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Late Cambrian magmatic arc activity in peri-Gondwana: geochemical evidence from metagranitoid rocks of the Basal Allochthonous Units of NW Iberia

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ABSTRACT

The North African section of the Gondwana margin was the site of voluminous, arc-related magmatism during the Late Neoproterozoic (Avalonian–Cadomian orogen). The lower (and older) metasedimentary sequence that constitutes the Basal Units of the Allochthonous Complexes of NW Iberia was deposited in that setting. In these units, sedimentation was followed by the intrusion of tonalites and granodiorites in the late Cambrian (*ca.* 493–489Ma). In the Late Paleozoic, the collision of Gondwana and Laurussia (Variscan orogeny) deformed and metamorphosed the whole ensemble.

New whole rock geochemical analysis performed in seven samples of metatonalites and fourteen samples of metagranodiorites are characterized by: i) slight enrichment in incompatible elements (Rb, Ba, Th, U), ii) negative anomalies in Nb, Ta, P, and Ti, and iii) negative anomalies in Eu. These chemical features are in agreement with a subduction-related setting for the genesis of both types of magma, which is also supported by chemical discrimination using tectonic setting diagrams. Positive anomalies of Pb suggest a crustal component. The new geochemical data reveal that the convergent orogen that ruled the paleogeography of the Gondwana periphery during the Neoproterozoic (Cadomian orogen) remained active beyond the Neoproterozoic-Cambrian transition, up to at least late Cambrian times.

KEYWORDS **Convergent margin. Subduction. Magmatism. Whole rock geochemistry. NW Iberian Massif.**

INTRODUCTION

The geochemical characterization of igneous rocks is the main source of information about the origin and evolution of magmas, and it is widely used to investigate the geodynamic setting of ancient terranes. The basic principles underlying this methodology assumes that magmas generated by similar geologic processes share common geochemical and isotopic features, making possible the comparison through tectonic setting discrimination diagrams (*e.g.* Pearce and Cann, 1973; Floyd and Winchester, 1975; Pearce *et al.*, 1984; Winchester *et al.*, 1995). Although the complexities of magmatic processes and the interaction of magmas with the wall rocks can sometimes make the interpretation of geochemical data not straightforward (*e.g.* Frost and Mahood, 1987; Castro *et al.*, 1991; Neves and Vauchez, 1995; Chappell, 1996), their use in combination with other independent geological evidences are still the best tool to interpret magmatism and its geological setting.

The northern margin of Gondwana was active during the Neoproterozoic (*e.g.* Nance *et al.*, 1991). This is evidenced in some sections of the Iberian Massif where Neoproterozoic deformation was accompanied by magmatic arc activity (Fernández-Suárez *et al.*, 1998; Nance *et al.*, 2002; Bandrés *et al.*, 2004; Castiñeiras *et al.*, 2008; Pereira *et al.*, 2011; Henriques *et al.*, 2015; Orejana *et al.*, 2015; Rubio-Ordóñez *et al.*, 2015). The long-lived tectonic activity along this margin, related to the dynamics of a coupled subduction-arc system, generated a complex ensemble of peripheral terranes, the peri-Gondwanan terranes (Avalonian–Cadomian orogeny; Quesada, 1990; Nance and Murphy, 1994; Eguíluz *et al.*, 2000; Linnemann *et al.*, 2000; Murphy *et al.*, 2004). Subduction polarity during the Neoproterozoic is unanimously considered as directed towards Gondwana.

It is generally accepted that the system of peripheral magmatic arcs flanking northern Gondwana by the late Neoproterozoic gradually gave way to a passive margin, through the development of a rifting and the corresponding back-arc that gave way to the opening of the Rheic Ocean during the Lower Paleozoic (Sánchez-García *et al.*, 2003; Linnemann *et al.*, 2007; Nance *et al.*, 2010; Fuenlabrada *et al.*, 2016). Most models propose that the back-arc rifting that gave birth to the Rheic Ocean was fully active during Cambro-Ordovician times (*ca.* 540–450Ma; Crowley *et al.*, 2000; Linnemann *et al.*, 2004, 2008; Murphy *et al.*, 2006; Díez Fernández *et al.*, 2015), and that extension was likely dominated by Iapetus slab pull (*e.g.* Nance *et al.*, 2010 and references therein). However, other models consider that subduction beneath peri-Gondwana remained during the Cambrian and Ordovician (Abati *et al.*, 1999, 2010; Santos *et al.*, 2002; Arenas *et al.*, 2009; Díez Fernández *et al.*, 2010; Rubio-Ordóñez *et al.*, 2012; Andonaegui *et al.*, 2012, 2016a; Dias da Silva *et al.*, 2016), and that the Lower Paleozoic rifting resulted from extension in a broad back-arc region (Arenas *et al.*, 2007; Abati *et al.*, 2010; Díez Fernández *et al.*, 2012a). The late Cambrian-Upper Ordovician magmatism in the Upper Parautochthon of the Galicia-Trás-os-Montes in Morais (NE Portugal) and in the Basal Units was originated in this back-arc setting and probably in the Gondwana side of the basin (extended continental crust evolving to a passive margin setting, Dias da Silva *et al.*, 2016).

Whether subduction existed or not during Lower Paleozoic at the margin of Gondwana, as well as the position of passive margin are still a matter of debate. In this work, we present the main geochemical characteristics of the oldest (Late Cambrian) group of magmatic rocks from the Malpica-Tui Complex (NW Iberia), in order to determine their geodynamic context of formation. We build up on previous models and further discuss about Late Cambrian paleogeographic reconstructions of the perigondwanan domain that is preserved in the NW Iberian Massif of the Variscan orogen. Our data support that a Late Cambrian subduction-related magmatic activity existed in the perigondwanan realm located next to north Africa thus strengthening the idea of a long-lived active margin for this region, which caused back-arc extension, detachment and drifting of perigondwanan terranes (and magmatic arcs), oceanization and establishment of a passive margin in N-Gondwana.

GEOLOGICAL SETTING

Neoproterozoic and Paleozoic rock series that formed in the margin of Gondwana are currently exposed as juxtaposed geotectonic units along the so-called Variscan belt (Quesada *et al.*, 1994; Martínez Catalán *et al.*, 1997; Franke, 2000; von Raumer *et al.*, 2003; Ballèvre *et al.*, 2009; Faure *et al.*, 2009; Rossi *et al.*, 2009; Schulmann *et al.*, 2009; Arenas *et al.*, 2016a). Juxtaposition resulted from the progressive collision of Gondwana and Laurussia during the Late Paleozoic (Matte, 1991; Ribeiro *et al.*, 2007; Martínez Catalán *et al.*, 2009; Kroner and Romer, 2013; Díez Fernández *et al.*, 2016).

One of the salient features of the Variscan orogen in NW Iberia (Fig. 1) is the presence of a Variscan tectonic pile of far-travelled units resting on top of sedimentary and igneous sequences (Ries and Shackleton, 1971) with Gondwana derivation (Martínez Catalán *et al.*, 2004). The overriding tectonic units are divided according to their continental or oceanic affinity, structural position, and tectonothermal evolution (Arenas *et al.*, 2016, and references therein). These units occur in tectonic klippen (Martínez Catalán *et al.*, 2007, 2009) that can be extended to SW Iberia (Díez Fernández and Arenas, 2015), and are collectively referred to as the Allochthonous Complexes (Arenas *et al.*, 1986).

In the upper structural position of the Allochthonous Complexes of NW Iberia (Fig. 1), the Upper Units show continental affinity and Gondwanan provenance (Fernández-Suárez *et al.*, 2003; Albert *et al.*, 2015a, 2015b). On the grounds of metamorphic, geochronological and geochemical data, these units are considered as tectonic slices of a Cambrian perigondwanan arc (Abati *et al.*, 1999; Santos *et al.*, 2002; Andonaegui *et al.*, 2002, 2012, 2016b; Castiñeiras, 2005; Fuenlabrada *et al.*, 2010; Albert *et al.*, 2015a). A group of ophiolitic units lies in an intermediate structural position (Fig. 1) and accounts for tectonic slices of Cambrian–Ordovician and Devonian oceanic to transitional crust, variably metamorphosed and

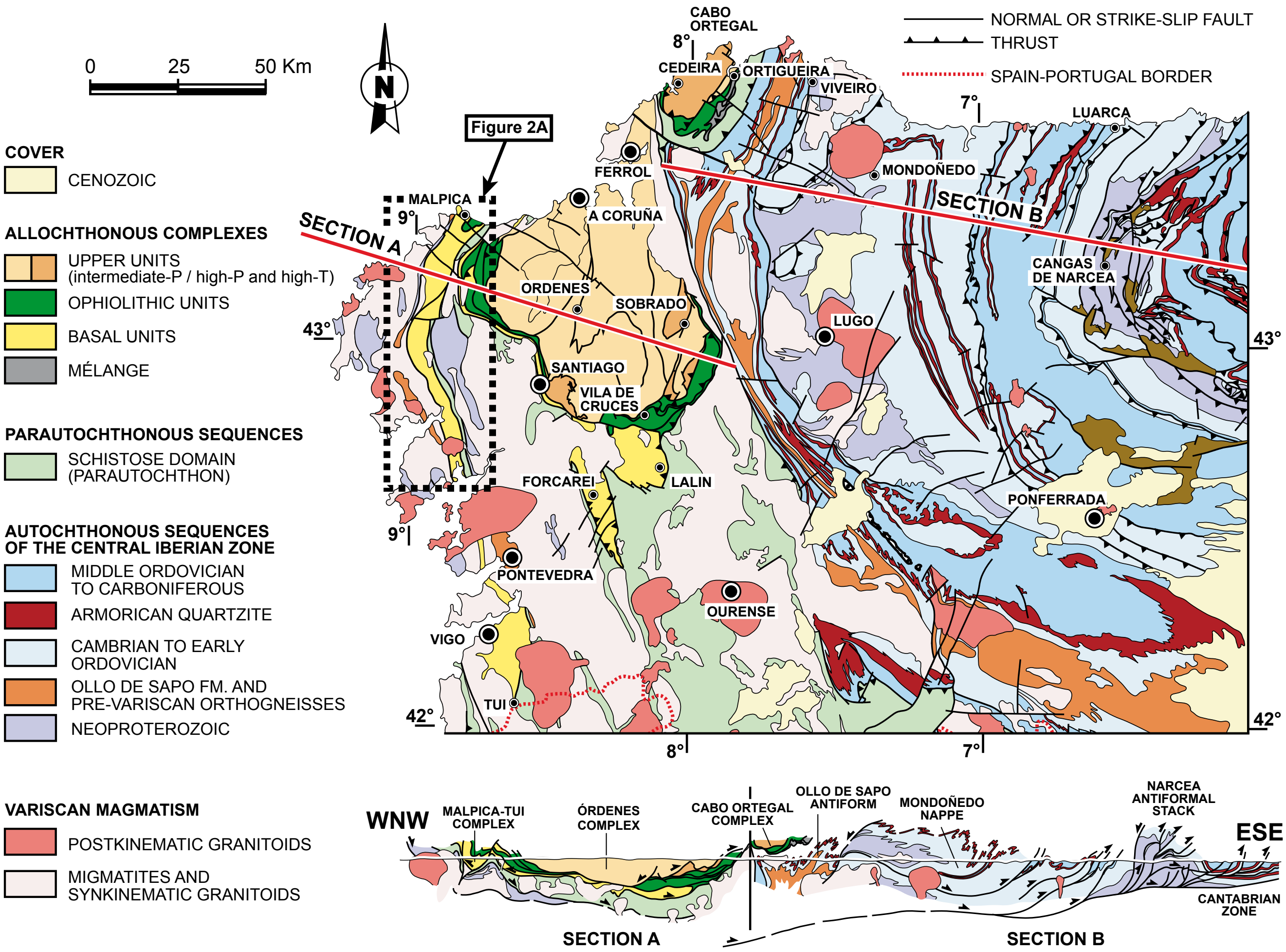

FIGURE 1. Map and composite cross-section of the NW part of the Iberian Massif. Note the structural position of the Basal Units of the Allochthonous Complexes (after Martínez Catalán *et al.*, 2007). The location of the inset shown in Figure 2A is indicated with a thick dashed line.

deformed during the Variscan orogeny (Arenas and Sánchez Martínez, 2015). In the lower structural position (Fig. 1), the Basal Units show continental affinity (Arenas *et al.*, 1986; Rodríguez Aller, 2005) and Gondwanan provenance (Díez Fernández *et al.*, 2010, 2013; Fuenlabrada *et al.*, 2012). The Malpica-Tui Complex is the best exposure of these lower units (Fig. 2A).

The Basal Units of the Allochthonous Complexes of NW Iberia

The Basal Units are variably affected by late Devonian high-P metamorphism (Santos Zalduegui *et al.*, 1995; Rodríguez *et al.*, 2003; Abati *et al.*, 2010), ranging from eclogite to blueschist facies conditions (Gil Ibarguchi and Ortega Gironés, 1985; Arenas *et al.*, 1995; Gil Ibarguchi, 1995; Rubio Pascual *et al.*, 2002; López-Carmona *et al.*, 2010, 2013, 2014). This event represents the westward oblique subduction of the Basal Units beneath the rest of the allochthonous units in late Devonian times (Martínez Catalán *et al.*, 1996; Díez Fernández *et al.*, 2012b). Deformation associated with the subduction-exhumation process is highly heterogeneous (*e.g.* Martínez Catalán *et al.*, 1996; Llana-Fúnez and Marcos, 2002; Díez Fernández *et al.*, 2011, 2012b), thus enabling observation of primary protolith features and reconstruction of the original lithostratigraphy (Fig. 2B; Díez Fernández *et al.*, 2010).

The Basal Units are formed by two tectonically juxtaposed sequences: i) a lower sequence dominated by felsic orthogneisses and metasedimentary rocks, and ii) an upper sequence that comprises metasedimentary rocks intercalated with MORB-type metavolcanic rocks (Floor, 1966; Arps, 1981; Llana Fúnez, 2001; Rodríguez Aller, 2005; Díez Fernández *et al.*, 2010).

They correspond, respectively, to the lower and middle allochthon of the Variscan nappe stack in the Ibero-

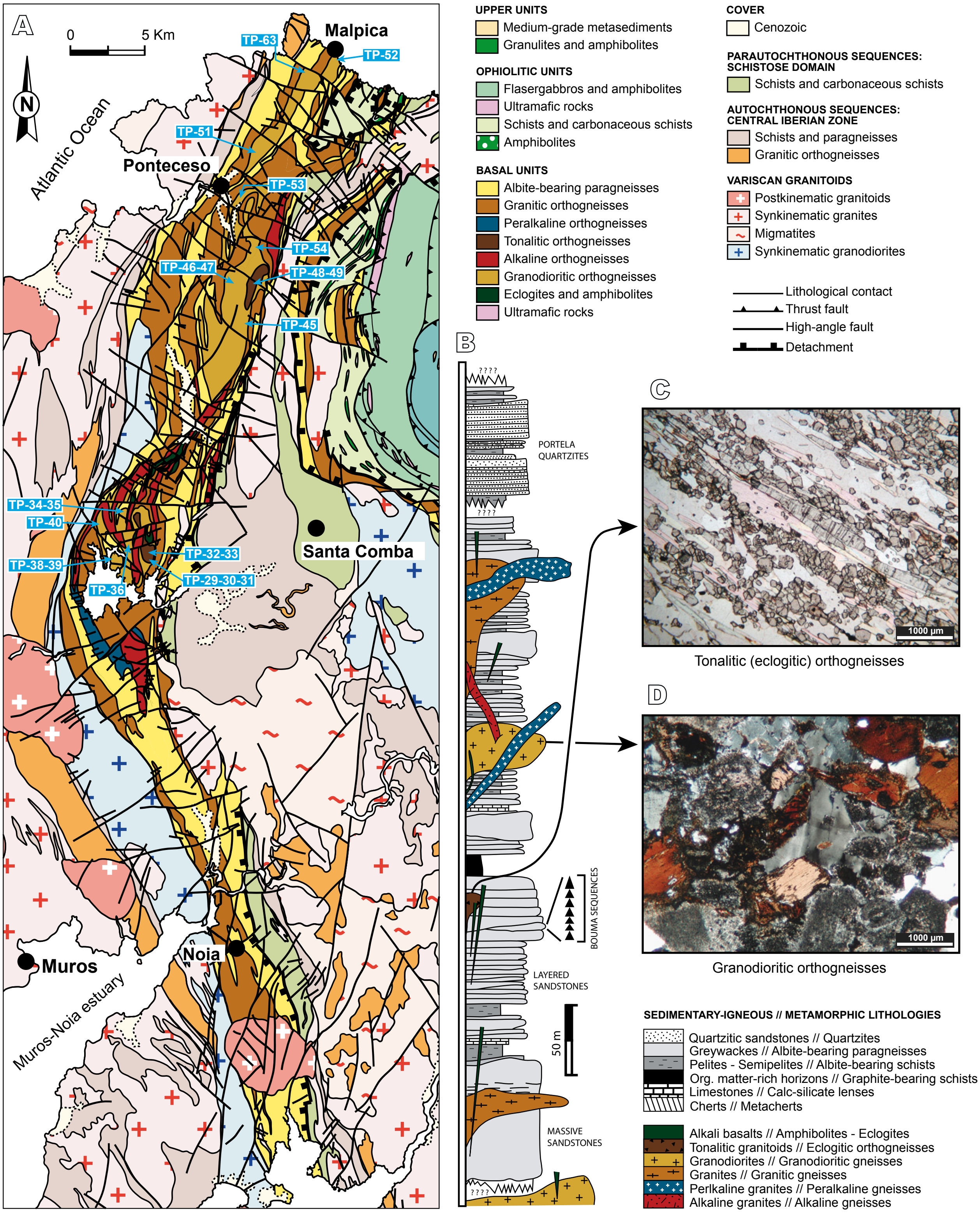

FIGURE 2. A) Geological map of the northern section of the Malpica-Tui Complex and its relative autochthon (Díez Fernández, 2011; Díez Fernández *et al.*, 2011). See regional location in Figure 1. The location of samples selected for geochemical analysis is included. B) Idealized lithostratigraphic column of the lower sequence of the Basal Units (Díez Fernández *et al.*, 2010). C) Main foliation of the metatonalites (eclogitic orthogneisses) defined by quartz, white mica, omphacite, garnet and zoisite (plane polarized light). D) Non-deformed metagranodiorite with hypidiomorphic inequigranular texture defined by plagioclase, quartz, biotite and K-feldspar. Note the growth of garnet coronas around biotite and the partial replacement of plagioclase by albite, clinozoisite, and phengite (cross polarized light).

Armorican Arc (Ballèvre *et al.*, 2014). The sedimentary series of the lower sequence was originally formed by greywackes, arranged as siliciclastic turbiditic cycles together with ampelitic shales, semipelites, and scarce carbonate-rich layers, cherts, and quartzites (Fig. 2B). The sediments of the upper sequence defined a series dominated by pelites and semipelites that intercalated thin layers of ampelitic shale, greywacke, quartzite, and carbonate-rich material. The depositional age of the metasedimentary rocks of the upper sequence ranges between Middle Cambrian and Ordovician, whereas the lower sequence is Ediacaran (maximum age calculated from detrital zircon; Díez Fernández *et al.*, 2010, 2013). Both sequences are separated by an extensional tectonic contact (López Carmona *et al.*, 2010).

METAIGNEOUS ROCKS OF THE MALPICA-TUI COMPLEX

The metasedimentary rocks of the lower sequence of the Basal Units are intruded by granitoids, later transformed into orthogneisses, with compositions ranging between quartz-syenites, high- K granites, granites, granodiorites and tonalites (Fig. 2A). This sequence also contains less abundant alkaline mafic rocks (Rodríguez Aller, 2005), which now occur as amphibolites and variably retrogressed eclogites. The granitic rocks define two compositional suites (Floor, 1966; Arps, 1970; Montero, 1993; Montero *et al.*, 1998, 2009; Rodríguez Aller, 2005): a dominant suite with calc-alkaline composition and intruded by the mafic rocks (*ca*. 493–480Ma; Montero *et al.*, 2009; Abati *et al.*, 2010; Díez Fernández *et al.*, 2012a), and a younger suite with alkaline-peralkaline affinity (*ca*. 480–470 Ma; Rodríguez *et al.*, 2007; Montero *et al.*, 2009; Díez Fernández *et al.*, 2012a). The alkaline-peralkaline granitoids are not intruded by the mafic rocks, which thence can be interpreted as a dyke swarm emplaced in between the two granitic suites. Dating of the alkaline-peralkaline granites places the age of the alkaline mafic dykes that intruded the calc-alkaline granites at ~480–475Ma.

The calc-alkaline suite comprises granitic compositions that range between high- K granites and granites (alkali granites), granodiorites and tonalites. However, the tonalites and granodiorites are consistently the oldest rocks among the suite and intruded, compared to the alkali granites, in a rather narrow time interval (*ca*. 493–489Ma; Abati *et al*., 2010; Díez Fernández *et al*., 2012a). The ages of the alkali granites spread towards the age of the alkaline-peralkaline granitoids, suggesting a transition between the two main suites.

Previous geochemical and geochronological studies proposed different interpretations for the origin of the two magmatic suites. Rodríguez Aller (2005) proposed a model in which both (calc-alkaline and alkaline-peralkaline) would be cogenetic post-collisional suites, related to a single magmatic evolution. In contrast, Abati *et al.* (2010) suggested two separate events. The Cambrian calc-alkaline magmatism would be related to the waning stages of arc activity associated with subduction beneath the northern margin of Gondwana. Then, a switch from subduction to rifting would be marked by the intrusion of alkaline magmas during the Ordovician (see Díez Fernández *et al.*, 2012a for further refinement).

Our contribution focuses on the oldest group of metagranitoids (metatonalites and metagranodiorites) intruding the lower sequence of the Basal Units. We have paid particular attention to this group because previous background suggests that it represents one of the compositional poles of the magmatism that affected these units. Therefore, characterizing its geochemical features and tectonic setting may contribute to a better understanding of the evolving paleogeography of the perigondwanan realm in Lower Paleozoic times. What follows is a short description of the two lithologies analysed.

Tonalitic gneisses

They are relatively scarce and appear as lens-shaped bodies associated with the granodioritic gneisses. Numerous tabular bodies of metabasites form a dike swarm intruding them, usually of several tens of cm thick. These relationships are evident in the field, despite the pervasive and strong plano-linear tectonic fabric developed under eclogite facies conditions. Non-deformed or poorly-deformed facies of these metatonalites are lacking. They preserve low-retrogressed eclogitic parageneses formed by quartz, white mica, omphacite, garnet and zoisite as major minerals, and kyanite, apatite and zircon as accessory minerals (Fig. 2C). A fine to medium-grained banding with quartz-mica rich felsic domains alternate with garnet-omphacite-zoisite rich mafic domains defining a gneissic structure. The mafic dykes are transformed into variably retrogressed eclogites, most of them containing garnet, omphacite and rutile ± phengite. The effects of a later retrogressive, amphibolite to greenschist facies metamorphic event are widespread.

Granodioritic gneisses

The metagranodiorites are affected by heterogeneous deformation. The original igneous texture is well preserved in the less deformed domains. It is hypidiomorphic inequigranular and formed by plagioclase, quartz, biotite, and K-feldspar (Fig. 2D). In such domains, the event of high-P metamorphism is only evident in coronitic textures, featured by the growth of garnet coronas around biotite, accompanied rarely by the partial replacement of biotite by fine-grained phengite and rutile, and a variable degree of replacement of plagioclase by albite, clinozoisite, and phengite. In very few cases, the corona textures around biotite include jadeite (Gil Ibarguchi, 1995), although this mineral is more commonly found in finer grained rocks, such as aplitic veins. The high-strain domains show a strong plano-linear tectonic fabric defined by a combination of variably deformed igneous porphyroclasts and metamorphic minerals. In these cases, quartz-feldspathic bands and lenses consisting of plagioclase, K-feldspar (sometimes with augen texture) and quartz, alternate with aggregates of biotite, titanite, allanite, zircon, apatite, opaque minerals, amphibole, garnet and white mica. In the most deformed facies of these gneisses, aggregates of garnet, phengite and epidote make most of the ferromagnesian fraction.

SAMPLING STRATEGY AND ANALYTICAL METHODS

Seven samples of metatonalites and 14 samples of metagranodiorites were selected for whole-rock chemical analysis. Sampling locations are shown in Figure 2A. The metatonalites were collected from sites located as far as possible from mafic dykes. The less deformed and metamorphosed facies of metagranodiorites were preferentially selected for analysis.

The samples were crushed with a steel jaw crusher and powdered to 200 mesh grain size in an agate mill at the Universidad Complutense de Madrid. Chemical analyses were carried out at Activation Laboratories Ltd. (Actlabs) in Canada using the 4Lithoresearch procedure. Chemical digestion with lithium metaborate/tetraborate was followed by measurement of elemental concentrations via inductively coupled plasma mass spectrometry (ICP-MS). Chemical data are included in Table 1.

GEOCHEMICAL DATA

Whole-rock geochemistry

In the following paragraphs, we will refer to the following compositional parameters: Fe number (Fe_n) = $FeO_t/(FeO_t+MgO)$; molar alumina saturation index (ASI) = $Al_2O_3/(CaO+Na_2O+K_2O)$; modified alkali lime index (MALI)= (Na_2O+K_2O)- CaO and Al/Na+K.

The tonalitic gneisses are intermediate rocks with SiO_2 contents (wt.%) between 51.61–64.06, low K_2O (0.16–1.99) and moderate Na_2O (1.91–3.65) contents (Table 1). The compositional variability expressed according to the above parameters is: Fe_n = 0.49 to 0.67; MALI = -8.19 to - 0.31 and ASI 0.76 to 0.99. Following the diagrams by Frost *et al.* (2001) (Fig. 3), they are calcic, magnesian,

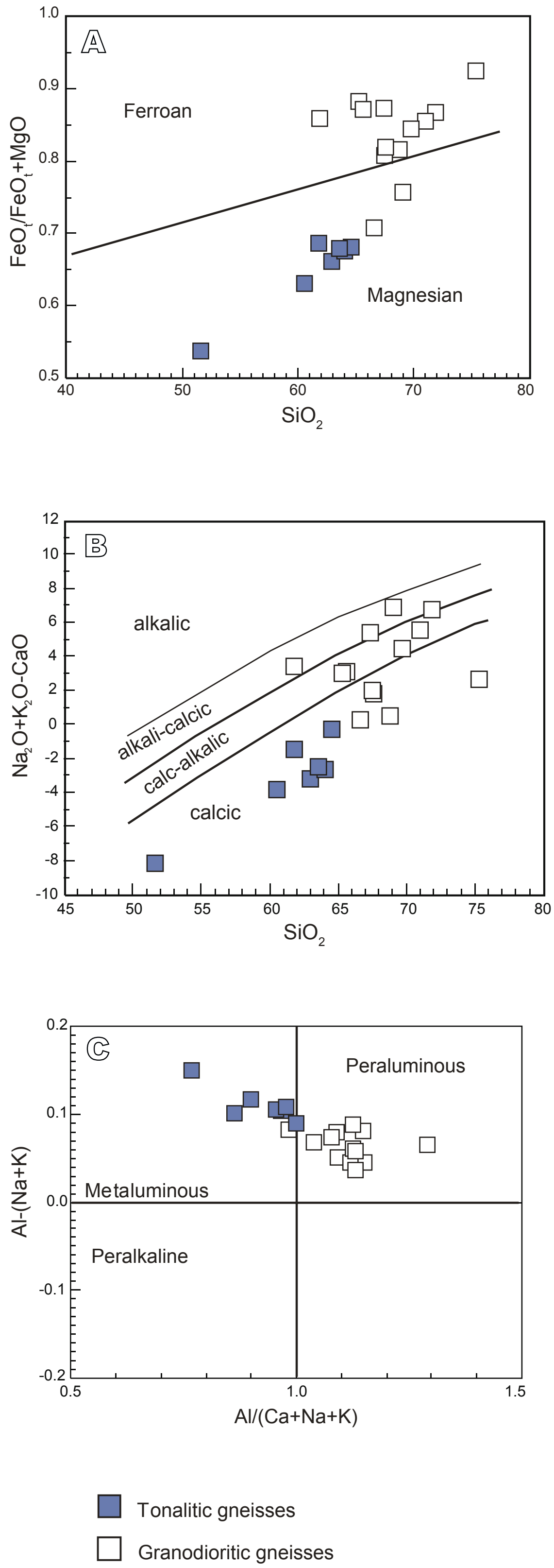

FIGURE 3. Geochemical classification for tonalitic and granodioritic gneisses (Frost *et al.*, 2001). A) $FeO_t/(FeO_t+MgO)$ *vs.* weight per cent SiO_2. B) Plot of modified alkali-lime index (MALI = Na_2O+K_2O-CaO) against % weight SiO_2. C) Molar alumina saturation index *vs.* $Al_2O_3/(Na_2O+K_2O)$.

TABLE 1. Representative whole rock composition from the tonalitic and granodioritic gneisses of the Basal Units

Label	TP 29	TP 30	TP 31	TP 32	TP 33	TP48	TP 49	TP34	TP35
Rock type			Tonalitic gneisses					Granodioritic gneisses	
Major elements (wt.%)									
SiO_2	61.79	62.94	64.06	64.54	63.59	51.61	60.50	69.09	75.35
TiO_2	0.52	0.47	0.54	0.44	0.48	0.48	0.47	0.397	0.83
Al_2O_3	17.20	16.13	15.80	15.95	16.41	21.51	17.78	15.2	12.10
FeOt	5.46	5.34	5.44	4.85	5.47	4.09	5.01	3.18	3.80
MnO	0.09	0.09	0.10	0.08	0.10	0.06	0.09	0.08	0.06
MgO	2.73	3.06	2.87	2.82	2.83	4.31	3.50	1.29	0.41
CaO	6.14	7.08	6.28	5.06	6.24	12.0	7.65	1.45	2.31
Na_2O	2.71	2.92	2.10	2.86	1.91	3.65	3.12	2.74	2.73
K_2O	1.99	0.94	1.52	1.89	1.83	0.16	0.67	5.62	2.19
P_2O_5	0.10	0.08	0.11	0.09	0.09	0.10	0.10	0.24	0.09
LOI	1.41	0.93	1.05	1.14	1.14	1.52	1.20	0.88	0.67
Total	100.14	100.07	99.87	99.72	99.82	99.49	100.09	100.24	100.10
Fe n	0.67	0.64	0.65	0.63	0.66	0.49	0.59	0.71	0.90
ASI	0.97	0.86	0.95	0.99	0.98	0.76	0.90	1.15	1.09
MALI	-1.44	-3.22	-2.66	-0.31	-2.5	-8.19	-3.86	6.91	2.61
Al/Na+K	2.70	2.77	3.10	2.36	3.15	3.48	3.03	1.43	1.76
Trace elements (ppm)									
Rb	73	35	43	63	67	2	18	292	78
Cs	1.9	1.2	0.6	1.6	2.4	nd	0.6	24.4	3.6
Be	2	1	1	1	1	2	2	6	2
Sr	149	186	215	127	217	599	373	233	110
Ba	705	310	605	703	618	79	326	613	760
Sc	26	27	23	24	25	33	26	10	12
V	149	149	145	139	138	164	147	42	29
Co	18	19	22	17	30	15	23	15	23
Zn	60	60	80	60	50	70	50	60	60
Ga	19	16	17	17	17	21	19	20	16
Y	20.2	19.9	15.9	15.3	20.6	19.9	19.1	30.7	25.9
Nb	10.4	6.8	6.5	1.8	5	6.4	5.7	12.5	7.1
Ta	0.47	0.35	0.43	0.26	0.31	0.4	0.43	1.59	0.55
Zr	158	149	158	167	172	145	150	307	402
Hf	4.2	3.8	3.7	4.3	4.1	3.5	3.8	7.5	8.3
Th	5.58	6.25	6.8	3.84	6.37	7.6	8.27	58.6	16.2
U	1.92	2.33	2.75	1.52	2.34	1.61	3.11	29.1	2.31
La	20.3	19.1	19.5	11	18.9	24.8	26.9	105	89.6
Ce	38.1	35.8	35.4	21.4	36.3	45.8	47.9	209	166
Pr	4.6	4.09	3.94	2.47	4.11	5.11	5.78	23	17
Nd	17.6	15.7	14.4	9.41	16	19	21.3	80.7	56.8
Sm	3.66	3.36	3.19	2.03	8.4	4.02	4.35	14.1	8.53
Eu	0.79	0.74	0.78	0.45	0.75	0.95	1.15	1.32	1.12
Gd	3.76	3.37	2.96	2.24	3.68	3.62	4.11	8.41	5.73
Tb	0.58	0.52	0.47	0.38	0.56	0.61	0.61	1.08	0.77
Dy	3.53	3.26	2.70	2.41	3.26	3.64	3.28	5.35	4.26
Ho	0.68	0.64	0.50	0.53	0.68	0.69	0.60	0.98	0.83
Er	1.94	0.87	1.51	1.55	1.98	1.76	1.75	2.66	2.48
Tm	0.30	0.28	0.22	0.24	0.27	0.24	0.26	0.40	0.378
Yb	1.99	1.83	1.65	1.65	1.95	1.52	1.83	2.39	2.4
Lu	0.315	0.307	0.283	0.272	0.339	0.238	0.30	0.331	0.314
Eu/Eu*	0.63	0.66	0.76	0.64	0.35	0.75	0.82	0.20	0.28

TABLE 1. (Cont.)

Label	TP36	TP38	TP39	TP 40	TP 45	TP 46	TP 47	TP 51	TP53
Rock type	Granodioritic gneisses								
Major elements (wt.%)									
SiO_2	61.84	70.96	69.70	65.30	66.59	65.59	67.49	68.71	71.85
TiO_2	0.83	0.53	0.58	0.98	0.31	0.32	0.52	0.45	0.41
Al_2O_3	17.97	14.51	15.36	13.96	15.32	17.59	14.40	15.12	14.28
FeOt	5.46	3.08	3.15	7.38	4.22	3.32	5.13	3.36	2.34
MnO	0.10	0.04	0.06	0.11	0.07	0.05	0.09	0.06	0.03
MgO	0.99	0.68	0.74	1.08	2.07	0.59	1.43	1.13	0.46
CaO	3.24	1.70	1.78	2.58	4.80	3.65	3.52	3.97	1.15
Na_2O	4.44	3.56	3.47	2.95	2.45	3.85	2.58	2.44	3.51
K_2O	2.24	3.69	2.73	2.63	2.60	2.93	2.94	2.01	4.38
P_2O_5	0.28	0.14	0.12	0.31	0.08	0.05	0.12	0.09	0.10
LOI	1.35	0.73	1.48	1.23	1.31	1.64	0.95	0.74	0.87
Total	98.74	99.63	99.14	98.50	99.82	99.58	99.17	99.90	99.38
Fe n	0.85	0.82	0.81	0.87	0.67	0.85	0.78	0.82	0.84
ASI	1.15	1.12	1.29	1.13	0.98	1.08	1.04	1.15	1.13
MALI	3.44	5.55	4.42	3.0	0.25	3.13	2.0	4.77	6.74
Al/Na+K	1.84	1.47	1.77	1.81	2.24	1.85	1.94	1.55	1.35
Trace elements (ppm)									
Rb	104	119	88	146	90	103	110	97	167
Cs	4.5	5.1	3.4	8.2	3	3.6	4	4.2	6.2
Be	3	3	3	3	2	2	2	2	2
Sr	165	165	74	99	108	187	109	216	71
Ba	1018	1967	1365	1121	785	1453	855	846	1301
Sc	19	11	12	23	22	11	22	17	9
V	59	40	43	65	97	40	73	39	36
Co	13	9	8	19	17	9	20	13	9
Zn	80	60	40	100	70	50	70	40	60
Ga	25	21	24	22	16	20	17	21	19
Y	75.2	60.7	68.5	79.4	15.9	20.4	33.8	32.4	39
Nb	13.7	10.3	10.1	14.6	4.7	5.2	7.3	6.7	9.3
Ta	1.1	0.83	1.19	1.11	0.6	0.45	0.65	0.69	0.93
Zr	578	476	423	779	122	171	226	156	343
Hf	13	10.6	10	18.4	3	3.7	5	3.9	8.6
Th	7.82	21	21.9	14.6	7.48	9.44	11	8.47	24.1
U	4.97	3.24	6.9	6.08	2.59	2.76	3.71	2.42	5.98
La	46	75.6	69.5	55.5	20.1	27	37.9	46.1	69.4
Ce	86.1	147	141	109	32.1	47.3	84.2	69.3	134
Pr	10.6	16.6	16.1	14.1	3.38	5.03	8.2	6.12	15.9
Nd	43.9	63.9	61.9	57.2	11.5	17.4	29.2	35.1	59
Sm	11.9	12.8	13.1	13.8	2.31	3.25	5.65	6.95	12.9
Eu	2.14	1.47	1.64	1.83	0.42	0.78	0.84	1.3	1.04
Gd	11.9	11	10.6	12.9	1.94	2.86	4.95	5.86	11.9
Tb	2.12	1.76	1.75	2.18	0.37	0.5	0.83	0.9	2.1
Dy	13.2	10.4	10.8	13.5	2.42	3.2	5.38	5.3	13.3
Ho	2.57	1.99	2.18	2.56	0.52	0.68	1.1	1.06	2.75
Er	7.4	8.59	6.76	7.93	1.58	2.07	3.37	2.85	8.06
Tm	1.09	0.86	0.98	1.23	0.26	0.32	0.53	0.40	1.13
Yb	6.98	5.4	6.39	8.14	1.89	2.2	3.33	2.61	7.49
Lu	1.11	0.83	1.05	1.2	0.30	0.35	0.44	0.42	1.13
Eu/Eu*	0.34	0.23	0.25	0.26	0.36	0.46	0.29	0.21	0.16

and moderately metaluminous rocks. In Harker diagrams, Al_2O_3, MgO, CaO, and Na_2O show negative correlation with SiO_2, whereas the correlation with FeO_t and K_2O is positive. The trace element patterns normalized to Silicate Earth (McDonough and Sun, 1995) show slight enrichment in incompatible elements (Rb, Ba, Th, U), with negative anomalies in Nb, Ta, P, and Ti (Fig. 4A). Additionally, a positive anomaly of Pb is observed. Rare earth element contents are moderate (ΣREE = 56.03–120.12), but chondrite normalized diagrams (McDonough and Sun, 1995) show an enrichment of 100 times in LREE, and ten times in HREE (Fig. 4B), with slightly fractionated patterns [$(La/Lu)_n$ = 4.2–10.8]. The fractionation is higher in LREE [$(La/Sm)_n$ = 1.4–3.8] than in HREE [$(Gd/Lu)_n$=1–1.8]. They also show negative Eu anomalies ranging between 0.36 and 0.82.

The granodioritic gneisses are felsic rocks with SiO_2 contents (wt.%) between 61.8–75.35, moderate K_2O (2.01–5.62) and Na_2O contents ranging between 2.44–4.44. In the diagrams by Frost *et al.* (2001), they mainly plot into the ferroan and calcic to calc-alkalic fields, and some of them reach de alkali-calcic field (Fig. 3). They have a marked peraluminous character (Fe_n = 0.67–0.90; MALI = 0.25–6.91; ASI = 0.98–1.15). Similarly to the tonalitic gneisses, the trace element patterns normalized to Silicate Earth (McDonough and Sun, 1995) (Fig. 4C) show slight enrichment in incompatible elements such as Rb, Ba, and U, being particularly high in the case of Th. Negative anomalies in Nb, Ta, P, and Ti and a positive Pb anomaly are also present. The total content in rare earth elements is higher than in the tonalites (ΣREE = 79.0–454.7). The enrichment in LREE is 200 to 70 times that of the chondrite, and 50 times in the case of HREE (Fig. 4D), with fractionated patterns (La/Lu_n=4.3–32.9). Fractionation is higher in LREE (La/Sm_n=2.4–6.5) than in HREE (Ga/Lu_n = 0.7–3.1). The Eu anomaly is negative and higher than in the metatonalites (Eu/Eu*=0.15–0.47).

Tectonic setting diagrams

One of the most used tectonic setting discrimination diagrams for igneous rocks is the Rb *vs.* Y+Nb published by Pearce *et al.* (1984). The metatonalites and metagranodiorites of this study plot mainly into the volcanic arc granites field, with some of the granodiorites lying within the within plate granites field (Fig. 5A). Moreno *et al.* (2014) considered the relations between Y/Nb, Th/Nb, Th/Ta and Ce/Pb normalized to Silicate Earth to construct a set of diagrams with the aim of discriminating between oceanic island rocks and convergent margin rocks. Using Y/Nb *vs.* Th/Ta the rocks of this study plot consistently in the convergent margin field (Fig. 5B).

TABLE 1. (Cont.)

Label	TP54	TP 63
Rock type	Granodioritic gneisses	
Major elements (wt.%)		
SiO_2	67.55	67.38
TiO_2	0.46	0.65
Al_2O_3	14.93	16.06
FeOt	4.04	2.89
MnO	0.07	0.04
MgO	1.10	0.58
CaO	3.56	2.19
Na_2O	2.63	3.55
K_2O	2.79	4.01
P_2O_5	0.08	0.05
LOI	1.50	1.54
Total	98.71	98.64
Fe n	0.79	0.83
ASI	1.08	1.13
MALI	1.86	5.37
Al/Na+K	2.03	1.58
Trace elements (ppm)		
Rb	106	154
Cs	7.4	5.2
Be	2	3
Sr	130	124
Ba	679	870
Sc	19	11
V	56	30
Co	15	12
Zn	70	30
Ga	19	20
Y	31.4	51.8
Nb	7.7	10.3
Ta	0.77	1.58
Zr	178	216
Hf	4.7	6.3
Th	10.2	18.3
U	3.13	7.36
La	30	55.2
Ce	60.5	142
Pr	6.73	13.4
Nd	26.4	49.3
Sm	5.54	10.8
Eu	0.9	1.03
Gd	4.47	8.97
Tb	0.76	1.41
Dy	4.78	8.3
Ho	1.01	1.61
Er	3.19	4.98
Tm	0.49	0.74
Yb	3.12	5.03
Lu	0.49	0.73
Eu/Eu*	0.33	0.19

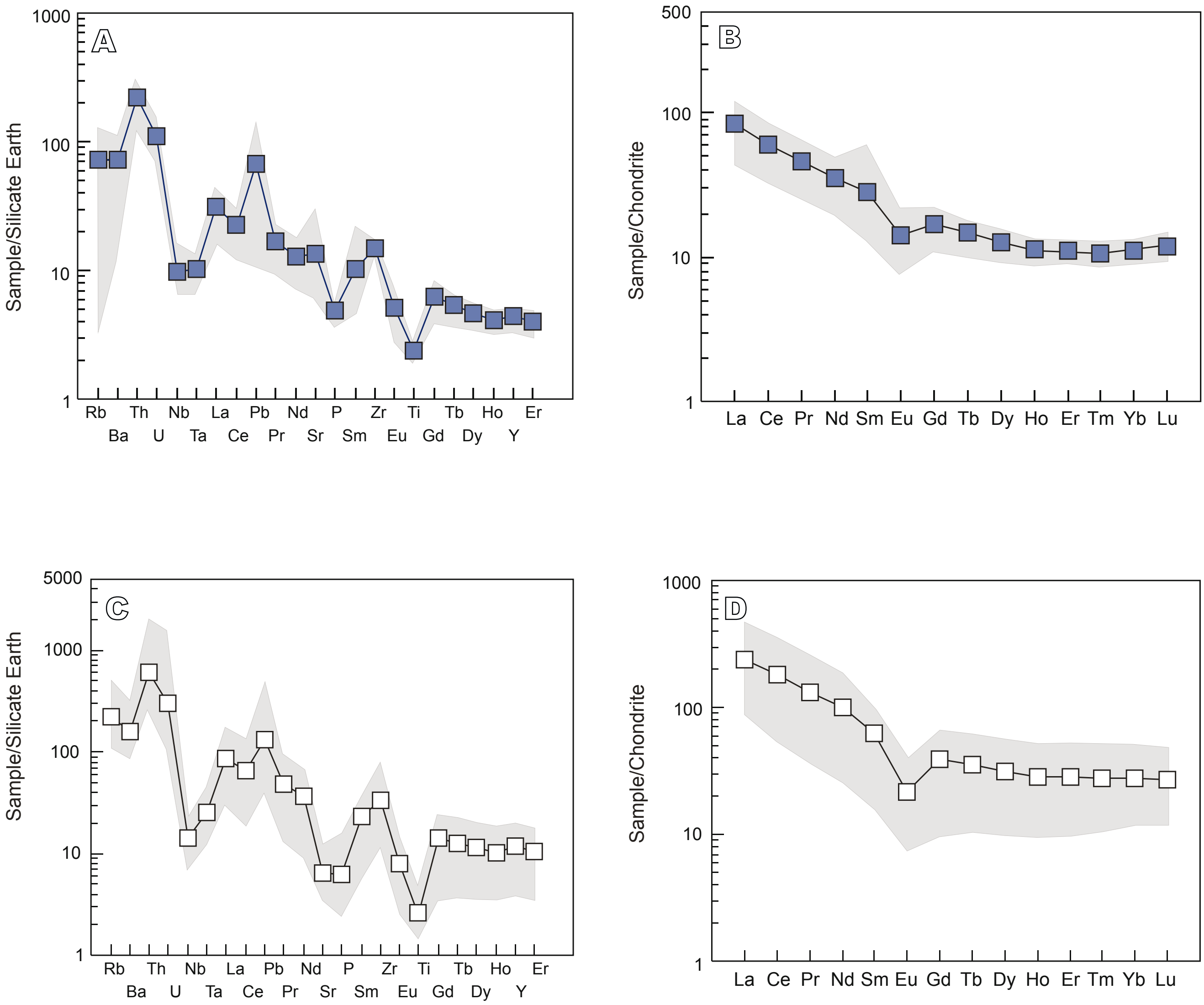

FIGURE 4. Normalized diagrams. Normalization values of McDonough and Sun (1995). A) Silicate Earth normalized trace-elements for tonalitic gneisses. B) Chondrite-normalize REE diagram for tonalitic gneisses. C) Silicate Earth normalized trace-elements for granodioritic gneisses. D) Chondrite-normalizated REE diagram for granodioritic gneisses. Gray field is the range and plotted rock is the average.

DISCUSSION: GEODYNAMIC AND PALEOGEOGRAPHIC CONSIDERATIONS

The study of the oldest granitoids that intruded the Basal Units of the Allochthonous Complexes of NW Iberia provides a reference point to discuss about the evolving paleogeography and geodynamic setting of the perigondwanan realm in the Lower Paleozoic. From a magmatic point of view, the onset of igneous activity intruding this section of Gondwana seems to have occurred in the late Cambrian (*ca.* 493–489Ma; Abati *et al.*, 2010; Díez Fernández *et al.*, 2012a). This event is represented by the intrusion of the tonalitic and granodioritic magmas analysed in this work. The geochemical analyses of these magmas (Figs. 3, 4 and 5) suggest that such activity was related to the subduction of oceanic crust (*i.e.* supra-subduction setting). In both types of magma, this is typified by: i) slight enrichment in incompatible elements (Rb, Ba, Th, U), ii) negative anomalies in Nb, Ta, P, and Ti, iii) negative anomalies in Eu, and iv) chemical discrimination carried out by tectonic setting diagrams. Additionally, positive Pb anomalies suggest a crustal component in the genesis of both types of magma.

According to detrital zircon provenance studies, the sedimentary sequences of the Basal Units were deposited in the periphery of the north Gondwanan continental margin, receiving the major input of sediments from the West African Craton (Díez Fernández *et al.*, 2010). Isotopic analyses of the metasedimentary rocks of these sequences are in agreement with this interpretation (Fuenlabrada *et al.*, 2012). Moreover, both approaches suggest that the lower sedimentary sequence, in which the Cambrian magmatism intruded, was deposited in close relation to a magmatic arc. For this sequence, the maximum age of sedimentation was constrained at ~560Ma using detrital zircon grains, although a comparison with other equivalent, well-dated sequences of the Iberian Massif and from other parts of the Variscan belt favours a latest Neoproterozoic age of deposit (~560–545Ma; Díez Fernández *et al.*, 2010, 2017). It not possible to constrain the precise position in the arc system based solely in geochemistry, but according to the probable polarity of the neoproterozoic subduction towards Gondwana, and with the fact that the granitoid rocks intrudes an Ediacaran synorogenic flysch basin, we suggest that the late Cambrian metatonalites and metagranodiorites intruded an incipient back arc basin. Furthermore, the upper sequence of the Basal Units point for a more oceanic realm in the N-Gondwana shelf than the lower sequence, which, together its present day structural position makes more probable a setting in the Gondwana side of the back-arc basin (Fig. 6).

There seems to exist a gap between the latest Neoproterozoic arc activity registered in the Basal Units and the late Cambrian magmatism that intruded later. Taking all these data together, the section of Gondwana represented in the Basal Units of the Allochthonous Complexes of NW Iberia was the site of (pulsed?) Andean type magmatic arc activity from the late Neoproterozoic up to at least late Cambrian times. Interestingly, a convergent margin with similar duration to that of the Basal Units has been also inferred for the Upper Units of the allocthonous Complexes of NW Iberia via integration of multi-proxy analyses (see compilation in Andonaegui *et al.*, 2016a).

Palinspastic restoration of major Variscan thrusts in NW Iberia provides an approach to the pre-collisional paleogeography across the perigondwanan realm (Martínez Catalán *et al.*, 2009; Díez Fernández *et al.*, 2016). In Lower Paleozoic times, the Upper Units of the Allochthonous Complexes would occupy the most external part of the margin, with some of the Ophiolitic and then the Basal Units located inboard. The relative autochthon to the Allochthonous Complexes would be located farther inwards, next to mainland Gondwana. The location of the Vila de Cruces ophiolite in between the Basal and Upper units suggests that these two latter sections of the margin would be separated by oceanic/transitional crust, dated at *ca.* 497Ma (Arenas *et al.*, 2007). The geochemical composition of this crust is typical for a supra-subduction setting (Sánchez Martínez *et al.*, 2009), which leads us to the conclusion that the Upper, Ophiolitic, and Basal units were members of a single magmatic arc system in the Lower Paleozoic (Fig. 6). Localized extension within this system gave way to back-arc basins in late Cambrian times, such as those represented by the Vila de Cruces ophiolite (Arenas *et al.*, 2007) or by the upper sequence of the Basal Units (Díez Fernández *et al.*, 2010). Further extensional activity across the margin heralded the onset of intra-continental rifting, which favoured the arrival of alkaline-peralkaline magmas during the Ordovician.

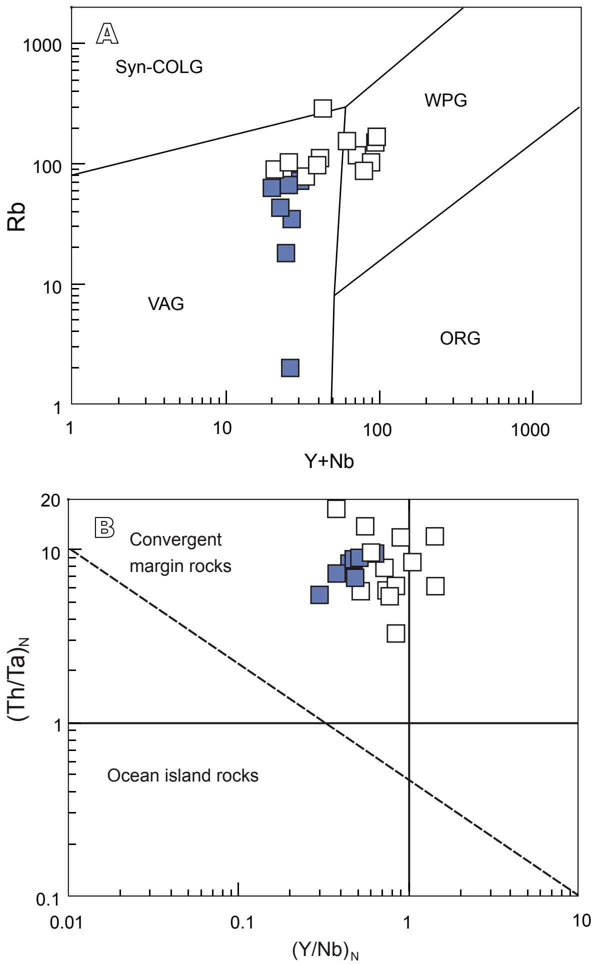

FIGURE 5. A) Granitoid discrimination diagram from Pearce *et al.* (1984). VAG = volcanic-arc granitoid, ORG = ocean ridge granitoid, Syn-COLG = Syn-collisional granitoid, WPG = within plate granitoid. B) Relationships between $(Y/Nb)_N$ and $(Th/Ta)_N$ for tonalitic and granodioritic gneisses. Compositional fields from convergent margin rocks and ocean island rocks taken from Moreno *et al.* (2014). Values normalized to Silicate Earth (McDonough and Sun, 1995).

CONCLUSIONS

New geochemical data obtained from late Cambrian metatonalites and metagranodiorites of the Basal Units of the Allochthonous Complexes of NW Iberia suggest that those granitoids were formed in a subduction-related setting. The section of the margin of Gondwana where they intruded (next to current North Africa) was part of an Andean-type margin during the Neoproterozoic. Our new data supports that ongoing subduction surpassed the Neoproterozoic-

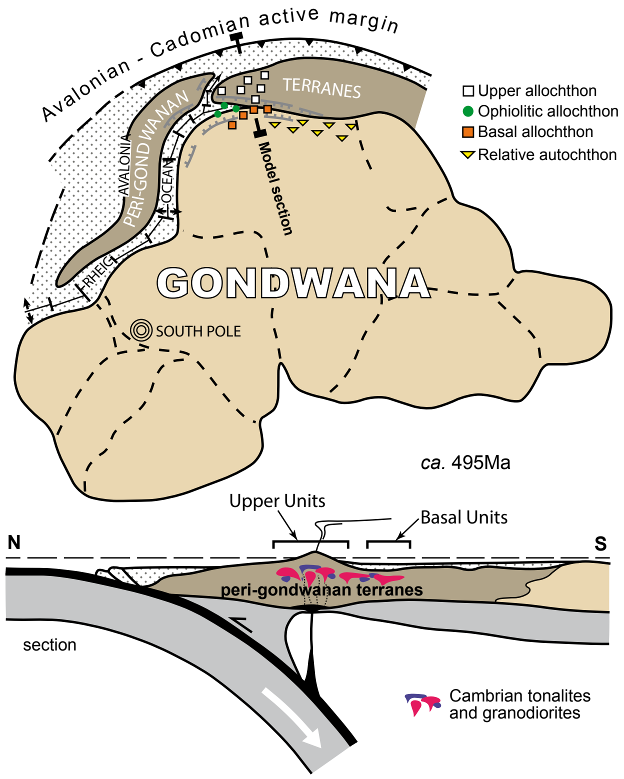

FIGURE 6. Synthetic paleogeographic model for the perigondwanan realm during the late Cambrian. The intrusion of the tonalites and granodiorites localized in the Basal Units took place in an arc-related setting, along with the felsic and mafic magmatism of similar age that is observed in the Ophiolitic and upper units of the Allochthonous Complexes of NW Iberia. Approximate paleogeographic locations were extracted from Fernández-Suárez *et al.* (2003), Gómez Barreiro *et al.* (2007), Díez Fernández *et al.* (2010), Bea *et al.* (2010), and Albert *et al.* (2015a).

Cambrian transition, what confers larger persistence to the peripheral orogens of Gondwana before the onset of rift-related activity.

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