basement as a LP-
619 HT metamorphic event: in the Ossa Morena Zone (e.g. Eguíluz and Ábalos, 1992), in the
620 Armorican Massif (e.g. Ballèvre et al., 2001; Linnemann et al., 2008b and references therein)
621 and in the Bohemian Massif (e.g. Zulauf et al., 1999). These data suggest that the Sardoal

Complex represents a deeper level of the exhumed Cadomian basement where the final stage of the Cadomian metamorphism was recorded.

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 1082

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

1-Bt Chl Pl Ms Grt Zo Ttn Qtz; 2-Bt Chl Pl Ms Grt Zo Ttn Qtz Rt; 3-Bt Chl Pl Ms Grt Zo Qtz Rt; 4- Bt Chl Pl Ms Grt Ttn Qtz;
 5-Bt Chl Pl Ms Ilm Grt Zo Ttn Qtz; 6-Bt Chl Pl Ms Ilm Zo Qtz Rt; 7-Bt Chl Pl Ms Ilm Grt Ttn Qtz; 8-Bt Chl Pl Ms Ilm Zo Ttn Qtz Rt;
 9-Bt Chl Pl Ms Ilm Zo Qtz Rt; 10-Bt Chl Pl Ms Ilm Zo Ttn Qtz; 11-Bt Chl Pl Ms Ilm Ttn Qtz; 12-Bt Chl Pl Ms Ilm Ttn Qtz Rt;
 13- Bt Pl Ms Pg Ilm Grt Qtz Rt; 14- Bt Pl Ms Pg Grt Qtz Rt; 15- Bt St Pl Ms Pg Ilm Grt Qtz Rt; 16- Bt St Pl Ms Ilm Grt Qtz Rt; 17- Bt St Pl Ms Pg Grt Qtz Rt;
 18-Bt St Pl Ms Grt Qtz Rt; 19-Bt St Pl Ms Grt Ky Qtz Rt; 20-Bt Pl Ms Grt Ky Qtz Rt; 21-Bt Pl Ms Ilm Grt Ky Qtz Rt;
 22-Bt St Pl Ms Pg Ilm Grt Qtz; 23-Bt St Pl Ms Ilm Grt Ky Qtz; 24-Bt St Pl Ms Ilm Grt Sil Qtz; 25-Bt Chl St Pl Ms Pg Ilm Grt Qtz;
 26- Bt Chl St Pl Ms Ilm Grt Qtz; 27-Bt Chl St Pl Ms Ilm Qtz; 28-Bt Chl Pl Ms Ilm Grt And Qtz; 29-Bt Chl St Pl Ms Ilm Grt And Qtz; 30-Bt Pl Ms Ilm Grt And Qtz;
 31-Bt Chl St Pl Ms Ilm And Qtz; 32-Bt St Pl Ms Ilm And Qtz; 33-Bt St Pl Ms Ilm Grt And Qtz; 34-Bt St Pl Ms Ilm Qtz;

Fig. 11

Fig. 12

Fig. 1. (a) Location of the studied area in the Iberian Massif. Subdivisions of the Iberian Massif after Ribeiro (2013); Location of Olivenza-Monesterio Antiform is from Eguíluz et al. (2000). (b) Location of representative samples (Tables 2 and 3) in the geological map adapted from Zbyszewski et al. (1983), Conde (1984), Romão and Esperancinha (2000) and Romão et al. (2014). Projection system: ETRS_1989_Portugal_TM06.

Fig. 2. Or–An–Ab ternary diagram showing plagioclase compositions of orthogneisses from Sardoal Complex.

Fig. 3. Petrographic and mineralogical features of the studied rocks. (a) Garnet porphyroclasts showing mostly inclusions of quartz. (b) Prismatic sillimanite surrounded by muscovite (Olalhas orthogneiss). (c) Staurolite porphyroclasts surrounded by fibrolitic sillimanite and muscovite. (d) Fine-grained and granoblastic texture observed in Cabeço da Moura da Moura amphibolite. (e) BSE image showing actinolite partially replacing diopside and location of microprobe analysis in plagioclase. A decrease in An content is observed from core to rim: points n° 19 (An₅₅), 18 (An₄₈) and 17 (An₃₇) indicate location analyses. (f) BSE image showing reaction rims of titanite on ilmenite, which are in contact with amphibole, plagioclase and quartz. Mineral abbreviations from Siivola and Schmid (2007): Act, Actinolite; Alm, Almandine; Am, Amphibole; Bt, Biotite; Di, Diopside; Ilm, Ilmenite; Mg-Hbl, Magnesiohornblende; Ms, Muscovite; Pl, plagioclase; Qtz, Quartz; Sil, Sillimanite; St, Staurolite; Ttn, Titanite.

Fig. 4. Chemical compositions of amphibole, plagioclase and pyroxene from amphibolites. (a) Plot of amphibole compositions in the diagram of Leake et al. (1997). (b) Plot of plagioclase compositions in the Or–An–Ab ternary diagram. (c) Plot of clinopyroxene compositions in

the Wo-En-Fs diagram of Morimoto (1988). (d) TiO_2 (wt.%) and CaO (wt.%) vs. Al_2O_3 (wt.%) plots showing higher contents of TiO_2 (wt.%) in Cabeço da Moura amphibolite and higher contents of CaO (wt.%) in Vila Nova amphibolite. En, Enstatite; Fs, Ferrosilite; Wo, wollastonite.

Fig. 5. Chemical composition of titanite rims surrounding ilmenite and dispersed titanite grains from Sardoal Complex amphibolites. (a) F (apfu) vs $\text{Al}+\text{Fe}^{3+}$ (apfu) plot (Enami et al., 1993) for metamorphic titanite from this study and metasomatic titanite from Gière (1992). (b) Ti (apfu) vs $\text{Al}+\text{Fe}^{3+}$ (apfu) plot showing a high degree of correlation (R^2) for titanite rims surrounding ilmenite, which represents the following chemical substitution: $\text{Ti}+\text{O} \leftrightarrow (\text{Al}, \text{Fe}^{3+})+(\text{OH}, \text{F})$ (e.g. Franz and Spear, 1985).

Fig. 6. Trace elements vs Nb (ppm) plots showing an immobile behaviour of Ta, Th and Ce (high degree of correlation: R^2) and some mobilization of Sr and Ba (lower R^2).

Fig. 7. Major and trace elements diagrams for Sardoal Complex orthogneisses. (a) Classification diagram of La Roche et al. (1980). R1 and R2 calculated from millication proportions. (b) AFM diagram (Wilson, 1989). $\text{A}=\text{Na}_2\text{O}+\text{K}_2\text{O}$ (wt.%), $\text{F}=\text{FeO}+\text{Fe}_2\text{O}_3$ (wt.%), $\text{M}=\text{MgO}$ (wt.%). (c) A/KN vs A/CNK diagram from Maniar and Piccoli (1989). A/NK and A/CNK ratios from Shand (1947). (d) Ta vs Yb discrimination diagram of Pearce et al. (1984). Syn-COLG: syn-collisional; VAG: volcanic arc granites; WPG: within-plate granites; ORG: ocean-ridge granites. (e) Th/Ta vs Yb discrimination diagram of Gorton and Schandl (2000). WPB: Within-plate basalts; WPVZ: Within-plate volcanic zones.

Fig. 8. Chondrite and MORB normalized trace element patterns for Sardao Complex orthogneisses. (a) Chondrite-normalized REE patterns. Normalizing values of Sun and McDonough (1989). (b) MORB-normalized patterns. Normalizing values of Pearce (1983). Continental crust values of Wedepohl (1995).

Fig. 9. Trace element diagrams for Sardao Complex amphibolites. (a) Classification diagram of Winchester and Floyd (1977). (b) Th/Yb vs Ta/Yb diagram of Pearce (1983) adapted by Wilson (1989). Vectors show the influence of the following components: s, subduction; c, crustal contamination; w, within-plate enrichment; f, crystal fractional crystallization. (c) Discrimination diagram of Wood (1980). (d) Discrimination diagram of Pearce and Cann (1973). Abbreviations: WPT, Within-plate tholeiites; WPA, Alkaline within-plate basalts; IAT, Island-arc tholeiites; CAB, Calc-alkaline arc basalts; WPB, Within-plate basalts.

Fig. 10. Chondrite- and MORB- normalized trace element patterns for Sardao Complex amphibolites. (a), (b) Chondrite-normalized REE patterns for N- and E-MORB amphibolites. Normalizing values of Sun and McDonough (1989). For comparison the N- and E-MORB patterns of Sun and McDonough (1989) were also plotted. (c), (d) MORB-normalized patterns for N- and E-MORB amphibolites. Normalizing values of Pearce (1983).

Fig. 11. (a, b) P - T diagram for sample 311-53, Souto orthogneiss, calculated for MnNCKFMASHT system. The ellipse represents the estimated P - T conditions in the observed stability field.

73 **Fig. 12.** (a, b) P - T diagram for sample 311-30, Olalhas orthogneiss, calculated for
74 NCKFMASH system. The ellipse represents the estimated P - T conditions in the observed
75 stability field.

Table 1a
Mineral chemistry features of Sardoal Complex orthogneiss.

Minerals		Souto		Carvalhal		Sardoal		Olalhas	
Plagioclase		An Porph	17–29	An Porph	15–33	An Porph	11–27	An Porph	12–26
		An Matrix	18–26	An Matrix	17–21	An Matrix	10–25	An Matrix	14–18
K-feldspar		Or Porph	–	Or Porph	89–97	Or Porph	87–97	Or Porph	96
		BaO Porph	–	BaO Porph	0.54–1.02	BaO Porph	0.47–1.73	BaO Porph	0.28–0.43
		Or Matrix	99	Or Matrix	91–98	Or Matrix	97	Or Matrix	98–99
		BaO Matrix	0.12–0.33	BaO Matrix	0–0.91	BaO Matrix	0.50–1.00	BaO Matrix	0.15–0.17
Biotite	Porph	X _{Mg} : 0.42–0.53 Mg:Fe: 0.79–1.12 Al ^{VI} : 0.298–0.620 Fe _t /Fe _t + Mg: 0.491–0.577		X _{Mg} : 0.42–0.50 Mg:Fe: 0.72–1.01 Al ^{VI} : 0.290–0.456 Fe _t /Fe _t + Mg: 0.520–0.598		X _{Mg} : 0.42–0.51 Mg:Fe: 0.71–1.03 Al ^{VI} : 0.261–0.508 Fe _t /Fe _t + Mg: 0.514–0.604		X _{Mg} : 0.43–0.52 Mg:Fe: 0.77–1.10 Al ^{VI} : 0.290–0.411 Fe _t /Fe _t + Mg: 0.497–0.581	
	Matrix	X _{Mg} : 0.44–0.52 Mg:Fe: 0.77–1.08 Al ^{VI} : 0.316–0.411 Fe _t /Fe _t +Mg: 0.500–0.586		X _{Mg} : 0.41–0.52 Mg:Fe: 0.69–1.08 Al ^{VI} : 0.245–0.415 Fe _t /Fe _t + Mg: 0.510–0.609		X _{Mg} : 0.39–0.49 Mg:Fe: 0.64–0.95 Al ^{VI} : 0.242–0.463 Fe _t /Fe _t + Mg: 0.527–0.614		X _{Mg} : 0.45–0.50 Mg:Fe: 0.82–1.00 Al ^{VI} : 0.334–0.393 Fe _t /Fe _t + Mg: 0.525–0.566	
	Inc. gt	–		–		–		X _{Mg} : 0.34–0.48 Mg:Fe: 0.52–0.93 Al ^{VI} : 0.329–0.423 Fe _t /Fe _t + Mg: 0.542–0.674	
Garnet	Porph	Alm = 62.9–67.5 Adr = 0.0–0.8 Grs = 5.5–8.2 Prp = 7.9–10.9 Sps = 14.0–20.6 Uv = 0.0–0.3 X _{Mg} = 0.11–0.14		–		–		Alm = 76.3–78.5 Adr = 0.0–1.6 Grs = 1.1–3.2 Prp = 9.9–13.9 Sps = 5.5–10.7 Uv = 0.0–0.2 X _{Mg} = 0.11–0.15	
	Matrix	Alm = 65.5–67.8 Adr = 0.0–0.7 Grs = 4.5–7.2 Prp = 9.7–10.3 Sps = 16.2–17.2 Uv = 0.1–0.3 X _{Mg} = 0.13		–		–		–	
Sillimanite		Fibrolitic		–		Fibrolitic		Fibrolitic; Prismatic	
Staurolite		–		–		–		X _{Mg} Porph	0.16–0.22
								X _{Mg} Matrix	0.16–0.19
Apatite		Fluorapatite F=0.734–0.807 Cl=0.009–0.029 OH=0.184–0.237		Fluorapatite F=0.797–1.119 Cl=0.000–0.011 OH=0.000–0.193		Fluorapatite F=0.747–1.189 Cl=0.000–0.006 OH=0.000–0.252		Fluorapatite F=0.594–0.665 Cl=0.000–0.028 OH=0.307–0.406	
Oxides		Ilmenite		Ilmenite, magnetite, arsenopyrite,		Ilmenite, magnetite, pyrite, pyrrhotite		Ilmenite, pyrite, rutile	

Porph: porphyroclasts; (–) absent; An, Or (mol %); BaO (wt%); Al^{VI}, F, Cl, OH (*apfu*); X_{Mg}=Mg/(Mg+Fe²⁺); inc. gt: included in garnet; Alm, Adr, Grs, Prp, Sps and Uv are in mol %; An: anorthite; Or: orthoclase; Alm: almandine; Adr: andradite; Grs: grossular; Prp: pyrope; Sps: spessartine; Uv: uvarovite.

Table 1b

Mineral chemistry features of Sardaoal Complex amphibolite.

Minerals		Cabeço da Moura	Vila Nova
Amphibole	Magnesiohornblende	Mg/(Mg+Fe ²⁺)=0.52–0.68; Si=6.62–7.50	Mg/(Mg+Fe ²⁺)=0.51–0.66; Si=6.52–7.43
	Ferrohornblende	Mg/(Mg+Fe ²⁺)=0.37–0.40; Si=6.54–6.72	–
	Actinolite	Mg/(Mg+Fe ²⁺)=0.65–0.74; Si=7.50–7.78	–
	Pargasite	–	Mg/(Mg+Fe ²⁺)=0.50–0.62; Si=6.24–6.37
	Ferropargasite	–	Mg/(Mg+Fe ²⁺)=0.49; Si=6.24–6.25
	Edenite	–	Mg/(Mg+Fe ²⁺)=0.56–0.73; Si=6.53–7.56
Plagioclase		An=37–92	An=47–61
Clinopyroxene	Diopside	Wo _{46–49} En _{34–38} Fs _{14–19} X _{Mg} =0.65–0.74	Wo _{48–50} En _{29–36} Fs _{14–21} X _{Mg} =0.62–0.75
	Hedenbergite	Wo _{47–50} En _{23–27} Fs _{25–29} X _{Mg} =0.44–0.53	–
	Augite	Wo _{28–41} En _{36–38} Fs _{22–34} X _{Mg} =0.53–0.63	–
Epidote (clinozoisite)		X _{Fe} =0.14–0.17	X _{Fe} =0.11–0.13
Titanite	Grains	X _{Al} = 0.03–0.04 F=0.00–0.17 wt. % Fe ₂ O _{3T} =0.28–0.62 wt. %	Grains X _{Al} =0.04–0.06 F=0.00–0.28 wt. % Fe ₂ O _{3T} =0.18–0.37 wt. %
	Rims	X _{Al} =0.03–0.06 F=0.00–0.20 wt. % Fe ₂ O _{3T} =0.11–0.26 wt. %	Rims X _{Al} =0.06 F=0.00–0.18 wt. % Fe ₂ O _{3T} =0.22–0.26 wt. %
Apatite		Fluorapatite F=0.564–0.576 Cl=0.014–0.073 OH=0.351–0.422	Fluorapatite F=0.491–0.511 Cl=0.028–0.072 OH=0.437–0.461
Oxides		Ilmenite	Ilmenite, pyrrhotite, pyrite and chalcopyrite

(–) absent; An, Wo, En, Fs (mol %); Si, F, Cl, OH (apfu) X_{Fe}= Fe³⁺/Al³⁺; X_{Al}= Al/(Al+Ti+Fe³⁺); An: anorthite; Wo: wollastonite; En: enstatite; Fs: ferrosilite.

Table 2
Whole rock chemical compositions of Sardoal Complex orthogneisses.

Orthogneiss	Souto						Carvalho								Sardoal						Olalhas				
Sample	311-59	311-15	311-66	311-56	321-140b	311-53	1A	100	124	322-15	125	gn	84B	5A	321-27	am4	322-AF6	10	102B	311-30	311-6	311-32B	311-37	311-31	
SiO ₂ (wt.%)	66.08	65.54	65.19	66.90	69.50	66.11	67.58	68.90	69.81	67.53	68.47	70.72	68.06	66.95	68.43	65.51	69.57	64.88	67.00	64.84	68.87	64.89	63.47	67.48	
TiO ₂	0.64	0.75	0.76	0.75	0.45	0.78	0.56	0.67	0.55	0.54	0.57	0.46	0.62	0.71	0.62	0.67	0.59	0.74	0.65	0.74	0.66	0.79	0.99	0.64	
Al ₂ O ₃	16.29	15.40	16.56	16.31	15.47	16.26	14.89	15.33	13.89	15.01	14.80	13.90	14.95	15.40	15.08	16.22	14.70	15.74	15.18	15.61	15.24	15.98	16.66	15.71	
Fe ₂ O ₃	1.58	2.07	1.75	0.71	0.98	1.53	0.24	0.57	1.27	0.64	0.65	0.01	0.67	1.63	0.91	0.72	1.48	0.39	0.86	0.82	0.08	1.57	1.10	2.38	
FeO	2.55	2.74	3.66	3.99	2.78	3.81	3.43	3.90	2.54	3.32	3.14	2.97	3.51	3.32	3.22	3.42	2.40	4.50	3.28	4.67	3.62	3.85	5.29	2.36	
MnO	0.05	0.04	0.06	0.05	0.04	0.07	0.05	0.04	0.05	0.05	0.05	0.04	0.05	0.05	0.04	0.04	0.05	0.05	0.05	0.04	0.05	0.05	0.08	0.04	
MgO	1.68	1.87	2.03	2.02	1.36	2.18	1.59	1.75	1.52	1.64	1.51	1.17	1.70	1.91	1.79	1.72	1.51	2.06	1.81	2.45	1.32	2.25	2.19	1.64	
CaO	1.30	0.89	1.08	1.37	1.36	1.69	1.20	0.88	1.47	1.90	1.26	1.33	1.10	1.45	1.02	1.11	0.84	1.82	1.71	0.72	1.30	1.04	1.15	0.85	
Na ₂ O	3.77	2.56	2.83	2.84	3.51	3.04	3.30	4.07	3.45	4.10	3.28	3.17	3.03	3.18	2.75	3.60	3.06	3.02	3.01	2.34	3.11	2.66	3.03	2.60	
K ₂ O	2.73	3.30	3.76	3.26	2.61	2.72	4.17	2.49	2.77	2.48	3.44	3.56	3.01	3.03	3.35	3.43	3.57	3.05	3.39	3.36	3.76	2.98	3.20	3.09	
P ₂ O ₅	0.11	0.05	0.14	0.06	0.08	0.12	0.12	0.15	0.15	0.17	0.19	0.19	0.16	0.13	0.13	0.19	0.20	0.42	0.20	0.11	0.24	0.07	0.09	0.19	
LOI	1.84	2.81	1.92	1.79	1.60	2.10	1.62	1.28	1.12	0.69	1.22	1.06	1.41	1.51	1.97	1.49	1.45	1.70	1.01	2.33	1.54	2.72	1.90	3.16	
Total	98.62	98.01	99.74	100.06	99.74	100.41	98.75	100.03	98.59	98.07	98.58	98.58	98.27	99.27	99.31	98.11	99.42	98.37	98.15	98.03	99.78	98.84	99.15	100.14	
Sc (ppm)	11	15	14	13	10	15	9	11	10	10	11	8	11	13	12	12	13	13	11	14	11	16	22	12	
Be	3	2	3	2	2	2	2	2	2	3	1	1	2	2	3	2	3	3	2	3	3	3	—	2	
V	89	118	107	112	70	120	72	81	72	67	69	54	92	98	97	83	78	96	81	144	58	139	142	92	
Cr	60	80	70	70	40	70	70	70	60	70	70	60	60	60	60	60	60	60	80	90	30	80	90	70	
Co	7	7	11	7	5	7	12	16	9	12	13	9	12	12	8	6	6	13	9	15	5	12	11	6	
Cu	20	40	20	30	10	20	10	20	10	—	—	—	30	30	10	10	—	20	—	40	—	30	30	30	
Zn	120	110	100	100	70	80	70	70	60	70	70	40	60	70	80	60	70	80	70	90	60	100	100	60	
Ga	18	21	21	19	20	20	15	18	17	18	17	15	18	19	19	19	19	20	20	20	18	20	20	20	
Ge	1.7	1.5	1.8	1.4	1.7	1.6	1.3	1.7	1.6	2	1.9	1.8	1.8	1.8	1.5	1.8	1.7	1.5	1.7	1.5	1.5	1.5	1.9	1.7	
Rb	103	86	122	90	68	82	143	100	93	106	124	99	111	107	111	120	117	108	124	107	119	84	98	94	
Sr	233	194	202	192	184	225	267	231	253	266	261	239	207	182	174	199	153	194	224	125	157	168	222	159	
Y	20.2	27.6	40.2	28.2	26.7	26	18.7	23.7	19.2	19.9	20.3	16.5	23.9	31.3	17.4	20.4	20.4	34.7	24.5	29	15.5	30.7	33.5	24.6	
Zr	190	240	215	214	144	229	231	243	206	187	194	220	289	246	183	277	173	247	255	242	202	222	270	207	
Nb	11.8	15.7	14.8	11.8	11.8	13.8	12.8	14.1	11.6	15.5	13	10.5	12.6	13.8	13.7	13.5	12.6	13.6	14.1	12.5	10.6	14.3	16	13.4	
Sn	2	1	3	2	—	—	2	3	5	3	6	5	3	2	3	5	6	2	3	2	5	—	—	4	
Cs	5.3	2.3	7.7	3.2	2.4	3.1	2.3	7.9	7.6	7.5	8.8	6.1	5.7	4.5	5.9	8.7	11.7	3.6	6.8	5.4	5.5	2.3	2.8	4.9	
Ba	605	913	823	824	799	851	664	699	723	382	809	840	828	770	889	714	658	751	862	828	758	850	1109	800	
La	30.6	49.9	43.3	36.8	26.8	39.1	29.5	36.5	26.8	32.8	30.2	29.5	38.2	42.7	39.9	40.8	26.4	31.2	37.6	29.8	14.5	33	47.7	31.6	
Ce	56.4	86.9	75.6	72.1	46.4	65.9	56.7	69.2	52	61.9	57.1	56.2	73.3	82.5	62.4	76.7	52.9	61.2	72.3	58.4	32.5	63.1	88.6	60.3	
Pr	7.3	11.6	10.1	9.09	6.67	10.6	6.79	8.17	6.24	7.01	6.77	6.9	8.73	9.35	7.07	8.73	6.45	7.18	8.19	7.22	4.33	7.92	10.8	7.38	
Nd	25.7	41.7	36.6	32.5	23.9	36.7	24.8	30.1	22.9	25.9	24.8	24.1	32.4	35	26.6	32.7	24.7	28.1	30.8	27.6	15.4	30	40	27.5	
Sm	5.01	8.41	7.41	6.45	5.07	7.35	4.76	5.77	4.4	5.04	4.81	4.35	6.15	6.86	5.16	6.4	4.33	6.39	6.09	5.76	3.28	5.81	7.54	5.3	
Eu	1.14	1.51	1.35	0.953	0.853	1.21	0.989	1.18	0.974	1.12	1.1	0.718	1.29	1.31	1.08	1.37	1	1.21	1.17	1.07	0.309	1.28	1.8	1.11	
Gd	4.02	6.87	6.37	5.14	4.35	5.11	3.85	4.8	3.76	3.99	3.88	3.37	5.09	5.7	3.94	5.21	4.26	6.41	5.08	4.99	2.53	5.16	6.27	4.38	
Tb	0.64	1.09	1.12	0.87	0.74	0.85	0.59	0.74	0.61	0.63	0.64	0.53	0.79	0.91	0.55	0.76	0.71	1.08	0.79	0.87	0.44	0.86	0.96	0.72	
Dy	3.65	5.6	6.68	5.24	4.54	4.99	3.44	4.21	3.47	3.45	3.6	3.11	4.51	5.17	3.05	4.07	4.33	6.52	4.27	4.94	2.82	5.1	5.55	4.2	
Ho	0.73	0.98	1.39	1.01	0.88	0.96	0.68	0.82	0.67	0.66	0.7	0.6	0.87	1.04	0.59	0.72	0.88	1.24	0.8	0.97	0.58	1.03	1.12	0.82	
Er	2.09	2.76	4.28	2.91	2.54	2.76	1.92	2.37	1.95	1.88	2.03	1.74	2.44	3.1	1.71	1.94	2.66	3.47	2.29	2.86	1.75	3.06	3.46	2.44	
Tm	0.32	0.40	0.65	0.45	0.38	0.43	0.29	0.36	0.29	0.28	0.31	0.26	0.37	0.47	0.26	0.28	0.41	0.51	0.34	0.43	0.28	0.48	0.54	0.37	
Yb	2.13	2.62	4.23	3.11	2.51	2.95	1.97	2.43	2.03	1.88	2.18	1.83	2.51	3.19	1.76	1.76	2.85	3.32	2.21	2.9	2.03	3.26	3.76	2.51	
Lu	0.35	0.42	0.69	0.50	0.40	0.47	0.31	0.38	0.32	0.29	0.35	0.28	0.41	0.53	0.29	0.27	0.48	0.53	0.36	0.46	0.33	0.53	0.62	0.41	
Hf	4.3	5.6	5.0	5.1	3.8	5.3	4.9	5.3	4.4	4.2	4.2	5.0	6.4	5.5	4.0	6.1	4.1	5.6	5.7	5.2	4.8	4.8	5.7	4.5	
Ta	0.94	0.95	1.24	1.05	0.92	1.19	1.02	1.13	1.15	1.5	1.42	1.41	1.04	1.09	0.83	1.21	0.92	0.98	1.24	0.92	1.46	0.99	0.83	1.18	
Th	8.44	11.2	12.2	12.3	6.76	9.93	9.39	10.4	8.67	9.61	8.87	8.41	11	12.3	10.8	11.6	8.57	8.74	11.4	9.47	10.2	10.4	14.3	10.2	
U	2.94	3.41	3.18	3.56	2.35	3.61	2.72	2.83	2.59	3.2	3.11	3.49	2.8	3.99	3.19	3.26	3.67	3.05	3.07	3.83	4.72	3.31	2.28	3.46	

— below the detection limit.

Table 3

Whole rock chemical compositions of Sardaoal Complex amphibolites.

Amphibolite	Cabeço da Moura					Vila Nova					
Sample	311-1	311-34	311-4	311-29	311-20A	311-54	311-68A	311-62	311-67	311-55B	321-37A
SiO ₂ (wt.%)	47.65	50.03	49.16	49.24	49.47	48.72	45.69	48.87	47.38	50.55	47.64
TiO ₂	1.37	1.19	1.17	1.49	1.12	1.51	0.69	1.31	1.06	1.29	1.07
Al ₂ O ₃	15.22	14.86	15.71	15.40	16.06	14.21	17.31	15.17	16.84	14.36	15.37
Fe ₂ O ₃	0.65	1.77	0.98	1.82	1.09	1.13	1.54	1.38	1.23	0.91	0.91
FeO	9.71	8.07	8.07	8.40	8.18	9.60	7.14	8.02	7.84	8.35	7.80
MnO	0.19	0.15	0.14	0.17	0.15	0.17	0.13	0.16	0.16	0.16	0.15
MgO	7.97	7.76	7.88	7.17	7.88	7.19	5.99	7.42	7.74	7.75	6.84
CaO	13.11	11.58	11.84	12.24	13.00	11.40	16.69	13.25	11.50	11.52	15.00
Na ₂ O	2.00	3.07	2.63	2.46	0.66	2.30	2.10	2.07	2.29	2.65	2.34
K ₂ O	0.22	0.23	0.32	0.40	0.69	0.48	0.25	0.29	0.52	0.33	0.24
P ₂ O ₅	0.13	0.09	0.11	0.10	0.07	0.13	0.04	0.11	0.08	0.13	0.07
LOI	0.53	1.11	1.00	0.65	1.41	0.92	2.21	0.96	2.04	1.48	1.18
Total	98.75	99.89	99.00	99.54	99.78	97.76	99.79	99.01	98.67	99.49	98.61
Sc (ppm)	48	43	43	47	36	45	33	46	39	45	41
V	318	302	288	315	237	335	204	303	252	286	260
Cr	350	300	290	130	610	100	270	350	360	180	420
Co	45	46	42	44	55	48	40	45	48	43	45
Ni	20	50	70	40	260	60	140	80	160	50	140
Cu	80	70	50	20	—	130	60	90	110	150	70
Zn	150	80	80	80	100	100	70	80	70	70	60
Ga	16	15	16	17	15	16	14	16	14	14	14
Ge	1.7	1.5	1.4	1.9	1.6	1.9	1.5	2.2	1.9	1.7	1.7
Rb	2	1	4	7	19	5	6	6	11	4	3
Sr	137	208	195	188	278	179	276	186	242	187	331
Y	27	21.5	24.7	29.5	19.4	26.5	15.5	23.9	21	22	20.1
Zr	69	74	69	98	79	93	31	80	65	76	57
Nb	4	6.2	4.3	4.6	6.2	8.6	2.5	9	5.9	5.9	3.6
Cs	0.4	1.2	1.3	0.4	3.7	0.5	6.5	8.7	0.9	4.8	0.2
Ba	9	64	39	16	141	84	36	106	127	103	28
La	3.23	5.86	3.35	3.76	4.84	6.32	1.53	5.91	4.33	5.08	3.09
Ce	9.31	12.7	8.69	9.97	11.2	14.6	3.75	13.2	9.88	11.9	7.84
Pr	1.37	1.81	1.46	1.75	1.73	2.26	0.65	2.13	1.63	1.91	1.34
Nd	7.69	8.23	7.68	9.43	7.87	10.8	3.48	10.2	7.75	9.04	6.26
Sm	2.6	2.42	2.59	3.28	2.35	3.24	1.29	2.97	2.34	2.74	2.14
Eu	1.02	0.929	0.999	1.28	0.799	1.09	0.646	1.08	0.94	1.02	0.831
Gd	3.86	3.09	3.4	4.24	2.96	3.99	1.93	3.61	3.02	3.38	2.8
Tb	0.74	0.59	0.66	0.82	0.54	0.74	0.39	0.68	0.55	0.62	0.53
Dy	4.83	3.73	4.26	5.15	3.45	4.62	2.63	4.26	3.6	4.13	3.56
Ho	0.99	0.76	0.88	1.04	0.71	0.93	0.55	0.86	0.71	0.84	0.73
Er	2.89	2.12	2.58	2.98	2.02	2.72	1.62	2.46	2.09	2.42	2.12
Tm	0.42	0.31	0.39	0.45	0.31	0.40	0.25	0.37	0.32	0.36	0.33
Yb	2.64	2.11	2.55	2.98	2.05	2.71	1.72	2.45	2.11	2.46	2.24
Lu	0.39	0.34	0.41	0.47	0.33	0.44	0.27	0.39	0.34	0.38	0.36
Hf	2.1	1.7	1.8	2.3	1.8	2.2	0.8	1.9	1.6	1.8	1.4
Ta	0.24	0.44	0.28	0.28	0.41	0.68	0.15	0.63	0.42	0.55	0.29
Th	0.06	0.44	0.22	0.09	0.57	0.49	0.07	0.37	0.22	0.38	0.16
U	0.01	0.43	0.21	0.08	0.47	0.19	0.75	0.23	0.1	0.23	0.11

— below the detection limit.

Table 4
REE contents of Sardoal Complex rocks.

Orthogneiss		REE_N	(La/Sm)_N	(La/Yb)_N	(Sm/Yb)_N	Eu/Eu*
Souto		12.51–210.55	3.41–3.94	7.34–13.66	1.95–3.57	0.51–0.78
Carvalhal		10.35–161.18	3.93–4.38	9.47–12.51	2.41–2.98	0.57–0.78
Sardoal		10.16–180.17	3.15–4.99	6.64–16.63	1.69–4.04	0.58–0.73
Olalhas		5.33–201.27	2.85–4.08	5.12–9.10	1.8–2.35	0.33–0.80
Amphibolite		REE_N	(La/Sm)_N	(La/Yb)_N	(Sm/Yb)_N	Eu/Eu*
Cabeço da Moura	N–MORB	13.63–22.07	0.74–0.84	0.88–0.94	1.09–1.22	0.98–1.05
	E–MORB	12.00–24.73	1.33–1.56	1.30–1.33	1.26–1.27	0.93–1.04
Vila Nova	(E–MORB)	6.13–26.67	0.77–1.28	0.64–1.73	0.83–1.35	0.93–1.25

Eu/Eu* = $\text{Eu}_N / \sqrt{[(\text{Sm}_N) \cdot (\text{Gd}_N)]}$ (Taylor and McLennan 1985 *in* Rollinson 1993).

Table 5

 $\delta^{18}\text{O}$ and SiO_2 contents from Sardoal Complex samples.

		Sample	Igneous age (Ma)	$\delta^{18}\text{O}$ (‰)	SiO_2 (wt.%)
Orthogneiss	Souto	311-66	692+77/-60	6.74	65.19
		321-140b	692+77/-60	11.52	69.5
	Carvalhal	84B	569 $\pm$ 3	11.98	68.06
		gn	569 $\pm$ 3	11.67	70.72
	Sardoal	321-27	548 $\pm$ 4	11.84	68.43
		322-AF6	548 $\pm$ 4	11.75	69.57
		10	548 $\pm$ 4	10.59	64.88
	Olalhas	311-30	–	11.41	64.84
		311-37	–	11.96	63.47
Amphibolite	Cabeço da Moura	311-1A	–	7.62	47.65
		311-20A	–	9.85	49.47
	Vila Nova	311-67	–	8.79	48.87
		311-62	–	5.58	47.38

– Unknown igneous age; Igneous age from Henriques et al. (2015).

Appendix 1
Main characteristics of orthogneiss and amphibolite from Sardoal Complex.

Rock-type		Igneous age (Ma)	Metamorphic age (Ma)	Occurrence	Deformation features	Mineral assemblage		Sources
						Major constituents	Other minerals	
Orthogneiss	Souto	692 ± 77/-60 (inferred age) (igneous zircon)	539 ± 2 (metamorphic monazite)	Northwest area of the reservoir in association with the quartzofeldspathic schist	Gneissic banding; mylonitic fabric (parallel alignment of minerals in the matrix, particularly biotite and muscovite flakes); S-C fabrics; porphyroblast granulation; rounded porphyroclasts; grain-size reduction; kink-band folds in muscovite; Quartz shows: stretched ribbon microstructures, undulose extinction, lobate and dentate boundaries, mortar textures	Qtz + Olg + Bt + Ms ± Kfs	Grt ± Sil + Zrn ± Tur ± Mnz + Ap + Ilm + Rt	Metasedimentary lower crust and meta-igneous lower crust
	Carvalhal	569 ± 3 (igneous zircon)	540 ± 5 (metamorphic monazite)	Southeast area of the complex in close association with migmatite		Qtz + Olg ± Ads + Or + Mc + Bt + Ms	± Tur + Zrn + Ap + Mnz ± Ilm ± Rt ± Mag	Metasedimentary lower crust and meta-igneous middle-upper crust
	Sardoal	548 ± 4 (igneous zircon)	—	Northwest area of the reservoir in association with the gneissic granite		Qtz + Olg + Or + Bt + Ms	± Sil ± Tur + Zrn + Ap ± Ilm ± Mag ± Rt ± Py	Meta-igneous middle-upper crust
	Olalhas	—	—	Olalhas klippe		Qtz + Olg + Bt + Ms ± Kfs	± Sil ± St ± Grt ± Tur + Zrn + Ap ± Ilm ± Py	—
Amphibolite	Cabeço da Moura	—	539 ± 3 (metamorphic zircon)	Elongated metre-size bodies interbedded in Olalhas orthogneiss	Granoblastic to nematoblastic texture; foliation	Mg-Hbl ± Fe ₂ -Hbl ± Fe ₂ -Ed + Lab ± Ads ± Byt + Di ± Aug	Ilm + Zrn + Ttn + Ap + Qtz ± Mag ± Py ± Act ± Ep	—
	Vila Nova	—	529 ± 5 (metamorphic titanite)	Elongated metre-size bodies interbedded in Souto and Sardoal orthogneiss	Granoblastic to nematoblastic texture; foliation; incipient gneissic banding	Mg-Hbl ± Prg + Ads + Lab + Di	Ilm + Ttn + Ap + Qtz ± Py ± Act ± Ep	—

Igneous and metamorphic ages from Henriques et al. (2015); Sources based on whole rock isotopic data (Sr, Sm–Nd) from Henriques et al. (2015). Mineral abbreviations from Siivola and Schmid (2007): Act, Actinolite; Ap, Apatite; Aug, Augite; Bt, Biotite; Di, Diopside; Ep, Epidote; Fe₂-Ed, Ferro-Edenite; Fe₂-Hbl, Ferrohornblende; Grt: garnet; Ilm, Ilmenite; Kfs, K-feldspar; Mag, Magnetite; Mc, Microcline; Mg-Hbl, Magnesiohornblende; Mnz, Monazite; Ms, Muscovite; Or, Orthoclase; Prg, Pargasite; Py, Pyrite; Qtz, Quartz; Rt, Rutile; Sil, Sillimanite; St, Staurolite; Ttn, Titanite; Tur, Tourmaline; Zrn, Zircon. Other mineral abbreviations: Ads, Andesine; Byt, Bytownite; Lab, Labradorite; Olg, Oligoclase.

Appendix 2 - Relict igneous texture of Sardaoal Complex orthogneiss.

Pl-plagioclase; Ms-Muscovite

Appendix 3a									
Representative chemical analyses of biotite from orthogneisses of the Sardaoal Complex									
Mineral	Biotite								
Orthogneiss	Souto		Carvalhal		Sardaoal		Olalhas		
Occurrence	Porph.	Matrix	Porph.	Matrix	Porph.	Matrix	Porph.	Matrix	Inc gt
SiO ₂	36,13	37,80	36,02	36,32	35,65	35,48	35,62	35,81	35,58
TiO ₂	2,00	1,73	3,00	3,20	3,03	3,56	2,40	1,34	2,20
Al ₂ O ₃	18,41	18,03	17,60	16,94	19,48	19,78	18,97	18,51	18,94
Cr ₂ O ₃	0,05	0,07	0,10	0,08	0,04	0,03	0,00	0,05	0,00
Fe ₂ O ₃	1,94	1,55	1,36	1,52	0,69	0,26	1,62	2,20	1,94
FeO	17,68	16,74	19,52	19,94	18,44	19,41	18,56	18,27	21,55
MnO	0,14	0,18	0,22	0,21	0,21	0,21	0,07	0,13	0,19
MgO	10,01	10,18	8,30	8,31	8,75	7,49	9,03	10,29	6,31
ZnO	0,00	0,00	0,00	0,00	0,11	0,00	0,20	0,21	0,02
CaO	0,01	0,02	0,03	0,00	0,01	0,00	0,00	0,00	0,01
Li ₂ O	0,11	0,11	0,15	0,15	0,14	0,18	0,14	0,11	0,23
Na ₂ O	0,29	0,08	0,05	0,03	0,14	0,10	0,28	0,04	0,09
K ₂ O	9,08	9,16	9,39	9,43	9,16	9,24	9,10	8,90	8,93
F	0,07	0,14	0,24	0,39	0,34	0,17	0,00	0,16	0,06
Cl	0,00	0,14	0,05	0,00	0,01	0,05	0,02	0,14	0,03
H ₂ O	3,95	3,91	3,82	3,76	3,82	3,88	3,97	3,86	3,89
	99,89	99,85	99,86	100,28	100,01	99,81	99,96	100,04	99,97
O≡F	0,03	0,06	0,10	0,16	0,14	0,07	0,00	0,07	0,03
O≡Cl	0,00	0,03	0,01	0,00	0,00	0,01	0,01	0,03	0,01
Total	99,86	99,76	99,74	100,12	99,86	99,73	99,96	99,94	99,94
Si	2,718	2,821	2,740	2,759	2,684	2,682	2,689	2,700	2,718
Al ^{IV}	1,282	1,179	1,260	1,241	1,316	1,318	1,311	1,300	1,282
ΣT	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Al ^{VI}	0,350	0,407	0,318	0,276	0,412	0,444	0,376	0,350	0,423
Ti	0,113	0,097	0,172	0,183	0,172	0,202	0,136	0,080	0,126
Cr	0,003	0,004	0,006	0,005	0,002	0,002	0,000	0,000	0,000
Fe ³⁺	0,110	0,087	0,078	0,087	0,039	0,015	0,092	0,130	0,112
Fe ²⁺	1,112	1,045	1,242	1,267	1,161	1,227	1,172	1,150	1,377
Mn	0,009	0,011	0,014	0,014	0,013	0,013	0,004	0,010	0,012
Mg	1,123	1,132	0,941	0,941	0,982	0,844	1,016	1,160	0,718
Zn	0,000	0,000	0,000	0,000	0,006	0,000	0,011	0,010	0,001
Li	0,035	0,033	0,047	0,047	0,043	0,055	0,041	0,030	0,070
ΣR	2,856	2,817	2,819	2,819	2,831	2,802	2,848	2,920	2,840
Ca	0,001	0,001	0,002	0,000	0,000	0,000	0,000	0,000	0,001
Na	0,043	0,012	0,008	0,004	0,020	0,014	0,040	0,010	0,013
K	0,872	0,872	0,912	0,914	0,880	0,891	0,877	0,860	0,870
ΣA	0,915	0,886	0,922	0,918	0,901	0,905	0,917	0,860	0,885
F	0,017	0,034	0,057	0,093	0,082	0,040	0,000	0,040	0,015
Cl	0,000	0,017	0,006	0,000	0,001	0,006	0,003	0,020	0,003
OH	1,983	1,948	1,936	1,907	1,918	1,954	1,997	1,940	1,982

Structural formulae based on 11(O) + F + Cl. Estimation of Fe₂O₃ and FeO (Bruyil et al., 1983); Calculation of Li₂O (Tischendorf et al., 1999); H₂O* values were calculated by stoichiometry; Porph: porphyroclasts; Inc gt: included in garnet;

Appendix 3b								
Representative chemical analyses of muscovite from orthogneisses of the Sardoal Complex.								
Mineral	Muscovite							
Orthogneiss	Souto		Olalhas		Sardoal		Carvalhal	
Occurrence	Porph.	Matrix	Porph.	Matrix	Porph.	Matrix	Porph.	Matrix
SiO ₂	46,68	46,17	47,22	46,37	45,24	48,33	48,22	47,27
TiO ₂	0,68	0,68	0,68	0,73	0,82	0,34	0,95	0,72
Al ₂ O ₃	35,36	35,27	35,36	34,60	36,93	33,12	35,32	33,49
Cr ₂ O ₃	0,03	0,03	0,11	0,02	0,04	0,00	0,07	0,03
FeO _t	1,04	1,31	0,97	1,56	0,87	1,25	1,21	1,62
MnO	0,00	0,00	0,00	0,00	0,03	0,00	0,02	0,00
MgO	0,54	0,64	0,55	0,78	0,66	0,98	0,74	0,81
ZnO	0,04	0,00	0,04	0,00	0,00	0,00	0,00	0,00
CaO	0,00	0,00	0,00	0,01	0,00	0,02	0,02	0,00
BaO	0,57	0,32	0,36	0,25	0,42	0,33	0,13	0,14
Li ₂ O	0,06	0,01	0,08	0,00	0,04	0,00	0,04	0,00
Na ₂ O	1,11	0,59	1,39	0,46	0,40	0,43	0,33	0,43
K ₂ O	9,12	10,28	8,66	10,54	10,28	10,63	8,43	10,71
F	0,23	0,07	0,29	0,02	0,18	0,00	0,19	0,00
Cl	0,01	0,00	0,02	0,00	0,00	0,00	0,02	0,01
H ₂ O (*)	4,41	4,47	4,41	4,48	4,44	4,51	4,50	4,49
	99,88	99,84	100,14	99,82	100,36	99,94	100,18	99,71
O≡F	0,10	0,03	0,12	0,01	0,08	0,00	0,08	0,00
O≡Cl	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total	99,78	99,81	100,02	99,82	100,28	99,94	100,10	99,71
Si	3,096	3,076	3,111	3,095	2,998	3,211	3,150	3,156
Al ^{IV}	0,904	0,924	0,889	0,905	1,002	0,789	0,850	0,844
ΣT	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Al ^{VI}	1,859	1,846	1,858	1,817	1,882	1,804	1,870	1,792
Ti	0,034	0,034	0,034	0,037	0,041	0,017	0,046	0,036
Cr	0,002	0,001	0,006	0,001	0,002	0,000	0,003	0,002
Fe ²⁺	0,058	0,073	0,054	0,087	0,048	0,070	0,066	0,091
Mn	0,000	0,000	0,000	0,000	0,002	0,000	0,001	0,000
Mg	0,053	0,064	0,054	0,078	0,066	0,097	0,072	0,081
Zn	0,002	0,000	0,002	0,000	0,000	0,000	0,000	0,000
Li	0,015	0,003	0,020	0,000	0,011	0,000	0,011	0,000
ΣR	2,023	2,022	2,027	2,021	2,052	1,988	2,070	2,001
Ca	0,000	0,000	0,000	0,001	0,000	0,001	0,002	0,000
Ba	0,015	0,008	0,009	0,007	0,011	0,009	0,003	0,004
Na	0,143	0,077	0,178	0,059	0,052	0,055	0,042	0,056
K	0,772	0,874	0,728	0,897	0,869	0,901	0,702	0,913
ΣA	0,930	0,958	0,915	0,964	0,932	0,966	0,750	0,972
F	0,048	0,015	0,060	0,004	0,038	0,000	0,039	0,000
Cl	0,002	0,000	0,002	0,000	0,000	0,000	0,002	0,001
OH*	1,951	1,985	1,937	1,996	1,962	2,000	1,960	1,999

Structural formulae based on 11(O) + F + Cl; FeOt of muscovite is total FeO; Calculation of Li₂O (Tischendorf et al., 1997); H₂O* values were calculated by stoichiometry; Porph-porphycroclasts.

Appendix 3c				
Representative chemical analyses of garnet from orthogneisses of the Sardoal Complex.				
Mineral	Garnet			
Orthogneiss	Souto		Olalhas	
Occurrence	Porph.	Matrix	Porph.	Porph.
SiO ₂	36,99	37,20	36,74	36,68
TiO ₂	0,07	0,07	0,05	0,01
Al ₂ O ₃	20,81	20,86	20,72	20,71
Cr ₂ O ₃	0,08	0,07	0,00	0,01
Fe ₂ O ₃	0,02	0,00	0,47	0,50
FeO	29,80	29,60	34,57	33,95
MnO	6,96	7,08	4,03	3,95
MgO	2,57	2,56	2,60	2,44
NiO	0,00	0,01	0,00	0,00
ZnO	0,08	0,00	0,05	0,10
CaO	2,12	2,25	0,87	1,62
Total	99,51	99,71	100,09	99,96
Si	3,000	3,006	2,981	2,979
Al ^{IV}	0,000	0,000	0,019	0,021
	3,000	3,006	3,000	3,000
Al ^{VI}	1,989	1,987	1,965	1,964
Ti	0,005	0,005	0,003	0,001
Cr	0,005	0,005	0,000	0,000
Fe ³⁺	0,001	0,000	0,029	0,031
	2,000	1,997	1,996	1,996
Fe ²⁺	2,021	2,004	2,346	2,306
Mn	0,478	0,485	0,277	0,272
Mg	0,311	0,308	0,315	0,295
Ni	0,000	0,001	0,000	0,000
Zn	0,005	0,000	0,003	0,006
Ca	0,184	0,195	0,076	0,141
	2,998	2,992	3,017	3,020
Almandine	68	67	78	76
Andradite	0	0	1	2
Grossular	6	6	1	3
Pyrope	10	10	11	10
Spessartine	16	16	9	9
Uvarovite	0	0	0	0
(mol%)				
Structural formulae based on 12 (O) and Fe ²⁺ /Fe ³⁺ calculated assuming full site occupancy; Porph-porphyroclasts.				

Appendix 3d		
Representative chemical analyses of staurolite from orthogneisses of the Sardoal Complex.		
Mineral	Staurolite	
Orthogneiss	Olalhas	
Occurrence	Porph.	Matrix
SiO ₂	28,24	28,02
TiO ₂	0,17	0,28
Al ₂ O ₃	53,96	54,63
Cr ₂ O ₃	0,09	0,00
FeO _t	11,00	11,12
MnO	0,46	0,42
ZnO	0,58	0,82
MgO	1,47	1,47
CaO	0,02	0,02
Na ₂ O	0,01	0,00
K ₂ O	0,02	0,03
Total	96,01	96,79
Porph-porphyroclasts.		

Appendix 3e				
Representative chemical analyses of apatite from orthogneisses of the Sardoal Complex.				
Mineral	Apatite			
Orthogneiss	Souto	Carvalhal	Sardoal	Olalhas
P ₂ O ₅	40,75	42,05	40,17	41,24
SiO ₂	0,03	0,06	0,15	0,07
TiO ₂	0,01	0,00	0,02	0,00
Al ₂ O ₃	0,01	0,00	0,01	0,00
FeO	0,28	0,02	0,06	0,01
MnO	0,10	0,05	0,14	0,00
MgO	0,01	0,03	0,02	0,03
CaO	56,54	55,55	56,83	56,56
BaO	0,00	0,08	0,00	0,00
Na ₂ O	0,00	0,00	0,00	0,00
K ₂ O	0,00	0,00	0,03	0,00
F	3,00	3,30	4,40	3,33
Cl	0,06	0,00	0,00	0,03
	100,79	101,15	101,84	101,27
O ≡ F	1,26	1,38	1,85	1,40
O ≡ Cl	0,01	0,00	0,00	0,01
H ₂ O*	0,33	0,22	0,00	0,19
Total	99,84	99,98	99,99	100,05
H ₂ O* values were calculated by stoichiometry.				

Appendix 3f

Representative chemical analyses of oxides and sulfides from orthogneisses of the Sardaoal Complex.

Mineral	Ilmenite				Rutile	Magnetite		Arsenopyrite
	Orthogneiss	Souto	Carvalhal	Sardoal		Carvalhal	Sardoal	
SiO ₂		4,64	0,02	0,09	0,04			
TiO ₂		52,88	51,70	57,62	54,59			
Al ₂ O ₃		0,07	0,00	0,04	0,01			
Cr ₂ O ₃		0,00	0,15	0,04	0,00			
V ₂ O ₃		0,00	0,28	0,00	0,00			
Fe ₂ O ₃		0,00	1,70	0,00	0,00			
FeO		39,15	44,06	37,90	44,04			
MnO		3,12	2,29	4,10	0,85			
MgO		0,04	0,07	0,02	0,03			
CaO		0,03	0,00	0,05	0,01			
Total		99,92	100,27	99,87	99,57			

	Rutile	
	Olalhas	
TiO ₂	99,78	
Cr ₂ O ₃	0,02	
Al ₂ O ₃	0,02	
FeO	0,18	
MnO	0,00	
MgO	0,01	
CaO	0,01	
SiO ₂	0,07	
Total	100,08	

	Magnetite	
	Carvalhal	Sardoal
SiO ₂	7,20	3,53
TiO ₂	0,01	0,00
Al ₂ O ₃	0,56	0,00
Fe ₂ O ₃	51,26	60,73
FeO	40,17	34,55
MnO	0,00	0,00
MgO	0,11	0,54
CaO	0,27	0,22
Cr ₂ O ₃	0,04	0,06
V ₂ O ₃	0,00	0,00
NiO	0,07	0,46
Total	99,69	100,09
Usp		
(mol %)	26.84	13.33

	Arsenopyrite	
	Carvalhal	
Fe	32,00	
Ni	2,00	
Co	1,53	
As	44,54	
S	20,41	
Total	100,48	

	Pyrite	
	Sardoal	Olalhas
Fe	45,91	49,27
Ni	0,39	0,13
Co	0,02	0
Cu	0,02	0,05
S	54,06	50,08
Total	100,40	99,53

	Pyrrhotite	
	Sardoal	
Fe	61,86	
Ni	0,30	
Co	0,00	
Cu	0,00	
S	37,38	
Total	99,54	

Fe₂O₃ and FeO from ilmenite calculated according to Droop (1987); Fe₂O₃, FeO and Usp (mol %) from magnetite calculated according to Carmichael (1967) using ILMAT spreadsheet (Lepage, 2003).

Appendix 4a

Representative chemical compositions of amphibole from amphibolites of the Sardao Complex.

Amphibolite	Cabeço da Moura							Vila Nova							
Mineral	Mg-hornblende			Fe-hornblende		Actinolite		Mg-hornblende			Fe-pargasite	Pargasite		Edenite	
SiO ₂	50,39	45,83	44,72	43,82	42,91	54,05	52,07	51,00	48,05	43,78	41,64	41,78	43,49	44,47	43,88
TiO ₂	0,47	1,28	1,87	0,32	0,79	0,13	0,26	0,23	0,34	0,53	0,77	0,80	0,44	0,51	0,80
Al ₂ O ₃	6,38	9,43	11,01	11,38	12,09	1,88	4,44	5,37	8,57	13,27	15,11	14,65	14,42	12,34	12,32
Cr ₂ O ₃	0,22	0,12	0,07	0,00	0,04	0,06	0,09	0,00	0,04	0,06	0,05	0,05	0,07	0,07	0,13
FeO	14,26	14,59	14,15	19,92	20,64	12,15	14,18	14,39	15,63	16,37	16,32	16,76	13,47	15,25	15,95
MnO	0,15	0,24	0,25	0,23	0,26	0,22	0,25	0,21	0,24	0,30	0,19	0,22	0,15	0,17	0,23
MgO	12,77	11,61	11,03	7,16	6,70	16,19	13,92	13,40	11,53	9,15	8,61	8,88	11,18	10,27	9,98
CaO	11,98	11,73	12,08	11,73	11,44	12,26	12,18	12,32	12,21	12,07	12,01	12,13	12,29	12,10	12,14
Na ₂ O	0,47	1,28	1,64	1,20	1,32	0,21	0,31	0,54	0,84	1,26	2,08	2,10	1,97	1,71	1,76
K ₂ O	0,18	0,12	0,26	0,43	0,67	0,02	0,13	0,13	0,25	0,54	0,26	0,25	0,28	0,20	0,19
Total	97,25	96,23	97,08	96,18	96,85	97,18	97,83	97,59	97,71	97,33	97,03	97,64	97,76	97,09	97,37
Si	7,339	6,819	6,635	6,716	6,565	7,778	7,525	7,412	7,046	6,523	6,253	6,246	6,374	6,606	6,533
Al ^{IV}	0,661	1,181	1,365	1,284	1,435	0,222	0,475	0,588	0,954	1,477	1,747	1,754	1,626	1,394	1,467
T	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00	8,00
Al ^{VI}	0,435	0,472	0,560	0,772	0,745	0,096	0,282	0,332	0,528	0,853	0,928	0,827	0,864	0,766	0,694
Ti	0,051	0,143	0,208	0,037	0,091	0,014	0,028	0,025	0,038	0,060	0,087	0,090	0,049	0,057	0,089
Fe ³⁺	0,119	0,178	0,012	0,094	0,149	0,089	0,115	0,123	0,147	0,112	0,075	0,144	0,122	0,079	0,104
Cr	0,025	0,014	0,009	0,000	0,005	0,006	0,010	0,000	0,004	0,007	0,006	0,006	0,008	0,008	0,016
Mg	2,773	2,576	2,440	1,635	1,528	3,473	2,999	2,903	2,521	2,034	1,927	1,980	2,443	2,275	2,215
Fe ²⁺	1,597	1,617	1,743	2,459	2,483	1,321	1,565	1,617	1,762	1,928	1,974	1,951	1,515	1,814	1,881
Mn	0,000	0,000	0,028	0,003	0,000	0,000	0,000	0,000	0,000	0,007	0,003	0,001	0,000	0,000	0,000
C	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00
Mg	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Fe ²⁺	0,020	0,020	0,000	0,000	0,009	0,053	0,034	0,009	0,008	0,000	0,000	0,000	0,014	0,001	0,000
Mn	0,018	0,030	0,003	0,027	0,033	0,026	0,030	0,026	0,030	0,032	0,021	0,027	0,019	0,022	0,02

Structural formulae based on 23 (O); Fe²⁺ and Fe³⁺ calculated according to Schumacher (1997). XMg=Mg/(Mg+Fe²⁺)

Appendix 4b				
Representative chemical composition of clinopyroxene from amphibolites of the Sardoal Complex.				
Amphibolite	Cabeço da Moura			Vila Nova
Mineral	Diopside	Augite	Hedenbergite	Diopside
SiO ₂	51,65	47,36	51,08	52,87
TiO ₂	0,27	1,90	0,12	0,00
Al ₂ O ₃	1,44	9,53	0,87	0,48
FeO	9,90	16,44	16,70	9,01
Cr ₂ O ₃	0,00	0,05	0,00	0,00
MnO	0,35	0,23	0,49	0,32
MgO	12,57	10,69	7,67	12,67
CaO	23,12	11,17	22,78	24,38
Na ₂ O	0,24	1,62	0,24	0,15
K ₂ O	0,01	0,52	0,00	0,01
Total	99,55	99,51	99,95	99,89
Si	1,947	1,792	1,986	1,985
Al ^{IV}	0,053	0,208	0,014	0,015
T	2,00	2,00	2,00	2,00
Al ^{VI}	0,011	0,217	0,026	0,006
Ti	0,008	0,054	0,004	0,000
Fe ³⁺	0,045	0,024	0,000	0,021
Fe ²⁺	0,230	0,100	0,526	0,262
Cr	0,000	0,002	0,000	0,000
Mg	0,706	0,603	0,445	0,709
M1	1,00	1,00	1,00	1,00
Mg	0,000	0,000	0,000	0,000
Fe ²⁺	0,037	0,396	0,017	0,000
Mn	0,011	0,007	0,016	0,010
Ca	0,934	0,453	0,949	0,981
Na	0,018	0,119	0,018	0,011
K	0,000	0,025	0,000	0,000
M2	1,00	1,00	1,00	1,00
Wo (mol %)	48	29	49	49
En (mol %)	36	38	23	36
Fs (mol %)	16	33	29	15
X _{Mg}	0,73	0,55	0,45	0,73
Structural formulae based on 6 (O). XMg=Mg/(Mg+Fe ²⁺).				

Appendix 4c		
Representative chemical compositions of clinozoisite from amphibolites of the Sardaoal Complex.		
Amphibolite	Cabeço da Moura	Vila Nova
SiO ₂	39,01	38,54
Al ₂ O ₃	26,97	29,22
FeO	6,49	5,41
MgO	0,04	0,03
MnO	0,15	0,06
CaO	23,92	24,11
Na ₂ O	0,00	0,00
K ₂ O	0,01	0,01
TiO ₂	0,13	0,00
Total	96,71	97,38
Si	3,000	2,981
Al ^{IV}	0,000	0,019
Z	3,00	3,00
Al ^{VI}	2,445	2,645
Ti	0,008	0,000
Fe ³⁺	0,418	0,350
Mg	0,004	0,003
Mn	0,010	0,004
M	2,88	3,00
Ca	1,971	1,998
Na	0,000	0,000
K	0,001	0,001
A	1,97	2,00
X _{Fe}	0,17	0,13

Structural formulae based on 12,5 (O). Normalization on the basis of 8 cations and when Si>3,05 renormalization on the basis of 3 Si (Armbruster et al., 2006).

Appendix 4d				
Representative chemical analysis of titanite from amphibolites of the Sardaoal Complex.				
Amphibolite	Cabeço da Moura		Vila Nova	
Location	Grain	Rim	Grain	Rim
SiO ₂	30,53	30,95	30,69	30,43
TiO ₂	38,52	38,98	38,61	37,11
Al ₂ O ₃	1,07	1,18	1,00	1,61
Fe ₂ O ₃	0,62	0,19	0,18	0,00
MnO	0,00	0,04	0,01	0,06
MgO	0,02	0,03	0,00	0,01
CaO	28,05	28,12	27,76	28,34
Na ₂ O	0,04	0,00	0,00	0,00
K ₂ O	0,00	0,00	0,01	0,00
F	0,00	0,10	0,28	0,00
Total	98,91	99,63	98,56	97,80
O=F	0,00	0,04	0,12	0,00
Total	98,91	99,59	98,44	97,80
Si	4,000	4,000	4,000	4,000
Ti	3,796	3,789	3,785	3,669
Al	0,166	0,180	0,154	0,249
Fe ³⁺	0,061	0,019	0,017	0,000
Σ Y	4,02	3,99	3,96	3,92
Mn	0,000	0,004	0,001	0,007
Mg	0,005	0,005	0,000	0,002
Ca	3,937	3,894	3,876	3,991
Na	0,009	0,001	0,000	0,000
K	0,000	0,000	0,001	0,000
ΣX	3,95	3,90	3,88	4,00
F	0,000	0,043	0,116	0,000
OH	0,226	0,156	0,055	0,249
Σ	0,23	0,20	0,17	0,25
X _{Al}	0,04	0,05	0,04	0,06
Structural formulae based on 4 Si. OH calculated according to Franz and Spear, 1985. X _{Al} =Al/(Al+Ti+Fe ³⁺)				

Appendix 4e		
Representative chemical analysis of apatite from amphibolites of the Sardaoal Complex.		
Amphibolite	Cabeço da Moura	Vila Nova
P ₂ O ₅	42,16	42,06
SiO ₂	0,01	0,10
TiO ₂	0,00	0,00
Al ₂ O ₃	0,02	0,03
FeO	0,04	0,13
MnO	0,06	0,06
MgO	0,03	0,02
CaO	55,37	55,38
BaO	0,00	0,00
Na ₂ O	0,00	0,00
K ₂ O	0,03	0,00
F	2,16	1,96
Cl	0,10	0,20
	99,98	99,94
O ≡ F	0,91	0,82
O ≡ Cl	0,02	0,05
H ₂ O*	0,73	0,80
Total	99,78	99,87
H ₂ O* values were calculated by stoichiometry.		

Appendix 4f

Representative chemical analysis of oxides and sulphides from amphibolites of the Sardao Complex.

	Ilmenite	
	Grain	Inc ttn
SiO ₂	0,01	0,13
TiO ₂	52,81	52,40
Al ₂ O ₃	0,00	0,02
Cr ₂ O ₃	0,00	0,01
V ₂ O ₃	0,32	0,00
Fe ₂ O ₃	0,21	0,57
FeO	46,22	44,02
MnO	0,93	1,84
MgO	0,18	0,61
CaO	0,00	0,14
Total	100,68	99,71
Inc ttn-included in titanite		

	Pyrrhotite
Fe	61,88
Ni	0,27
S	37,76
Total	99,91

	Pyrite
Fe	46,39
Ni	1,20
Co	0,00
Cu	0,62
As	0,06
S	51,75
Total	100,03

	Chalcopyrite
Cu	34,81
Fe	31,76
S	33,40
Total	99,97

Fe₂O₃ and FeO from ilmenite calculated according to Droop (1987);