The Corredoiras orthogneiss (NW Iberian Massif): Geochemistry and geochronology of the Paleozoic magmatic suite developed in a peri-Gondwanan arc

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ABSTRACT

The Corredoiras orthogneiss belongs to the intermediate pressure upper units of the Órdenes Complex (Variscan belt, NW Spain), mainly composed by granodioritic orthogneisses, with small bodies of tonalitic orthogneisses, amphibole-rich orthogneisses and metagabbronorites. In this work we study their chemical and isotopic composition, to gain insight into the linkage between plate tectonics and magmatism and to improve the knowledge of the paleogeographic evolution of the European Variscan Belt.

Granodioritic and tonalitic orthogneisses range from intermediate to felsic rocks, with K_2O/Na_2O ratios ≈ 1, typical of calc-alkaline rocks, and high Na_2O content, characteristic of I-type granites. Metagabbronorites are basic rocks, but some of them are contaminated by interaction with the felsic magmas, showing enrichment in SiO_2, Na_2O and K_2O. All Corredoiras metaigneous rocks are enriched in large ion lithophile elements (LILE) and light rare earth elements (LREE) relative to high field strength elements (HFSE), resulting in a high LILE/HFSE ratio. These geochemical features are the most characteristic of magmas related to subduction zones; furthermore all orthogneisses display significant negative anomalies in Ta, Nb and Zr, which together with their low contents in Y and Yb match up with granitoids generated in volcanic arcs or subduction zones. SHRIMP U–Pb zircon dating provides a concordia age of 492 ± 3 Ma. Granodioritic orthogneiss has negative $\varepsilon Nd_{(492\ Ma)}$ values (-2.2 to -3.6) and high $(^{87}Sr/^{86}Sr)_i$ ratios (0.707 to 0.708), on the other hand tonalitic orthogneisses and metagabbronorites have positive $\varepsilon Nd_{(492\ Ma)}$ (1.0 to 2.4) and low $(^{87}Sr/^{86}Sr)_i$ (0.703 to 0.705), suggesting that granodioritic orthogneisses have a clear crustal influence in their generation, whereas tonalitic orthogneisses and metagabbros can be related to basic magmas extracted from the mantle or from a basic lower continental crust.

The Corredoiras chemical characteristics permit us to interpret that this rocks were probably generated in an ensialic island arc and may represent a peri-Gondwanan fragment drifted away to open the Rheic Ocean.

1. Introduction

The basement of the European Variscan Belt is composed of several early Paleozoic crustal fragments. The origin of these pieces has been attributed to tectonic processes that occurred along the northern margin of Gondwana during its protracted geological history involving varied events, such as plate subduction, generation of magmatic arcs and rifting (Martínez Catalán et al., 2009; Matte, 1991; Pin, 1990). The study of the chemical and isotopic composition of igneous rocks in ancient orogens like the European Variscan Belt, where the original geological relationships are extremely reworked, is very useful in the reconstruction of paleotectonic environments. Specifically, calc-alkaline affinity rocks, which are mainly generated in mature magmatic arcs, can help us to determine the existence of an ensialic basement in these arcs. This ensialic basement makes possible the appearance of geochemically evolved plutonic rocks, as it occurs in the Izu–Bonin, Cuba or New Britain arc systems, which contain volumetrically important tonalite and granodiorite batholiths (Kawate and Arima, 1998; Marchesi et al., 2007; Rojas-Agramonte et al., 2004; Woodhead et al., 1998). The study area is located in the northwestern region of the Iberian Massif, which preserves one of the best sections of the internal part of the European Variscan Belt, with several allochthonous complexes located in Galicia (Órdenes, Cabo Ortegal and the Malpica–Tui unit) and Portugal (Bragança and Morais).

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In this work, we study the chemical and isotopic composition of the Corredoiras unit, which is part of the intermediate pressure upper units (Díaz García et al., 1999b; González Cuadra, 2007). The metaigneous rocks that form part of the Corredoiras unit, include a varied range of rocks types, dominated by a granodiorite–granite association, with small amounts of tonalite and gabbro. The study of these rock associations is important to gain insight into the linkage between plate tectonics and magmatism and to improve the knowledge of the paleogeographic evolution of the European Variscan Belt.

2. Geological setting

The European Variscan Belt is a Devonian–Carboniferous orogen generated during the progressive collision between Gondwana and Laurussia, and the consequent closure of the Rheic Ocean (Martínez Catalán et al., 2009). The axial zone of the Variscan Belt is characterized by the presence of several allochthonous complexes constituted by exotic terranes with ophiolites and high-P metamorphic rocks (Arenas et al., 1986). These exotic terranes outline the intricate Pangea suture in Europe, which is rootless and it was transported within the allochthonous complexes towards more external regions of the Variscan Belt. In the NW Iberian Massif, five allochthonous complexes are preserved in late synformal structures: three of them outcropping in Galicia (Cabo Ortegal, Órdenes and the Malpica–Tui unit) and two in the Portuguese region of Trás-os-Montes (Bragança and Morais complexes). The Órdenes Complex is the largest one (Fig. 1) and it is constituted by basal, ophiolitic and upper units (Martínez Catalán et al., 2002, 2007).

In the Galician allochthonous complexes it is possible to distinguish several slices with different origins. These slices can be grouped in three sets of units named, from bottom to top: basal, ophiolitic and upper units (Martínez Catalán et al., 2002, 2007). These units converged at the onset of the Variscan Orogeny, and thereafter, during their accretion and exhumation, they were dismembered and thinned, reaching their present configuration as a consequence of late orogenic processes of folding and faulting (Martínez Catalán et al., 2009). As the ophiolitic units are considered to represent a collisional suture (Arenas et al., 2007a; Sánchez Martínez et al., 2007a, 2007b), the basal units are interpreted as the most external continental margin of Gondwana (Abati et al., 2010; Arenas et al., 1995, 1997; Martínez Catalán et al., 1996; Rodríguez et al., 2003), whereas the upper units represent exotic terranes with Gondwanan affinity. These upper units can be divided in two sets with contrasting pressure and temperature conditions; on one hand, the high-pressure and high-temperature units (HP–HT), occupying the lower structural position and, on the other hand, the intermediate pressure units (IP) on top of the orogenic pile (Abati et al., 1999, 2003; Fernández Suárez et al., 2007; Ordoñez Casado et al., 2001).

There is a variety of felsic metaigneous rocks in the basal and the upper units and the study of their chemical and isotopic composition is essential to establish their tectonic setting. This knowledge will contribute to the paleogeographic reconstruction of the different ognized in the allochthonous complexes. For example, in the basal units, two igneous series with different (Rodríguez Aller, 2005): an older series with calc-alkaline affinity (490–480 Ma; Abati et al., 2010; Díez Fernández et al., 2011; Santos Zalduegui et al., 1995), and a younger series with alkaline–peralkaline composition (480–470 Ma; Díez Fernández et al., 2011; Montero et al., 2009; Rodríguez et al., 2007). This bimodal magmatism and its geochemical characteristics point to a Cambro–Ordovician extensional episode in the most external margin of Gondwana that signals the origin of the Rheic Ocean (Abati et al., 2010; Díez Fernández et al., 2011; Martínez Catalán et al., 2009).

In the upper units there is a wider diversity of igneous rocks, including ultramafic, mafic and felsic types (Arenas et al., 2007b). The ages of magmatism vary between 520 and 500 Ma (Abati et al., 1999, 2007; Castiñeiras et al., 2010; Fernández Suárez et al., 2007; Ordóñez

Casado, 1998; Santos et al., 2002). There are a few studies on the geochemistry of the igneous rocks in the HP–HT units (Galán and Marcos, 1997; Gil Ibarguchi et al., 1990; Mendia Aranguren, 2000) and the mafic rocks in the IP units (Andonaegui et al., 2002); however, no geochemical study has been carried out nowadays in the felsic rocks from the IP upper units.

2.1. Units of the Órdenes Complex

The basal units consist of metasediments alternating with granitic orthogneisses and metabasites. The sediments include phyllites, schists, metagraywakes and paragneisses. The metagranitoids have meta- to peraluminous character, and calc-alkaline, alkaline and peralkaline compositions (Abati et al., 2010; Díez Fernández et al., 2011). The metabasites have tholeiitic composition and some of them may correspond to alkali basalts. The calc-alkaline orthogneisses are related to a magmatic arc generated during subduction and they yield U–Pb ages between 490 and 475 Ma (Abati et al., 2010; Díez Fernández et al., 2011; Santos Zalduegui et al., 1995). The bimodal, partially alkaline magmatism reflects
tween 480 and 475 Ma (Díez Fernández et al., 2011; Montero et al., 2009; Rodríguez et al., 2007), which probably resulted in the breaking and drifting away of a peri-Gondwanan terrane, and the opening of the Rheic Ocean (Díez Fernández et al., 2011; Martínez Catalán et al., 2009). The basal units are interpreted as fragments of the most external edge of the Gondwanan continental margin because they are not separated from the lower allochthon by ophiolites.

The ophiolitic units crop out discontinuously underlying the upper units and they are composed of at least two different
lites (Arenas et al., 2007b). Those occupying the higher structural position represent the basal section of an ophiolite sequence, and their geochemistry indicates a supra-subduction character (Sánchez Martínez et al., 2007b). Zircon grains extracted from leucogabbros of this unit yield a concordant U–Pb age of 395 Ma (Díaz García et al., 1999a; Pin et al., 2002). The structurally lower ophiolitic units consist of greenschist facies, volcanic and plutonic mafic rocks (greenstones) and metapelites, with rare felsic orthogneisses, serpentinites, and cherts, all strongly sheared. These ophiolites are interpreted as remnants of an oceanic crust which has been related to the early opening of the Rheic Ocean, during Cambrian times (Arenas et al., 2007c).

The upper units occupy the core of the Órdenes Complex and they are composed of terrigenous metasediments, orthogneisses and metabasites (metagabbros, eclogites, mafic granulites and amphibolites), with ultramafic rocks in the HP–HT upper units. The gabbros and orthogneisses yield U–Pb ages around 500 Ma, whereas detrital zircons in the metasediments indicate a maximum depositional age of 530–500 Ma for the uppermost greenschist facies metagraywackes (Fernández Suárez et al., 2003; Fuenlabrada et al., 2010). The geochemical signature of the igneous rocks in the HP–HT upper units has been compared to MORB and related to continental rifting (Gil Ibarguchi et al., 1990), whereas mafic rocks in the intermediate P upper units have arc tholeiitic affinities (Andonaegui et al., 2002; Castiñeiras, 2005).

The Corredoiras unit is one of the intermediate pressure upper units of the Órdenes Complex (Fig. 2). It crops out to the southwest of the Complex, occupying a lower structural position (González Cuadra, 2007). This unit displays a heterogeneous deformation and distribution of metamorphism. Two burial and exhumation episodes can be deduced based on its structure, relative chronology and metamorphism, the first occurs in granulite facies conditions and the second in amphibolite facies conditions (González Cuadra, 2007). Available ages point out to an igneous protolith emplacement for this unit at 500 Ma, a first burial episode between 493 and 484 Ma, and a second episode with exhumation finished at 375 Ma (Abati et al., 1999; Dallmeyer et al., 1997). The Corredoiras Unit consists of

metasediments and the metaigneous rocks of the Corredoiras massif. Metasediments are pelites (granulitic gneisses and schists) and grey-wackes (paragneisses and migmatites). Metaigneous rocks derive from acid and intermediate intrusive bodies (granodioritic, tonalitic and amphibole-rich orthogneisses) and basic bodies (metagabbros and amphibolites). They show a heterogeneous deformation, ranging from virtually undeformed and preserving their igneous texture to rocks with a strong mylonitic fabric. We have selected the less deformed samples for the geochemistry study, although some protomylonitic rocks have also been analyzed.
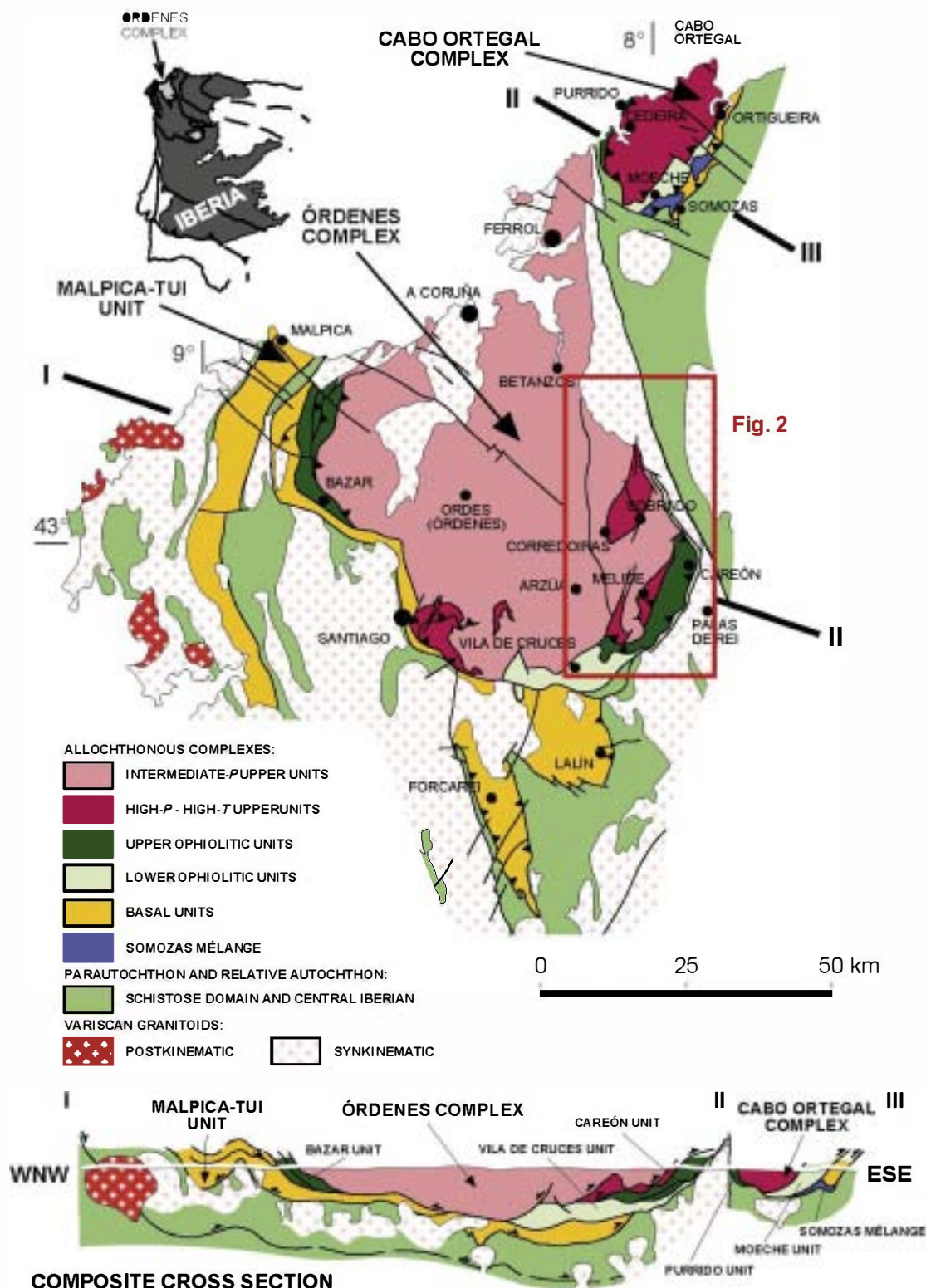

Fig. 1. Terrane distribution in the allochthonous complexes of NW Iberia (Galicia) and a WNW–ESE oriented general cross section. The map shows the synformal structure of the complexes where a rootless branch of the main suture of Pangea in Europe is exposed. The location of the geological map presented in Fig. 2 is also shown.

3. Description of the Corredoiras orthogneisses and related rocks

The Corredoiras metaigneous massif is mainly composed of a large body of orthogneisses. In detail, the following lithologies can be distinguished in the Corredoiras massif (Fig. 2): granodioritic orthogneiss, which constitutes the major part of the unit and it has been mapped in different color tones according to their deformation degree; tonalitic orthogneiss, which crops out at a small area to the NW of the massif; amphibole-rich orthogneiss, which is very scarce and appears associated to the previous lithology; and small bodies of metagabbros scattered within the orthogneisses. The orthogneisses include centimeter to meter-scale metapelitic xenoliths of ellipsoidal shape when they are not deformed. When deformed, they are thinner and develop boudinage textures. The undeformed xenoliths show granulite facies metamorphic conditions, with quartz, biotite and garnet. The deformed xenoliths are transformed into staurolite schists.

The most abundant lithology in the Corredoiras massif is a hypidiomorphic granular coarse-grained granodiorite. Principal minerals are potassium feldspar and plagioclase phenocrysts, quartz and biotite; minor minerals include garnet, apatite, ilmenite, rutile, zircon, titanite, monazite and tourmaline, the latter only present in undeformed or slightly deformed rocks. Muscovite, chlorite and epidote appear as secondary minerals. Most of the Corredoiras orthogneisses have a weak foliation or are isotropic, except in shear zones where
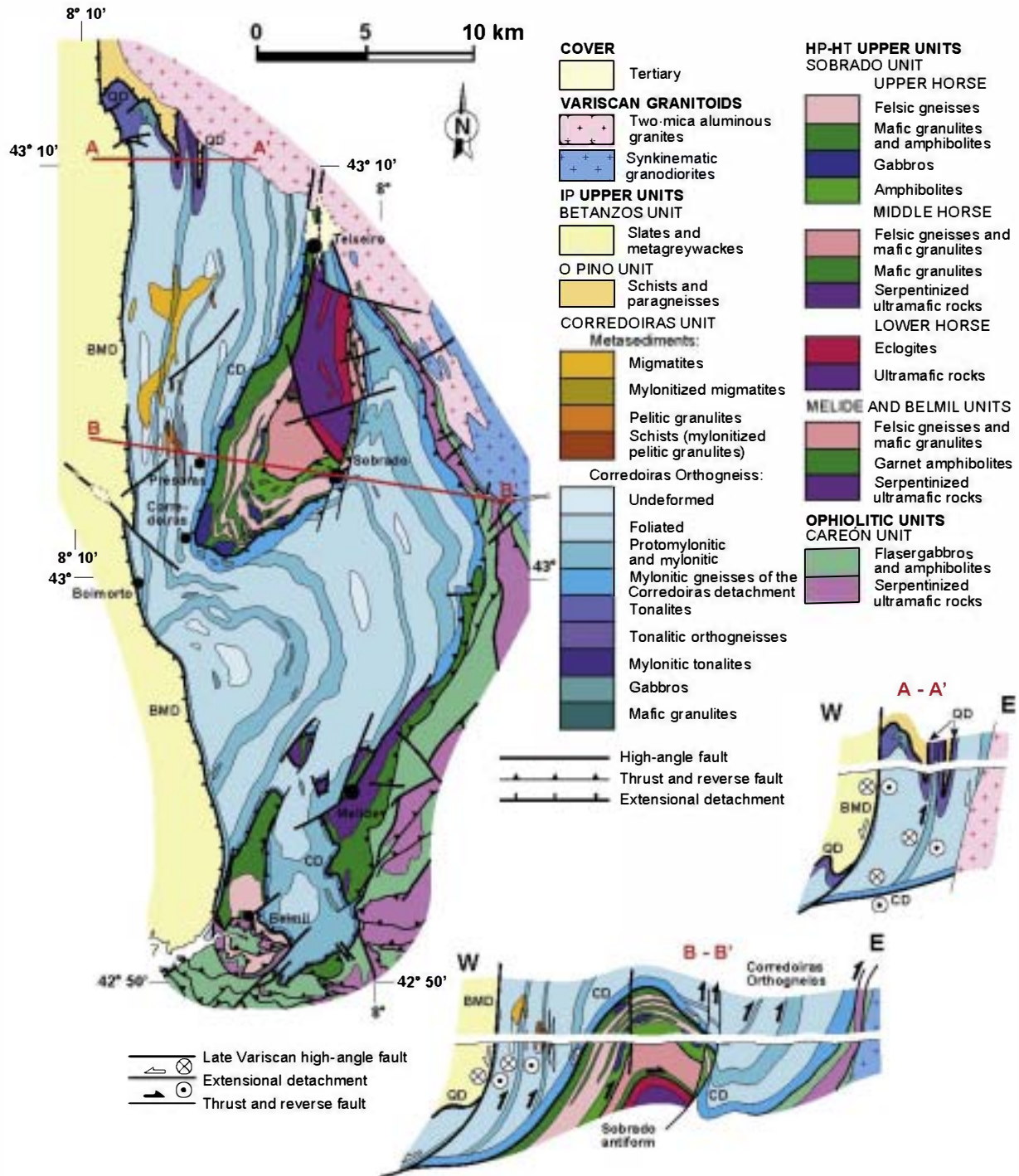

Fig. 2. Geological map of the Corredoiras massif and other important units in the eastern part of the Órdenes Complex (González Cuadra, 2007).

the texture is gneissic grading to mylonitic or cataclastic. Plagioclase is present in two different

subhedral lath lamellae twin phenocrysts with weak oscillatory zonation, or as small myrmekite crystals surrounding potassium feldspar. Perthite microtextures are common in potassium feldspar phenocrysts, which also exhibit simple twinning and include small plagioclase crystals. Garnet is anhedral and free of inclusions. Deformation in these rocks is accompanied by grain size reduction and mineral stretching (González Cuadra, 2007). Quartz is deformed and recrystallized forming irregular aggregates with biotite, making the rock look darker and apparently richer in biotite. Potassium feldspar, plagioclase and garnet preserve its initial aspect, and develop a microscopically incipient foliation. When the deformation increases these minerals are finally broken and recrystallized, in parallel bands with grain size reduction and developing a gneissic compositional layering.

Tonalitic orthogneisses are medium grained, granular and hypidiomorfic. They are composed of quartz, plagioclase, potassium feldspar, biotite, garnet and, in some samples, hornblende. Subordinate minerals are apatite, zircon, ilmenite, titanite and monazite. These orthogneisses have mainly tonalitic to granodioritic composition, but rare monzogranitic types can also be found. Their texture consists of a plagioclase and potassium feldspar network with intergranular quartz. Their petrographic features are similar to those of the granodioritic orthogneisses. When amphibole is present, it forms intergrowth aggregates with biotite. Garnet may exhibit opaque and quartz inclusions. Deformed types develop a biotite lepidoblastic texture with elongated quartz–feldspar aggregates and an intense grain size reduction.

Macroscopic and microscopic enclaves have been found in both types of orthogneisses, formed by biotite, quartz, plagioclase and muscovite. The micas of the enclaves are quite different

rock ones, biotite is greenish and has fewer accessory minerals included, and muscovite is more birefringent. Less common minerals are hornblende, garnet, tourmaline, titanite and epidote.

Amphibole-rich orthogneisses appear as boudins within the tonalitic orthogneisses, ranging in size from decimeters to meters. They are composed of hornblende, garnet, plagioclase, potassium feldspar and quartz. Accessory minerals are ilmenite, zircon and titanite. Chlorite, epidote and zoisite appear as secondary minerals. They exhibit nematoblastic texture with medium grain size and a strong orientation of hornblende and plagioclase–quartz aggregates defining a compositional layering. Plagioclase, quartz and potassium feldspar appear as more or less equigranular aggregates. Potassium feldspar has thin perthites, whereas plagioclase can appear either as medium sized crystals with lamellar twinning or as small crystals with myrmekite texture around potassium feldspar. Garnet forms small aggregates, usually inclusion-free, but in some samples there is a core with microfolded opaque inclusions and a rim without inclusions.

The metagabbros are found as dispersed bodies within the orthogneisses. The field relationships between both rocks are not clear; nevertheless, some gabbroic bodies contain small amounts of quartz and potassium feldspar, suggesting some mechanical contamination with the granodiorites. For that reason, we interpret that the metagabbros probably intruded the orthogneisses when they were still unconsolidated, generating contaminated lithologies. An additional evidence for mechanical contamination is a tonalitic orthogneiss outcrop, where an area with abundant metagabbro enclaves shows a possible magma mingling process between both lithologies. All these observations suggest that all the different

the Corredoiras Unit are coeval, and they intruded at virtually the same time. Some metagabbros preserve a granular or intergranular to subophitic igneous texture, with medium to coarse grain size, moreover this igneous texture can be recognized because plagioclase crystals are hypidiomorfic with polysynthetic twinning and weak optic zoning, and pyroxene crystals are large (up to 8 mm) and exhibit a subophitic texture. They are composed of plagioclase,

orthopyroxene, clinopyroxene and sporadic olivine, whereas subordinate minerals are biotite, ilmenite, and apatite, allowing a more precise classification as metagabbronorites. Amphibole and garnet can develop depending on the metamorphic conditions. Secondary minerals are chlorite, epidote and actinolite–tremolite. The pyroxenes are always intergranular with exsolution lamellae, and olivine shows pyroxene–amphibole symplectitic rims.

Quartz appears as small interstitial crystals and as bigger xenocrysts in the contaminated metagabbronorites.

4. Geochemistry

4.1. Analytical methods

Forty-nine samples (> 5 kg each) of the different lithologies Corredoiras massif selected from the best-preserved outcrops were analyzed for whole rock geochemistry (major, minor and trace elements). Among them there are twenty-nine granodioritic orthogneiss samples, nine tonalitic orthogneisses, two amphibole-rich orthogneisses and nine metagabbronorites. Taking into account their deformation features, the granodioritic orthogneisses can be divided into undeformed (13 samples), weakly foliated (9 samples) and foliated/protomylonitic (7 samples).

The samples were crushed with a steel jaw crusher and powdered to 200 mesh grain size in an agate mill at the laboratories of the Universidad Complutense de Madrid, and the subsequent chemical analyses were carried out at the Activation Laboratories Ltd. (Actlabs) in Canada using the procedure 4Lithoresearch. The digestion procedure was lithium metaborate/tetraborate fusion, and the analytical technique used to measure elemental concentrations was inductively coupled plasma mass spectrometry (ICP-MS).

U–Th–Pb analyses of zircon were conducted at the Bay SHRIMP-RG (co-owned between the U.S. Geological Survey and the Stanford University) during one analytical session in October 2005. Zircon separation was carried out at the Universidad Complutense (Madrid) following standard techniques, including crushing, pulverizing, sieving, Wilfley

were handpicked under a binocular microscope and representative grains were chosen in accordance with their size, length-to-breadth ratio, roundness, color, and other salient morphological features. They were mounted on a double-sided adhesive on glass slides in 1×6 mm parallel rows together with some chips of zircon standard R33 (Black et al., 2004). After being set in epoxy resin, the zircon grains were ground down to expose their central portions. Internal structure, inclusions, fractures and physical defects were identified with transmitted and reflected

and with cathodoluminescence on a JEOL 5800LV electron microscope (housed at USGS-Denver).

Secondary ions generated from the target spot with an O^{2-} primary ion beam varying from 4 to 6 nA. The primary ion beam produced a spot with a diameter of ~30 μm and a depth of 1–2 μm for an analysis time of 8–10 min. Five scans were collected, and the counting time for ^{206}Pb was increased according to the Paleozoic age of the sample to improve counting statistics and precision of the $^{206}Pb/^{238}U$ age. Concentration data for zircon are standardized against zircon standard CZ3 (550 ppm U, Pidgeon et al., 1995), and isotope ratios were calibrated against R33 ($^{206*}Pb/^{238}U = 0.06716$, equivalent to an age of 419 Ma, Black et al., 2004) which were analyzed repeatedly throughout the duration of the analytical session.

Data reduction follows the methods described by Ireland and Williams (2003) and Williams (1998), and SQUID (version 1.08) and ISOPLOT (version 3.00) software (Ludwig, 2002, 2003) were used. The Pb composition used for initial Pb corrections was $^{204}Pb/^{206}Pb = 0.0554$, $^{207}Pb/^{206}Pb = 0.864$ and $^{208}Pb/^{206}Pb = 2.097$, calculated by SQUID using the Stacey and Kramers (1975) model.

Twelve samples were selected for Sm–Nd and Rb–Sr geochemistry, five granodioritic orthogneisses, four tonalitic orthogneisses and three metagabbronorites. The analyses were carried out at the U.S. Geological Survey (Denver), following the analytical procedures described in Premo and Loucks (2000). Whole rock powders were dissolved in 7 ml PFA teflon

$+HNO_3$, and then spiked with a dilute mixed tracer of ^{84}Sr–^{87}Rb and ^{150}Nd–^{149}Sm. The effluent

(30 ml resin-volume) column with AG50W-X8 cation exchange resin, separating Rb, Sr, and REE. Sm was separated from Nd using AG50W-X8 cation exchange resin and alpha-hydroxyisobutyric acid method of Lugmair et al. (1975), and then they were both loaded with dilute H_3PO_4 acid onto tantalum filaments in triple filament mode and run on a multi-sample VG lsomass 54R mass spectrometer.

4.2. Major and trace element geochemistry

4.2.1. Major element composition

Average values of the results for major oxides and trace element analyses of the Corredoiras massif are listed in Table 1, (the complete dataset is provided in the Supplemental data Table A1). Granodioritic orthogneisses are felsic rocks, with SiO_2 wt.% varying from 66.6 to 75.1 (average 69.8). The compositional ranges for the rest of the major elements vary between 15.7 and 13.9 for Al_2O_3, 6.2–1.5 for Fe_2O_3T, 1.4–0.3 for MgO, 3.5–1.2 for CaO, 3.5–2.5 for Na_2O and 4.9–2.2 for K_2O. Tonalitic orthogneisses range from intermediate to felsic compositions (58.1–73.7 SiO_2 wt.%) with an average composition of 64.9 and they have higher contents in Al_2O_3, Fe_2O_3T, MgO, CaO and Na_2O than the granodioritic orthogneisses (16.1–13.4, 9.6–2.4, 2.4–

Table 1
Major and trace element average composition of Corredoiras metaigneous rocks.

Sample	Granodioritic orthogneisses			Tonalitic orthg.	Metagabbros		Amphibole orthg.
	Undeformed (n=13)	Foliated (n=9)	Protomylonitic (n=7)	(n=9)	Uncontaminated (n=6)	Contaminated (n=3)	(n=2)
SiO_2	70.53	69.13	69.69	64.86	47.83	51.69	71.54
TiO_2	0.50	0.55	0.63	0.83	0.84	1.32	0.69
Al_2O_3	14.55	14.90	14.00	14.94	17.65	15.62	12.37
Fe_2O_3T	3.30	3.71	4.13	6.61	8.80	9.87	4.53
MnO	0.05	0.06	0.07	0.11	0.13	0.15	0.06
MgO	0.78	0.89	0.85	1.30	10.29	7.21	0.80
CaO	2.25	2.28	2.36	2.54	9.10	8.63	5.15
Na_2O	3.13	3.17	3.04	3.70	2.36	2.79	3.03
K_2O	3.32	3.29	3.58	3.12	0.24	0.73	0.19
P_2O_5	0.22	0.21	0.23	0.30	0.10	0.15	0.20
LOI	0.88	1.11	0.82	0.82	2.23	1.72	1.07
Total	99.51	99.30	99.40	99.13	99.58	99.88	99.63
#Mg	0.18	0.16	0.15	0.16	0.48	0.37	0.15
ACKN	1.13	1.15	1.06	1.06	0.85	0.74	0.85
Ba	1204	1250	1297	593	100.83	317	45.50
Rb	84	85	93	103	6	14	4
Sr	183	187	161	153	208	174	509
Ta	0.66	0.77	0.82	1.08	0.19	0.38	0.77
Nb	9.80	10.90	12.50	14.60	3.30	6.50	10.20
Hf	5.89	6.84	9.16	9.38	1.98	4.33	6.25
Zr	224	270	301	355	78	167	249
Y	49	55	69	46	16	33	29
Th	15.13	16.39	21.46	9.86	0.94	6.08	6.27
U	1.88	2.20	2.13	2.72	0.11	0.43	1.72
Cr	55	54	64	69	418	350	75
Ni	19	19	19	20	157	83	19
V	38	44	45	73	129	204	73
Pb	34	33	38	26	4	11	4
Zn	47	53	50	101	72	90	40
Th/Ta	22.92	21.29	26.17	9.13	5.59	16.03	8.14
Th/Yb	3.38	3.33	3.09	2.09	0.57	1.82	2.46
La	41.31	46.71	57.77	29.20	7.17	20.57	25.42
Ce	86.54	94.49	124.01	75.68	15.32	44.20	52.35
Pr	10.55	11.95	14.49	8.20	2.09	5.54	6.84
Nd	41.19	46.71	55.44	33.11	9.28	23.33	26.70
Sm	9.47	10.26	12.49	7.80	2.49	5.70	6.15
Eu	1.50	1.56	1.70	1.73	1.03	1.40	1.33
Gd	9.36	1.026	12.22	8.05	2.94	6.24	5.99
Tb	1.59	1.75	2.08	1.37	0.48	1.03	1.04
Dy	8.81	9.79	11.96	7.67	2.82	5.93	5.40
Ho	1.70	1.92	2.46	1.54	0.57	1.18	1.03
Er	4.99	5.60	7.38	4.67	1.70	3.48	2.81
Tm	0.74	0.82	1.12	0.74	0.25	0.53	0.41
Yb	4.47	4.92	6.94	4.71	1.64	3.33	2.54
Lu	0.63	0.69	0.99	0.69	0.24	0.49	0.36
$\sum$ REE	222.50	246.56	310.70	183.73	48.02	122.97	137.33
$(La/Yb)_N$	6.18	6.35	5.57	4.15	2.98	4.11	6.69

$\#Mg = (Mg^{+2}/[Mg^{+2} + Fe^{+2}T])$.

0.4, 4.4–0.9, 4.0–3.4, respectively) and similar content in K_2O (4.1–1.9). Na_2O concentration is relatively high (≥ 3 wt.%), which is characteristic of I-type granites (Hine et al., 1978), even though the K_2O/Na_2O ratios are near 1, typical of calc-alkaline rocks.

The two amphibole-rich orthogneisses samples are felsic in composition (66.8–76.3), with similar MgO and CaO contents (0.9–0.7 and 0.18–0.19, respectively) and different
of the major elements, so sample 107939 has higher Al_2O_3, Fe_2O_3T and Na_2O contents and lower CaO than sample 107940.

The SiO_2 wt.% from metagabbronorites varies from 45.6 to 52.5, as corresponds to basic rocks. As mentioned above, some metagabbronorites seem contaminated by interaction with the felsic magmas, which is also supported by the chemistry: compared to the uncontaminated metagabbronorites, the contaminated ones are enriched in SiO_2 (average 51.7 wt.% compared to 47.8 wt.%), Na_2O (2.8 compared to 2.4) and K_2O (0.7 compared to 0.2), whereas they are depleted in Fe_2O_3T (9.5

against 9.8), MgO (7.2 against 10.3), CaO (8.5 against 9.1) and Al_2O_3 (15.6 against 17.7).

All of the Corredoiras rocks show systematic trends of decreasing Al_2O_3, Fe_2O_3T, MgO, TiO_2 and P_2O_5 with increasing SiO_2. MgO content in orthogneisses is low, with #Mg ($\#Mg = (Mg^{+2}/[Mg^{+2}+Fe^{+2}T])$) ranging from 0.17 to 0.09, decreasing with increasing SiO_2. The metagabbronorites show higher #Mg from 0.53 to 0.38, but these are relatively low for basic rocks, meaning that they do not represent primary magmas. These basic rocks are probably equivalent to the Monte Castelo gabbros, a huge gabbroic massif outcropping in the western part of the intermediate pressure upper units (Andonaegui et al., 2002).

In an AFM diagram, (Fig. 3a, Irvine and Baragar, 1971) the orthogneisses define a calc-alkaline suite, whereas the metagabbronorites plot in the tholeiitic field close to the line dividing both fields. In order to precisely determine the magmatic series of the metagabbronorites, we have used the Th vs. Co diagram (Fig. 3b, Hastie et al.,
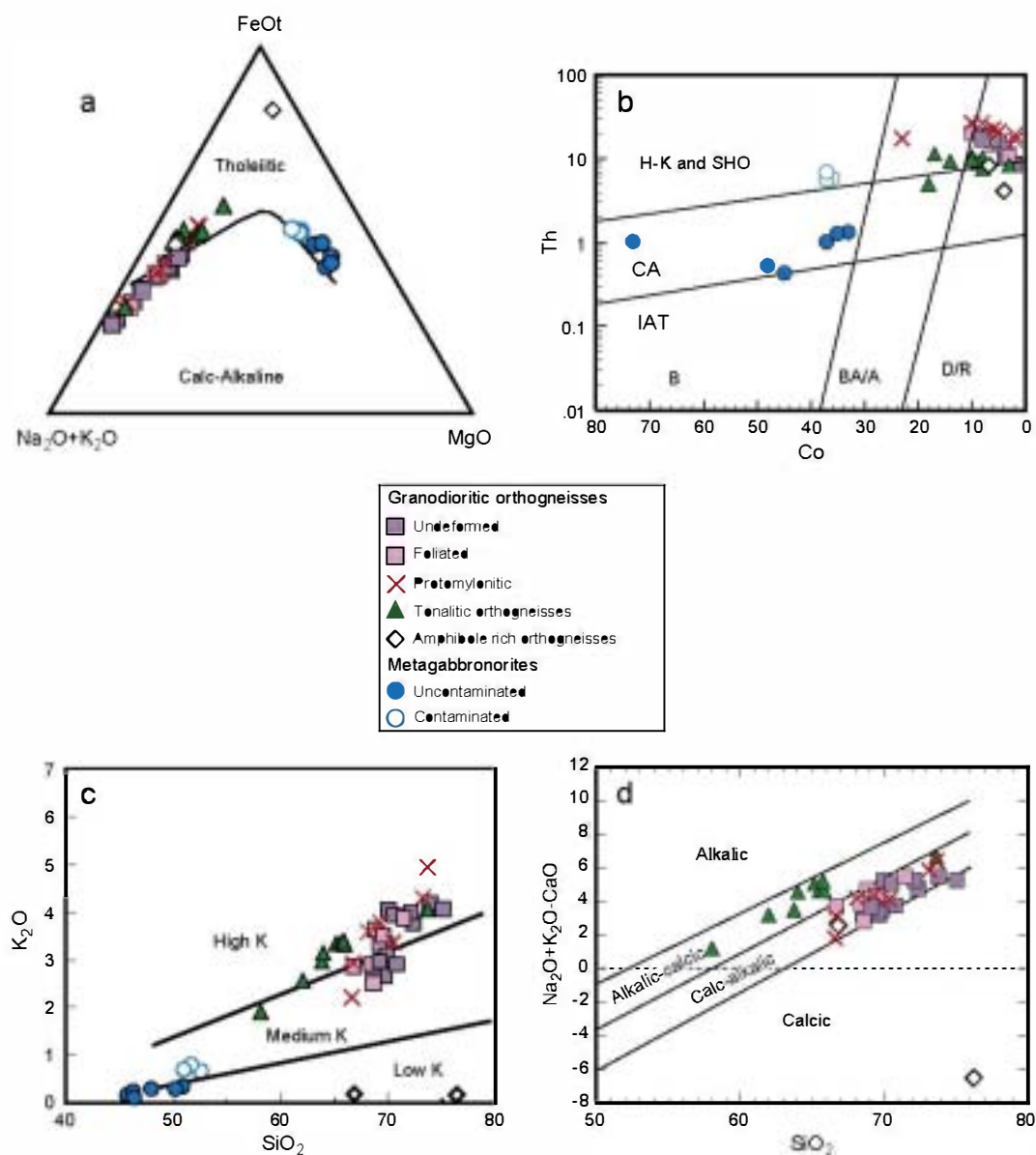

Fig. 3. (a) AFM diagram showing tholeiitic and calc-alkaline fields form Irvine and Baragar (1971); (b) Th–Co discrimination diagram (Hastie et al., 2007) IAT = island arc tholeiites, CA = calc-alkaline, HK and SHO = high potassium and shoshonites, B = basalt, BA/A = basaltic andesites/andesites, D/R = dacites/rhyolites; (c) SiO_2–K_2O diagram (Peccerillo and Taylor, 1976) and (d) plot $Na_2O + K_2O$–CaO against SiO_2 (Frost et al., 2001) showing the fields for the alkalic, alkalic-calcic, calc-alkalic and calcic rocks series, for the metaigneous rocks of the Corredoiras massif.

2007), where island arc tholeiites can be discriminated from the calc-alkaline series. The uncontaminated metagabbronorites plot in the field of the calc-alkaline basalts, whereas the contaminated ones are detached from them, plotting in the field of high-potassium basalts. The orthogneisses also plot in the field of high-potassium rocks.

In the Peccerillo and Taylor (1976) diagram (Fig. 3c), the orthogneisses define a high-potassium calc-alkaline suite, whereas the metagabbros plot in the low-potassium field, except for the contaminated gabbros that plot in the medium-potassium field. Amphibole-rich orthogneisses are depleted in potassium and plot in the low-potassium field accordingly.

In the $Na_2O + K_2O$–CaO vs. SiO_2 diagram (Fig. 3d, Frost et al., 2001) the granodioritic orthogneisses plot in the field of the calc-alkalic series, whereas the tonalitic orthogneisses plot in the field of the alkalic-calcic series, owning to their higher CaO content.

The A/CKN ratios (molecular $Al_2O_3/[CaO + Na_2O + K_2O]$) range between 1.09 and 1.38 in the granodioritic orthogneisses and from 1.01 to 1.09 in the tonalitic orthogneisses, indicating a transitional character between low peraluminous to peraluminous. The lower A/CKN values in the tonalitic orthogneisses suggest a more basic precursor. Furthermore, the tonalitic orthogneisses show a marked negative correlation in P_2O_5 with increasing silica, a diagnostic feature of I-type granites when apatite reaches saturation in less peraluminous magmas (Chappell, 1999). Both metagabbronorites and amphibole-rich orthogneisses are metaluminous.

4.2.2. Trace element composition

Average values of trace elements are listed in Table 1. All orthogneisses show enrichment in incompatible elements (Rb, Ba, K, Th, U), with some differences are more enriched in Ba (1550–734 ppm) and Th (26.9–8.39 ppm) than the tonalitic orthogneisses (Ba 785–326 ppm; Th 4.92–11.2 ppm); they have the opposite behavior regarding Rb, the tonalitic orthogneisses have slightly higher average values (103 ppm) than the granodioritic orthogneisses (87 ppm). The metagabbronorites are less enriched in incompatible elements than the orthogneisses, but again there are differences between contaminated and uncontaminated metagabbronorites; the former are richer in incompatible elements (Ba: 317 ppm, Rb: 14 ppm, Th: 6.1 ppm and U: 0.4 ppm, average values) than the latter (100.9 ppm, 6 ppm, 0.9 ppm, and 0.1 ppm, respectively). Finally, the amphibole-rich orthogneisses have the lowest contents in incompatible elements.
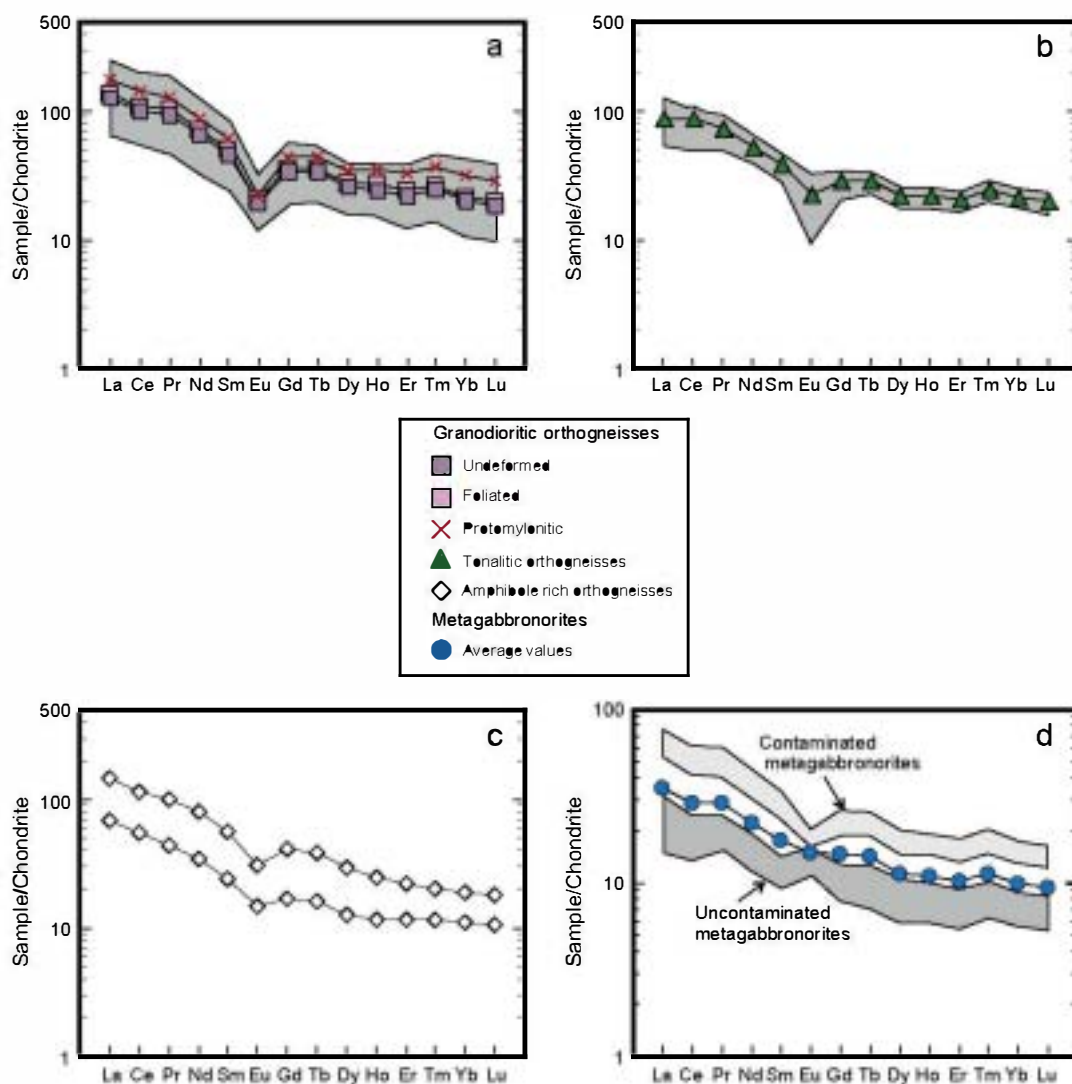

Fig. 4. Chondrite-normalized rare earth elements plots for the different metaigneous rocks of the Corredoiras massif, normalizing values are from Nakamura (1974). Shading zone is the rank of total samples variation, and the individual lines correspond to the average of each type rocks. a) Granodioritic orthogneisses; b) tonalitic orthogneisses; c) amphibole-rich orthogneisses; d) metagabbronorites.
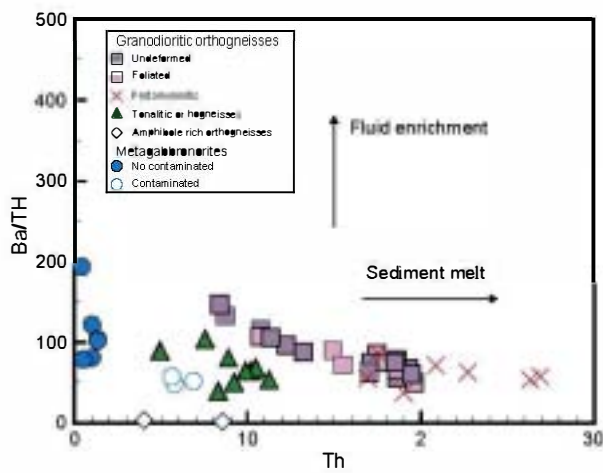
Fig. 5. Ba/Th–Th diagram (Münker et al., 2004) showing that partial melting of sediments had a clear influence on the generation of part of the metaigneous rocks included in the Corredoiras massif.

On primitive mantle normalized diagrams, samples display moderate to strong depletion in Nb, Ta, Sr, P and Ti, a typical feature of subduction-related magmatic rocks (Brown et al., 1984; Rogers and Hawkesworth, 1989). The tonalitic orthogneisses have higher values in Nb (average of 14.6 ppm) and Ta (average of 1.1 ppm) with respect to the granodioritic orthogneisses (Nb: 11.1 ppm, Ta: 0.8 ppm, average values). Strontium is slightly higher in the granodioritic orthogneisses (177 ppm average) than in the tonalitic orthogneisses (103 ppm average). The uncontaminated metagabbros have the lowest values in Nb and Ta (3.3 and 0.2 ppm, respectively), and they are slightly enriched in Sr (208 ppm), while the contaminated metagabbros have somewhat higher Nb (6.5 ppm) and Ta (0.4 ppm) and lower contents in Sr (174 ppm). Finally, the amphibole-rich orthogneisses have the highest contents in Sr (509 ppm), probably because they are richer in plagioclase. These rocks have Nb and Ta values similar to those of the other orthogneisses (Nb: 10.2 ppm, Ta: 0.8 ppm).

The orthogneisses also have high Th/Ta ratios (16.2–31.8 for the granodiorites, and 4.4–10.4 for the tonalites), which is typical of subduction-related magmas (Gorton and Schandl, 2000; Rogers and Hawkesworth, 1989).

The granodioritic orthogneisses have total rare earth element (REE) contents ranging between 120 and 425 ppm, and show a negative correlation with the increase in SiO_2. The REE concentrations are 10 to 250 times chondritic abundances (Nakamura, 1974), and show fractionated chondrite-normalized patterns $[(La/Yb)_N = 2.9{-}10.7]$ (Fig. 4a), typical of calc-alkaline rocks. The light rare earth elements (LREEs) $[(La/Sm)_N = 2.5{-}3.1]$ are fractionated compared to the heavy rare earth elements (HREEs) which exhibit a flatter $Yb)_N = 0.9{-}2.7]$ with negative Eu anomalies ranging from moderate
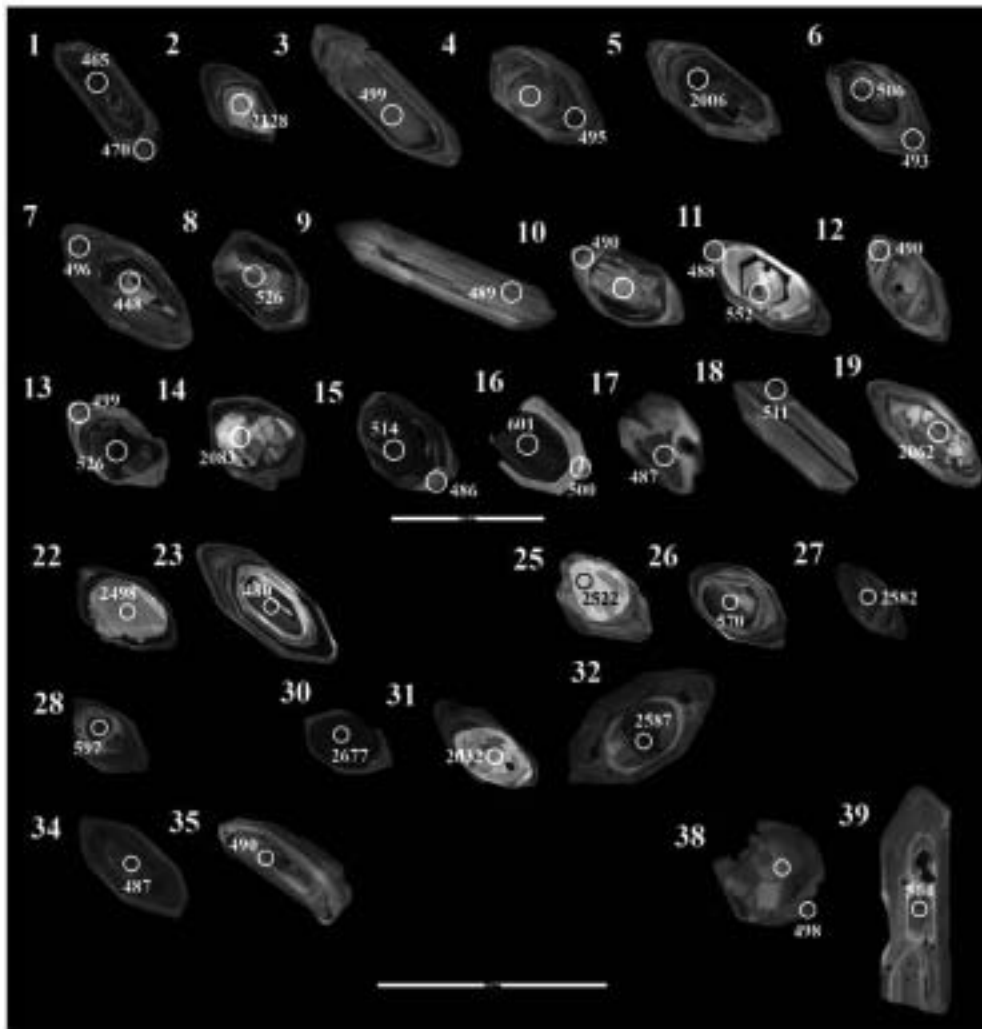

Fig. 6. Cathodoluminescence images for selected zircons from the analyzed sample of orthogneiss.
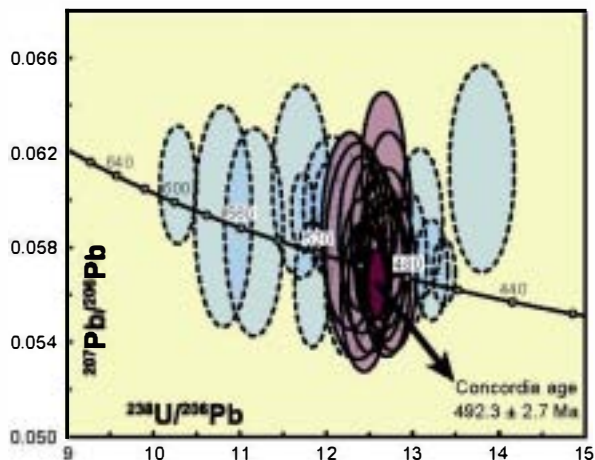
Fig. 7. U–Pb concordia diagram showing the result of zircon analyses.

to pronounced ($(Eu/Eu^*) = 0.3–0.7$). The tonalitic orthogneisses have lower total REE contents (125–225 ppm), with less variation than the granodioritic orthogneisses, and they also show a negative correlation with the increase in silica content. They have concentrations between 15 and 130 times the chondritic abundances. Their chondrite-normalized pattern (Fig. . 4b) is parallel to those of the previous samples, although it is less fractionated [$(La/Yb)_N = 2.5–7.1$] than in the granodioritic orthogneisses. The Eu anomalies are similar in both lithologies ($Eu/Eu^* = 0.4–0.9$).

The two amphibole-rich orthogneisses samples have total REE contents lower than the previous orthogneisses (90–190 ppm), with concentrations between 10 and 105 times the chondritic abundances (Fig. . 4c). Their fractionation is similar to the other orthogneisses [$(La/Yb)_N = 5.7–7.3$] and they also have negative Eu anomalies ($Eu/Eu^* = 0.6–0.8$).

The metagabbronorites have the lowest total contents in REE (150–40 ppm), the highest values corresponding to contaminated metagabbronorites. The concentrations range between 14.9 and 31.6 ppm (20 to 5 times chondritic values) for the uncontaminated metagabbros, and between 52.8 and 77.2 ppm (80 to 12 times chondritic values) for the contaminated metagabbros. The latter show higher fractionation [$(La/Yb)_N = 3.8–4.1$] than the former [$(La/Yb)_N = 1.7–4.0$] (Fig. . 4d). In both cases, the fractionation in HREE is

similar [$(Gd/Yb)_N = 1.4–1.5$]. The contaminated metagabbros have negative Eu anomalies ($Eu/Eu^* = 0.7–0.8$), whereas the uncontaminated metagabbros have positive Eu anomalies ($Eu/Eu^* = 1.1–2.3$).

The Corredoiras metaigneous rocks exhibit an enrichment in large ion lithophile elements (LILE) and light rare earth elements (LREE) relative to high field strength elements (HFSE), resulting in a high LILE/HFSE ratio. These geochemical features are the most characteristic of magmas related with subduction zones (Davidson, 1996; Tatsumi and Eggins, 1995). The depletion in HFSE is the consequence of mass flux

tle. Typically there is a preferential mobilization of LILE in hydrous fluids

concentrated in the continental crust and can be indicative of crustal contamination of magmas.

Nonetheless, there are some geochemical tracers to evaluate if the LILE enrichment is either a consequence of fluid

sult of sediment melting or crustal contamination (Hawkesworth et al., 1997; Münker et al., 2004), for example Ba/Th vs. Th. The rationale behind this diagram is that magmas generated in an intra-oceanic supra-subduction zone derive from the partial melting of the mantle wedge enriched by slab fluids

low concentration in Th and high Ba/Th ratio; on the other hand, if the enrichment is due to sediment melting or contamination in continental crust shallow levels, magmas will have high Th concentrations and low Ba/Th ratio. In this diagram (Fig. 5), the Corredoiras metaigneous rocks show low Ba/Th ratio and high Th contents, defining a path that indicates a connection with sediment or continental crust melting. In the case under discussion, we favor continental crust melting. This feature is also evident in the contaminated gabbros as they are richer in Th and more depleted in Ba/Th ratio than the uncontaminated gabbros.

Other ratios in the Corredoiras metaigneous rocks that support the influence

high Th/Ce and Th/Ta ratios. Specifically, both the granodioritic orthogneisses and the contaminated metagabbronorites show high Th/Ta ratios, the latter with an average value of 16.03. This high value contrasts with the values obtained in the uncontaminated metagabbronorites (average 5.58). High Th/Ta values clearly point out to an influence

continental crust. The tonalitic orthogneisses show Th/Ta ratios slightly higher (average 9.13) than the uncontaminated metagabbronorites, indicating an origin from more primitive liquids than the granodioritic orthogneiss with little interaction with continental

Table 2
Nd and Sr isotopic data of Corredoiras orthogneisses.

Sample	Age (T) (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd} at T	T_{DM} (Ma)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{87}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ (at T)
Granodiorite orthogneiss												
107890	492	4.63	20.27	0.13789	0.512294	−2.98	1484	96	156	1.782	0.719774	0.707075
107891	492	5.94	25.43	0.14103	0.512274	−3.57	1578	96	157	1.771	0.719517	0.706899
107899[a]	492	8.76	41.55	0.12728	0.512241	−3.34	1403	61	227	0.778	0.713232	0.707690
107908	492	9.26	44.31	0.12623	0.512298	−2.17	1297	62	230	0.780	0.713615	0.708055
107928	492	10.24	46.89	0.13187	0.512277	−2.93	1413	83	172	1.397	0.717186	0.707230
Tonalite orthogneiss												
107930	492	8.11	34.11	0.14352	0.512546	1.59	1103	66	149	0.849	0.710523	0.704475
107931	492	5.58	22.74	0.14832	0.512597	2.28	1069	149	56	7.733	0.755395	0.700296
107934	492	6.48	29.76	0.13139	0.512550	2.43	949	108	147	2.203	0.718899	0.703205
107937	492	7.28	31.80	0.13818	0.512541	1.83	1042	91	183	1.439	0.714712	0.704455
Metagabbros												
107898	492	2.31	8.89	0.15670	0.512560	1.04	1291	3	150	0.058	0.705182	0.704770
107913	492	4.11	17.13	0.14504	0.512436	−0.65	1341	12	162	0.214	0.706684	0.705157
107925	492	1.87	7.44	0.15152	0.512575	1.83	1165	9	196	0.133	0.705082	0.704136

[a] Zircon sample.

crust materials (Hawkesworth et al., 1997). Furthermore, the meta-gabbronorites show high Th/Yb ratios (>1 for contaminated and <1 for uncontaminated) which are displaced from the MORB-OIB array (Pearce, 2008), suggesting either an upper crustal interaction or an interaction with a mantle lithosphere containing an inherited sub-duction component.

5. SHRIMP U–Pb geochronology

5.1. Sample description

One undeformed granodiorite (sample 107899) was selected for geochronological characterization by U–Pb SHRIMP in zircon to con-firm the crystallization age of the protolith, previously dated by Abati et al. (1999), and to investigate zircon inheritance. Morpholog-ically, the studied sample contains two zircon populations (Fig. 6), one with high breadth-to-length ratio and rounded edges, and other with acicular shape and idiomorphic habit. Under cathodolumines-cence (CL), it is possible to distinguish three different central areas, there are discontinuous zones which are interpreted as inherited xenocrystic cores. Generally, these cores are mantled by subsequent zircon growth episodes, which developed oscillatory zones, characteristic of igneous zircon. Finally, the oscillatory zones might be cut by a discontinuous non-luminescent rim with homoge-neous zoning. Acicular zircon grains can be inherited, but they usually lack xenocrystic cores.

5.2. Results

Forty-eight analyses were performed on 38 zircon grains. The whole set of analytical data is in Supplemental data Table A2. Seven-teen analyses yielded ages older than 1000 Ma (reported as [204]Pb-corrected [207]Pb/[206]Pb) and after rejecting seven discordant analyses, two distinct populations can be distinguished at ~2.1 and ~2.5 Ga. Ages younger than 1000 Ma (reported as [207]Pb-corrected [206]Pb/[238]U) vary between 450 and 600 Ma, with an acme at ~490 Ma, and their uncorrected radiogenic compositions are plotted in a Tera-Wasserburg diagram (Fig. 7).

After calculating the median age of the young data and pooling the most concordant ages around the median value, we obtain a concor-dia age (sensu Ludwig, 1998) of 492.3 ± 2.7 Ma (Fig. 7). Taking into account this result together with the CL images, we interpret that this date represents the crystallization age of the granodioritic proto-lith. Younger ages can be the result of a subsequent metamorphic event or lead loss occurred in the magmatic zircon, whereas slightly older ages can be interpreted as Pan-African inheritance (see Abati et al., 1999, 2007). Other less abundant inherited components include Paleoproterozoic (between 2.0 and 2.1 Ga) and Neoarchean (around 2.6 Ga).

6. Sm–Nd and Rb–Sr geochemistry

The results are in Table 2. The granodioritic orthogneisses have slight-ly lower [143]Nd/[144]Nd values (0.512241–0.512298) than the tonalitic orthogneiss (0.512541–0.512597) or the metagabbros (0.512436–0.512575). εNd values have been calculated using the crystallization age obtained in sample 107899 by SHRIMP (492 Ma). Initial [87]Sr/[86]Sr ver-sus εNd$_{(492\,Ma)}$ values are plotted in Fig. 8, and a clear difference can be established between the felsic and the intermediate to basic Corredoiras rocks. On one hand, the granodioritic orthogneiss samples cluster around negative εNd$_{(492\,Ma)}$ values (−2.2 to −3.6) and high ([87]Sr/[86]Sr)$_i$ ra-tios (0.707 to 0.708). On the other hand, tonalitic orthogneisses and metagabbronorites have positive εNd$_{(492\,Ma)}$ values (1.0 to 2.4) and low ([87]Sr/[86]Sr)$_i$ ratios (0.703 to 0.705). Additionally, two samples from this group are anomalous, a tonalitic orthogneiss (sample 107931) that has
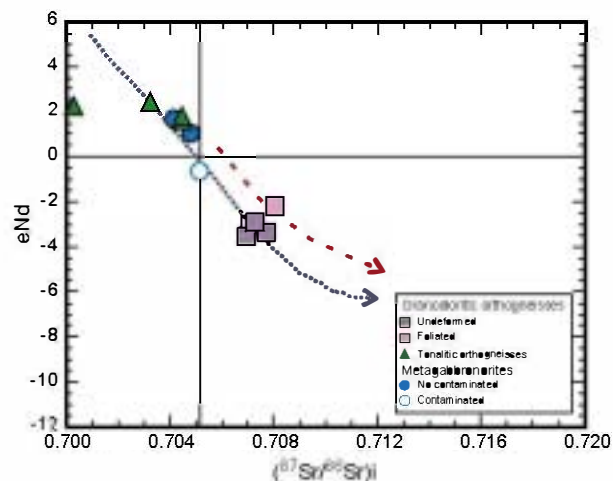

Fig. 8. ε$_{Nd}$ versus ([87]Sr/[86]Sr)$_i$ diagram for some of the most typical lithologies of the Corredoiras massif. Dotted line: pattern of Andean batholiths (Rogers and Hawkes-worth, 1989), broken line: pattern of Lachlan Fold Belt I-type batholiths (McCulloch and Chappell, 1982).

the lowest ([87]Sr/[86]Sr)$_i$ ratio, which probably reflects isotopic bance during metamorphism, and contaminated metagabbronorite (sample 107913) that has slightly negative εNd$_{(492\,Ma)}$ value and higher
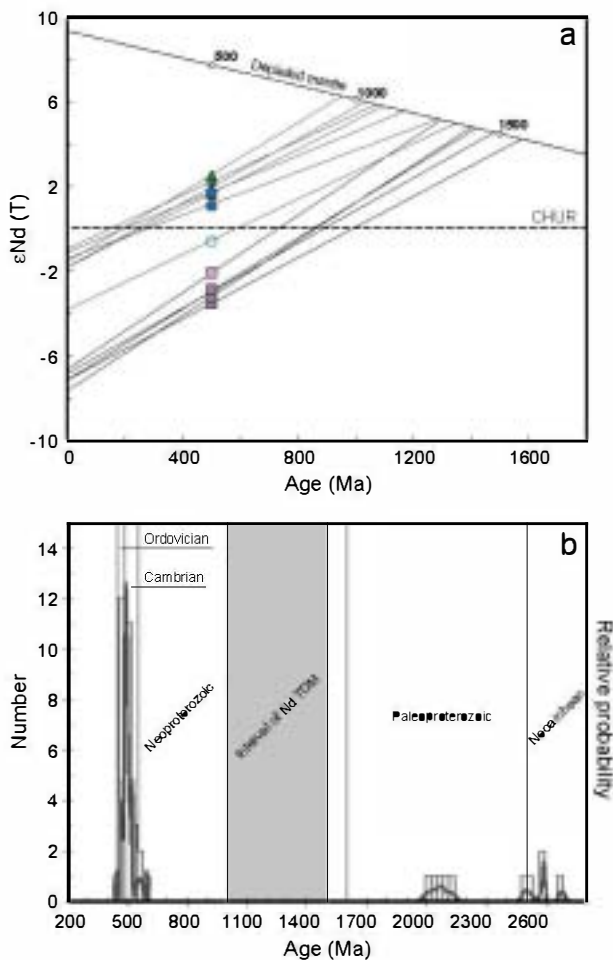

Fig. 9. a) ε$_{Nd}$ versus age diagram. Depleted mantle evolution calculated according to DePaolo (1981). b) Probability density plot with the ages obtained from inherited grains and xenocrystic cores. The gray field represents the model ages calculated from the Nd isotopes (TDM).

(^{87}Sr/^{86}Sr)$_i$ ratio, owing to crustal contamination during its generation. The relatively high values in Sr$_i$ and negative values in εNd of the grano-dioritic orthogneisses suggest that these rocks have a clear crustal influence in their generation, in contrast to the tonalitic orthogneisses and uncontaminated metagabbronorites, where the influence component is negligible and their origin can be related to basic magmas extracted from the mantle or from a basic lower continental crust.

In Fig. 8 we have also included the pattern followed by the Andean batholiths, studied by Rogers and Hawkesworth (1989) and the Lachlan Fold Belt batholiths (I-type) studied by McCulloch and Chappell (1982). It is evident that the Corredoiras metaigneous rocks are very similar to Andean batholiths, strengthening the hypothesis that these rocks were generated in a subduction zone where continental crust already existed.

Calculated depleted mantle model ages (TDM, see Table 2 and Fig. 9a; DePaolo, 1981) for the granodioritic orthogneisses range between 1300 and 1600 Ma, whereas tonalitic orthogneisses and metagabbros have slightly younger model ages (1000–1300 Ma). The absence of inherited zircon with these ages (Fig. 9b), the presence of older inherited zircon and the varied lithological constitution of the Corredoiras massif (basic to felsic rocks) suggest that the Nd model ages represent a mixture between juvenile material and
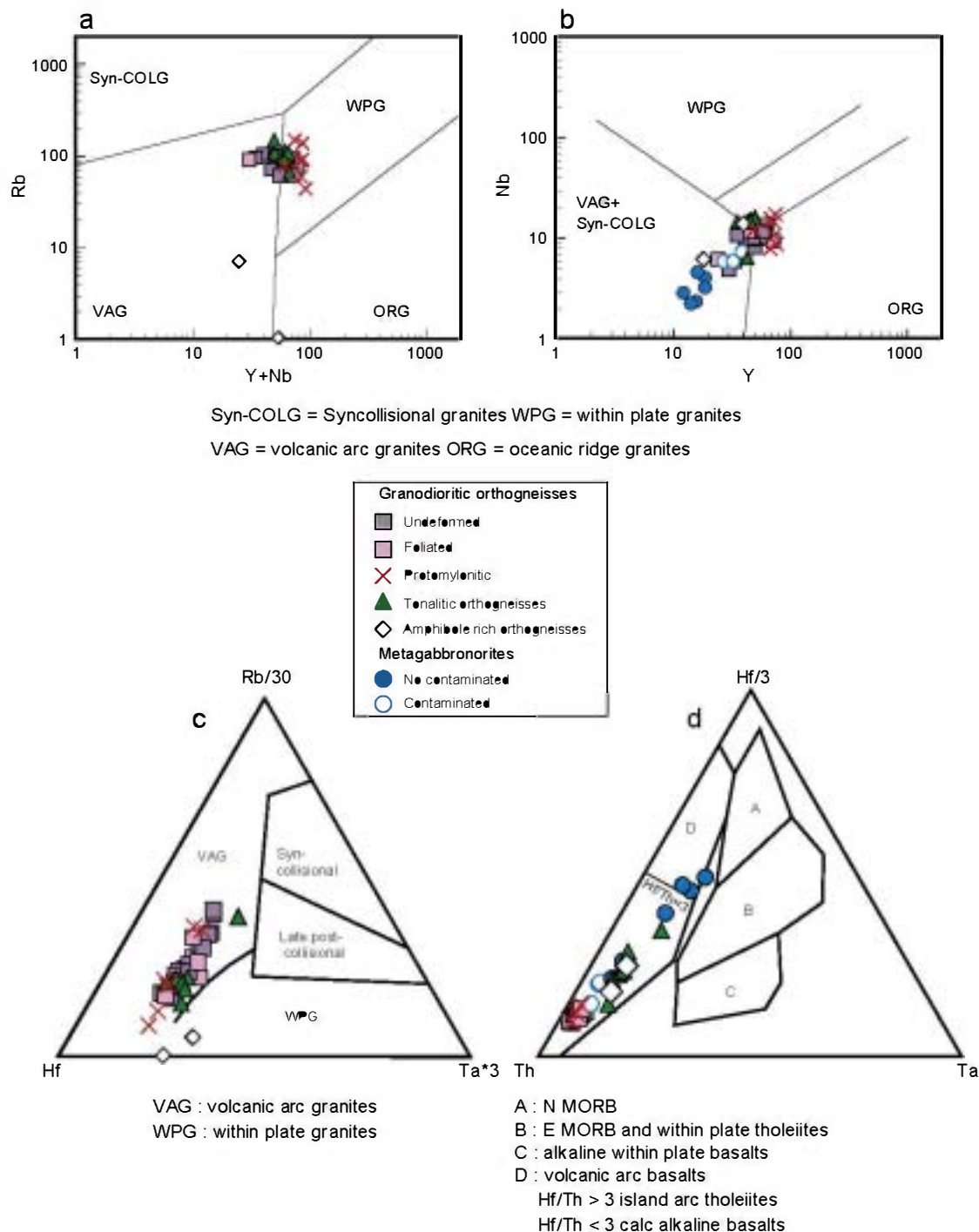

Fig. 10. Trace element discrimination diagrams for the metaigneous rocks of Corredoiras massif. a) Rb–Y + Nb and b) Nb–Y diagrams after Pearce et al. (1984); c) Rb–Hf–Ta diagram (Harris et al., 1986); d) Hf–Th–Ta diagram (Wood, 1980).

melting of an old crust. The older model ages of the granodioritic orthogneisses would indicate a higher proportion of old crustal components in the mixture, whereas more juvenile material would be necessary to explain the younger model ages of the tonalites and gabbros.

7. Tectonic setting

Calc-alkaline volcanic and plutonic rocks have long been recognized as the products of arc magmatism occurring at convergent plate boundaries. The plutonic roots of those arc systems are often exposed in old terranes, generally following collision/accretion, uplift and erosional events. To determine the tectonic setting of the Corredoiras massif, we have used standard discrimination diagrams for granitoids, i.e., Y + Nb vs. Rb, Y vs. Nb (Pearce et al., 1984) and Rb/30–Hf–Ta 30 (Harris et al., 1986). In the Y + Nb vs. Rb and Y vs. Nb diagrams (Fig. 10a and b, respectively), the Corredoiras felsic and intermediate rocks plot in the volcanic arc granites field (VAG) close to the ocean ridge granites (ORG) or the within plate granites (WPG). The Rb/30–Hf–Ta 30 diagram better discriminates the tectonic setting for these rocks (Fig. 10c); all of the felsic and intermediate metaigneous rocks plot in the volcanic arc granites field. We have also plotted all the Corredoiras rocks in the Hf/3–Th–Ta diagram (Wood, 1980) (Fig. 10d), which allows an accurate discrimination of subduction related rocks. Most of the samples plot in the volcanic arc field with calc-alkaline affinity (Hf/Th<3), except for three gabbros that have tholeiitic affinity (Hf/Th>3).

In the Zr/Y vs. Zr diagram (Pearce, 1983), the metagabbronorites plot in the continental island arc field (Fig. 11a). In the $(La/Sm)_N$ vs. Zr/Y diagram (Fig. 11b), where the La/Sm ratio is normalized to primitive mantle (Bolhar et al., 2003), all of the Corredoiras metagabbronorites plot as crustally contaminated rocks, which is consistent with their low MgO and Cr content and relatively high Na_2O and K_2O contents.

Trace element abundances for each group of Corredoiras samples can be normalized to the average composition of rocks from a specific geodynamic setting to determine more accurately their origin. We have used the average ORG composition from Pearce et al. (1984) for all the orthogneisses, whereas the basic rocks have been normalized to the N-MORB composition (Pearce, 1996). All orthogneisses are characterized by a highly fractionated trace element pattern (Fig. 12), with a strong enrichment in Th and slightly enriched in Ce and Hf compared to ORG. They display significant negative anomalies in Ta, Nb and Zr, which together with their low contents in Y and Yb are characteristic of granitoids generated in volcanic arc or subduction zones. The amphibole-rich orthogneisses also have negative anomalies in Ta and Nb and the same low content in Yb. Comparing our samples with the average andesite–dacite–rhyolite association from island and continental arcs according to Drummond et al. (1996), the granodioritic and tonalitic orthogneiss patterns are similar to the continental arc association (Fig. 12d), even though the Corredoiras orthogneisses are slightly enriched in most of the elements. Amphibole-rich orthogneisses plot between the island and continental arc patterns. In a similar diagram, the metagabbros pattern (Fig. 13) resembles continental arc basalts with high K (Pearce, 1996). They also show a slight enrichment in Th, more pronounced in the contaminated gabbros. All the metagabbros have a negative anomaly in Nb, which is typical of igneous rocks generated in a subduction zone.

8. Discussion and conclusions

The Corredoiras massif metaigneous rocks have geochemical, U–Pb and Sm–Nd compositions indicating that they belong to the Cambro–Ordovician (520–495 Ma) magmatic episode recorded in the upper units of the allochthonous complexes (Abati et al., 1999, 2007; Santos et al., 2002). The geochemical characteristics point out that the Corredoiras metaigneous rocks have been generated in a magmatic arc and that continental crust was involved in the origin of the magma. This hypothesis is also backed up by the presence of metasedimentary enclaves and biotite-rich microenclaves within them. Major element geochemistry resemble I-type granite features (high K_2O and Na_2O contents, negative slope in P_2O_5 with increasing SiO_2 and weak peraluminous character). Their incompatible elements enrichment, negative anomalies in Nb, Ta, Sr, P and Ti are typical of continental arcs. High Th values and low Ba/Th ratios indicate a sediment participation or continental crust contamination in the magmas that originated the Corredoiras rocks. A negative εNd value in the granodioritic orthogneisses may be also considered as evidence for the involvement of felsic crustal material during the genesis of these rocks. On the contrary, tonalitic orthogneisses and metagabbros have a positive εNd value that can be produced by mantle derived melts or by lower crustal melts.

The presence of inherited zircons that also appear in other igneous rocks of the upper units, suggests that this continental crust could belong to the West African Craton. Detrital zircon ages from low grade metasediments of the upper units (Martínez Catalán et al., 2009) also record the major crust forming events in NW Africa: this evidence points to a common basement for the upper units, and suggests that the island arc was ensialic and may represent a peri-Gondwanan fragment which drifted away opening the Rheic Ocean. Martínez
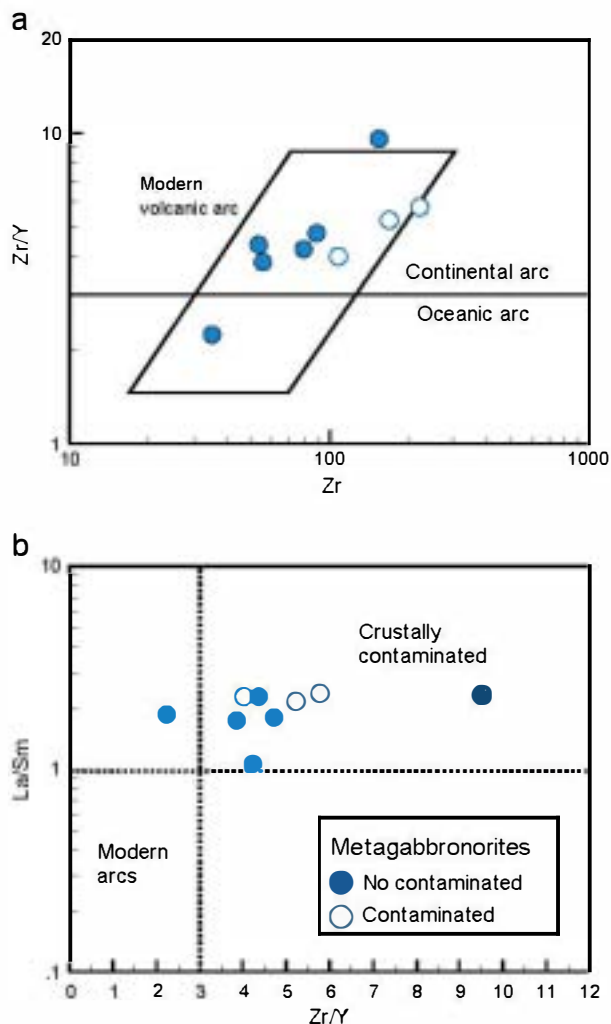

Fig. 11. a) Zr/Y–Zr diagram (Pearce, 1983) and b) La/Sm–Zr/Y diagram (Bolhar et al., 2003) for metagabbronorites samples.
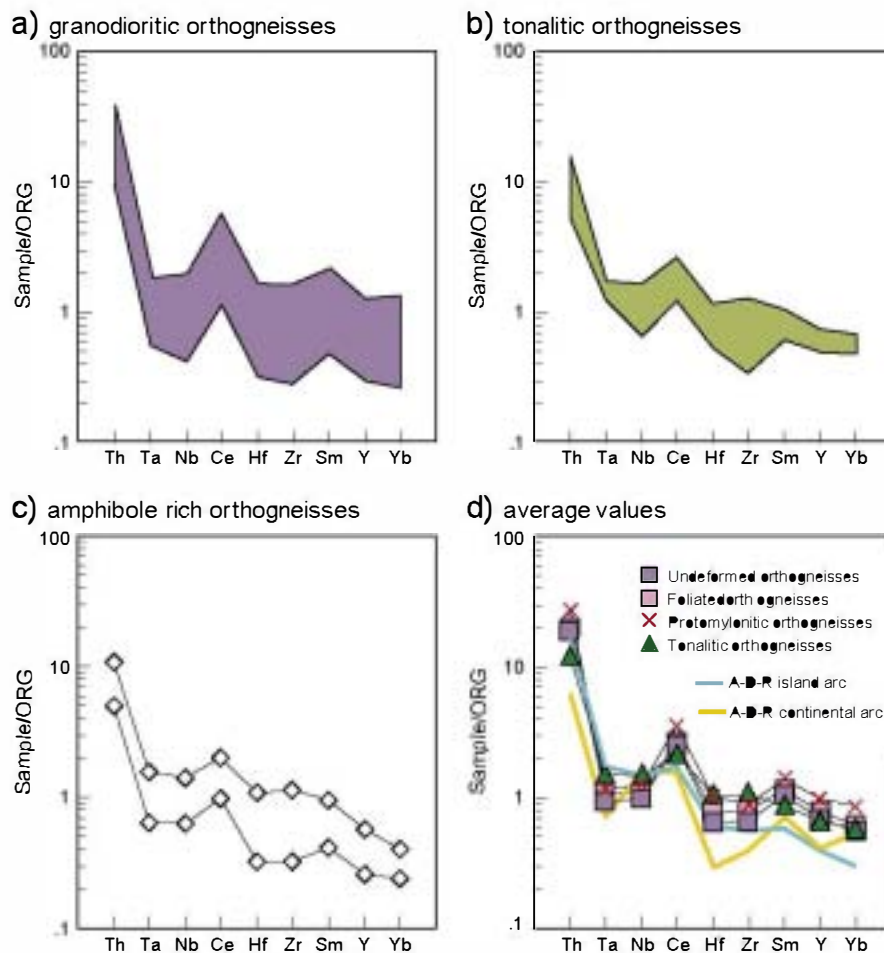
Fig. 12. Immobile trace element plots of the Corredoiras orthogneisses. Normalizing values correspond to ORG average composition according to Pearce et al. (1984). In a) and b) plots is represented the variation rank of the samples; d) plot shows the comparison of the Corredoiras orthogneisses with the average compositions of andesite–dacite–rhyolite (A–D–R) from island arcs and continental arcs (Drummond et al., 1996).

Catalán et al. (2007) proposed a model reconstructing the tectonic evolution of the allochthonous complexes from Galicia. In this model can be seen that around 500 Ma a Peri-Gondwanan terrane is detached from the Gondwana margin by slab roll-back and an arc-related magmatic activity during Late Cambrian–Early Ordovician.
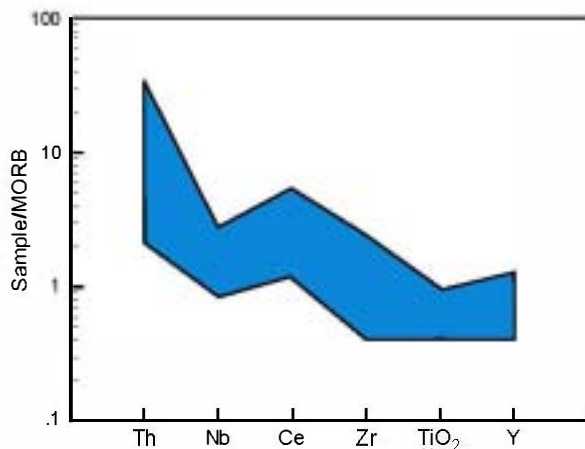

Fig. 13. Immobile trace element plot of the Corredoiras metagabbros. Normalizing values correspond to N-MORB average composition according to Pearce (1996). Shading zone is the compositional range for all samples.

We propose that the magmatic rocks of the Corredoiras massif were generated in this realm, probably located in the arc inner zone, where the magmas can be strongly influenced by the continental crust (Fig. 14).

Later on, this arc was involved in the Variscan collision. A Cambro–Ordovician arc-related metamorphism was preserved in the intermediate-P units, but was overprinted by a Silurian–Early Devonian tectonometamorphic event in the high-P and high-T units. This event involved subduction of part of the arc, as a consequence of its accretion to Laurussia while the Rheic Ocean was still open.

Supplementary materials related to this article can be found on-line at doi:10.1016/j.lithos.2011.11.005.
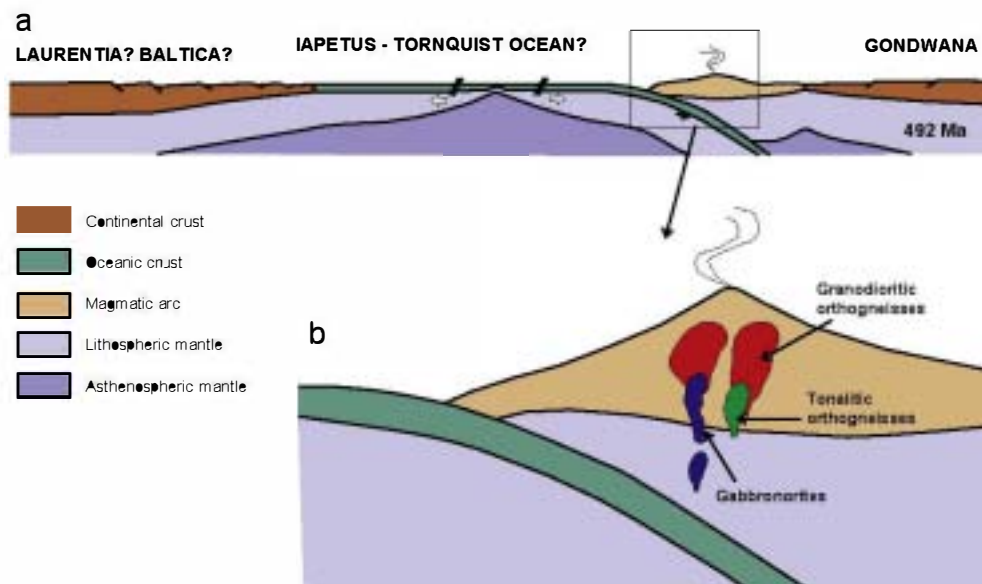
Fig. 14. Geodynamic sketch showing the magma generation of the Corredoiras metaigneous rocks. a: General location of the magmatic arc in the Gondwana margin. b: Sketch of the possible source of the Corredoiras metaigneous rocks: granodioritic orthogneisses probably were generated in the arc crust, tonalitic orthogneisses could be either generated in the lower crust or in the mantle, and gabbronorites were generated in the mantle and some of them were contaminated by either the arc crust or by a granodioritic magma.

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