A peri-Gondwanan arc in NW Iberia
I: Isotopic and geochemical constraints on the origin of the arc—A sedimentary approach

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Keywords:
Cambrian turbidites
Sediment geochemistry
Nd isotope composition
Provenance
Peri-Gondwanan arc
Allochthonous complexes
NW Iberia

ABSTRACT

The arc-derived upper terrane in the NW Iberia Variscan belt contains a 3000 m thick turbiditic formation at its structural top. Most of the sandstones are feldspathic greywackes with a framework of quartz and weakly altered plagioclase. Rock fragments of vitric and microgranular texture are common in polymictic conglomerates and coarse-grained greywackes, together with slates, cherts and bipyramidal volcanic quartz fragments. Although recrystallization under greenschists facies conditions (chlorite and biotite zones) and the presence of two cleavages hinder detailed textural analysis, the sandstones appear to be typically immature, first-cycle sandstones. The metagreywackes have average major and trace element compositions similar to PAAS (Post Archean Australian Shale), which is considered to reflect the composition of the upper continental crust. Their trace element composition is very consistent and records deposition within a convergent tectonic setting, probably in an intra-arc basin located in a volcanic arc built on thinned continental margin. Detrital zircon populations suggest a Middle Cambrian maximum depositional age (530–500 Ma) and a Gondwanan provenance located at the periphery of the West African Craton. Nd isotope data suggest mixing Ediacaran and Paleoproterozoic sources for the provenance of the greywackes, with T_{DM} ranging between 720 and 1215 Ma with an average of 995 Ma ($n=20$)—an age range unrepresented in the detrital zircon population. The Nd model ages are similar to those exhibited by West Avalonia, Florida or the Carolina terrane, but younger than those of Cambrian and Ordovician sandstones and shales from the autochthonous realm. These data suggest a westernmost location along the Gondwanan margin for the upper terrane of NW Iberia relative to other terranes located in the footwall of the Variscan suture, consistent with several previously proposed paleogeographic models for the NW Iberia terranes.

1. Introduction

The European Variscan Belt and its continuation through the Appalachian Orogen is a major orogenic belt developed during the final stages of the assembly of Pangea as a result of the closure of the Rheic Ocean (Casini and Oggiano, 2008; Nance et al., 2010-this issue; Keppie et al., 2010-this issue; Melleton et al., 2010) and the collision between Gondwana and Laurussia (Matte, 1991; Martínez Catalán et al., 2007), which was probably oblique (Arenas et al., 2009). In Europe, the most internal part of this belt includes a succession of allochthonous complexes that define the main suture zone and are considered to be remant klippen of a large nappe pile (Fig. 1). The allochthonous complexes in the NW Iberian Massif include three main terranes designated, from bottom to top, the basal units, ophiolitic units and upper units (Fig. 2). The basal units are considered to be the most external margin of Gondwana subducted beneath Laurussia at the onset of Variscan deformation (c. 370 Ma; Arenas et al., 1995; Martínez Catalán et al., 1996; Rodríguez et al., 2003; Abati et al., 2010), whereas the upper units are interpreted to be an arc-derived terrane. This arc also has a peri-Gondwanan provenance (Fernández-Suárez et al., 2003), but left the main continent during the Middle Cambrian–Early Ordovician and drifted north contemporaneously with the opening of the Rheic Ocean, which is represented within the stack of allochthonous units by different types of ophiolites (Díaz Garcia et al., 1999; Pin et al., 2002; Arenas et al., 2007; Sánchez Martínez et al., 2007a,b). This rifted arc was finally accreted to the southern margin of Laurussia during the Lower or Middle Devonian (Gómez Barreiro et al., 2007).

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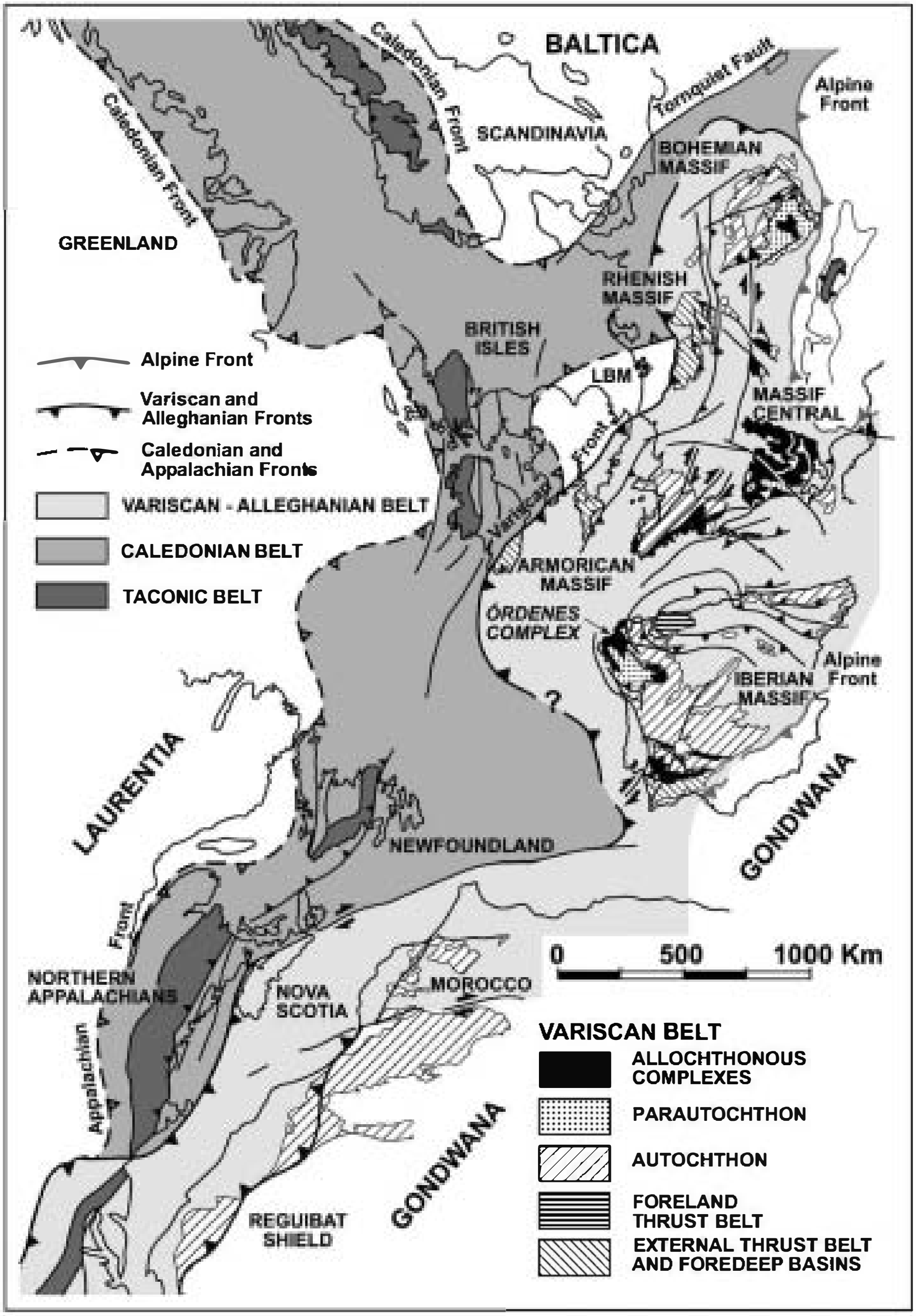

Fig. 1. Sketch showing the distribution of the Paleozoic orogens in a reconstruction of the Baltica–Laurentia–Gondwana junction developed during the assembly of Pangea. The distribution of the most important domains described in the Variscan Belt is also shown, together with the position of the Órdenes Complex in NW Iberia. LBM: London-Brabant Massif. From Martínez Catalán et al. (2002).

Different articles have described the structure and general metamorphic evolution of the arc-derived upper units of the allochthonous complexes of NW Iberia (see Martínez Catalán et al., 2002 and references therein), and data also exist on the geochronology of the tectonothermal events and main magmatic pulses. However, most previous work on the tectonothermal evolution of these units has focussed on events related to the accretion of the arc to Laurussia, and its subsequent Variscan history. Details of the arc's tectonothermal evolution during its development at the periphery of Gondwana are less well known. In addition, the location of the arc within peri-Gondwana and whether it was built on the Gondwanan continental margin or was generated above an intra-oceanic subduction zone at some distance from the margin, remain unknown. To help resolve these issues, we present two consecutive papers on aspects related to the initial development of this magmatic arc. The first paper describes the geochemical features, tectonic setting and provenance of the thick low-grade greywacke series that occupies the uppermost structural position in the upper units of the Órdenes Complex (Figs. 1 and 2) in order to constrain the tectonic setting of the magmatic arc, its internal constitution and its location within peri-Gondwana. The second describes the internal structure of the metagreywacke series and presents new U–Pb age data for a diabasic dyke swarm that intrudes the metasediments (Díaz García et al., 2010-this issue). The new age data constrains the origin of the main fabric at the upper structural levels in the Órdenes Complex and its relationship to magmatic arc dynamics.

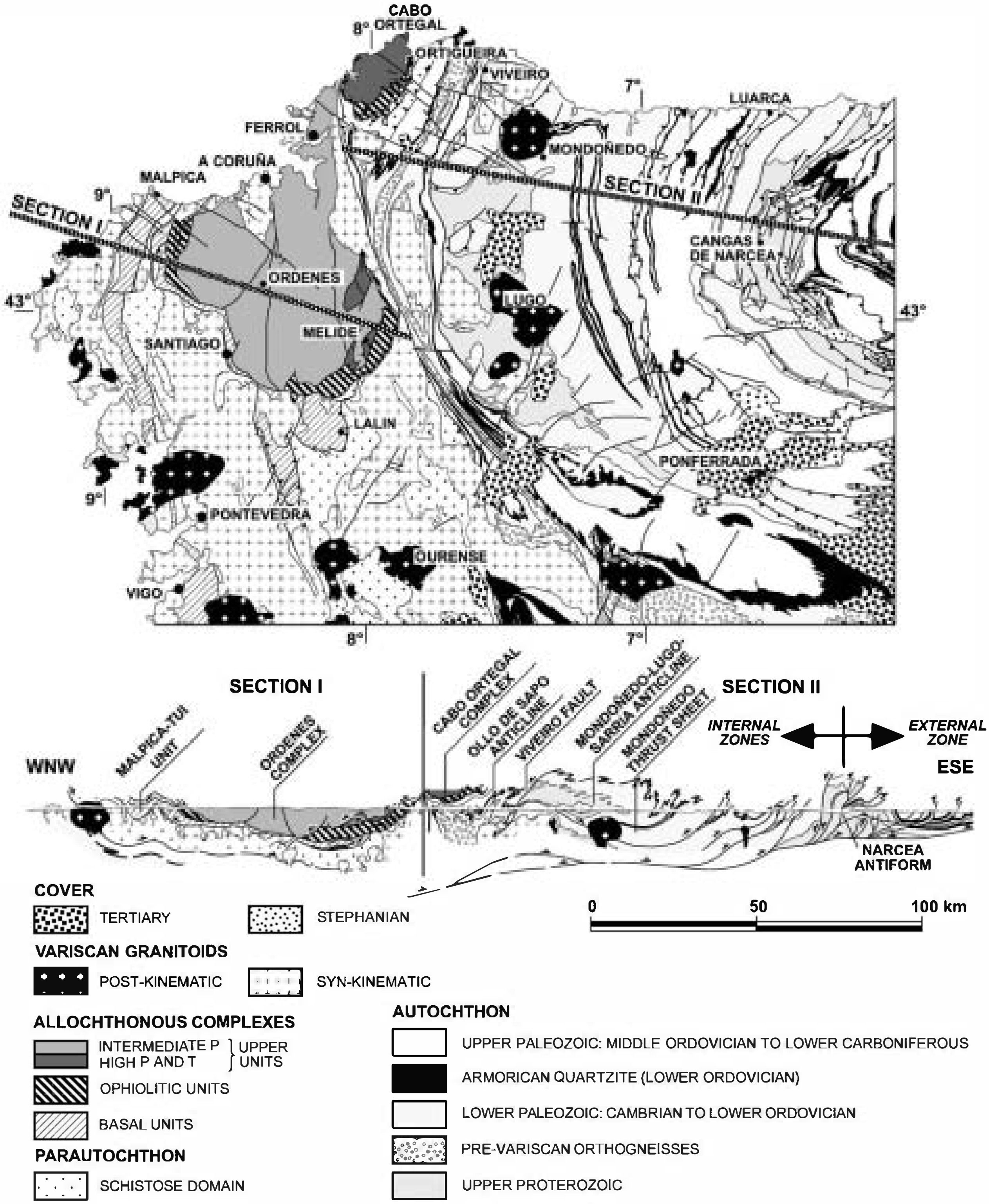

Fig. 2. Geological map of NW Iberia. It shows the distribution of the Autochthon and Parautochthon domains and the main terranes involved in the allochthonous complexes located in the most internal part of the belt.

2. Geological setting of the arc-derived terrane

The upper units of the allochthonous complexes of NW Iberia represent a well-preserved section of a peri-Gondwanan magmatic arc. These units are well exposed in the Cabo Ortegal and Órdenes complexes, and include a large variety of lithologies (Fig. 3). The internal structure of the upper units is characterized by the presence of two sheets that display slightly different tectonothermal histories.

The lower sheet (HP–HT upper units) is a polymetamorphic assemblage affected by a widespread high-pressure and high-temperature metamorphic event, the age of which is estimated to be 410–390 Ma (Ordoñez Casado et al., 2001; Fernández Suárez et al., 2007). This

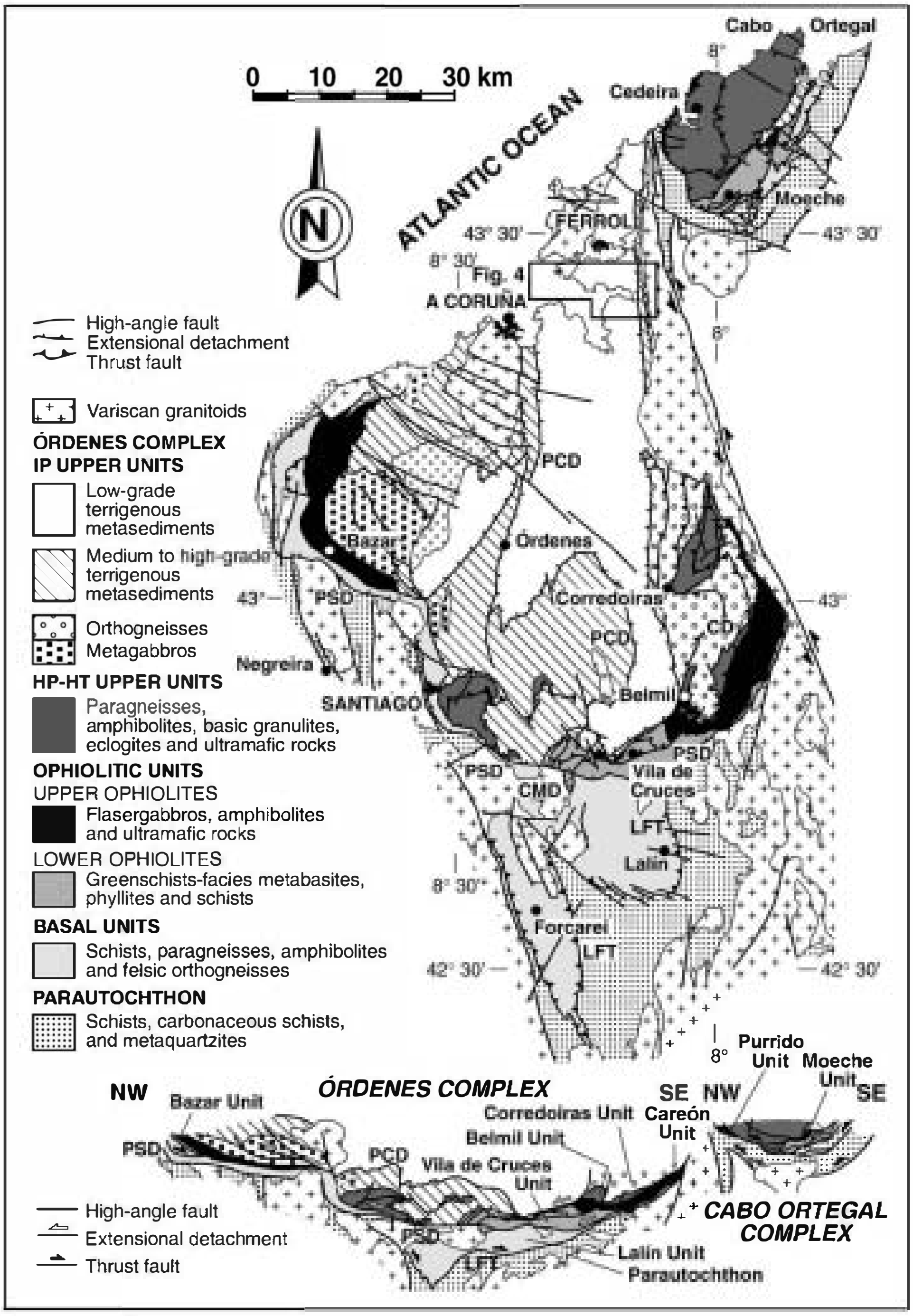

Fig. 3. Geological sketch and cross-section of the Órdenes and Cabo Ortegal complexes (Martínez Catalán et al., 2002; Arenas et al., 2007), with the distribution of the main allochthonous terranes, the basal, ophiolitic and upper units. The position of the area represented in Fig. 4 is also shown. CD, Corredoiras detachment; CMD, Campo Marzo detachment; LFT, Lalín-Forcarei thrust; PCD, Ponte Carreira detachment; PSD, Pico Sacro detachment.

metamorphic event is considered to be related to the accretion of the arc to the southern margin of Laurussia, which facilitated imbrication of a basal sheet that subducted until the development of the HP–HT event. The metamorphic P–T conditions reached around 800 °C and 20–23 kb, obscuring preservation of tectonothermal events prior to the accretion of the arc to Laurussia. Nevertheless, Fernández-Suarez et al. (2002) identified a widespread metamorphic event dated at ca. 490–480 Ma in paragneisses of the lower sheet. This early event reached high-temperature and medium-pressure conditions, but its significance is uncertain. It may be related to the dynamics associated with the magmatic arc while it occupied a position at the periphery of Gondwana.

The upper sheet (intermediate-pressure upper units) consists of medium- to low-grade metasedimentary sequences of problematic age, massifs of variably deformed and metamorphosed gabbros and granitoids, and a thick metagreywacke series occupying the uppermost position (Fig. 3). Both gabbros and granitoids have typical volcanic arc compositions, and have been dated at c. 500 Ma. Abati et al. (1999) have dated (TIMS U–Pb zircons) the Monte Castelo gabbro (western part of the Órdenes Complex) at 499 ± 2 Ma and the Corredoiras orthogneiss (easter part of the same complex) at 500 ± 2 Ma. The upper sheet shows a widespread medium-pressure and variable low- to high-temperature event (see Abati et al., 2003 and references therein), with which most of the regionally distributed fabrics can be associated. The significance of this metamorphic event is uncertain, although it has been repeatedly dated at c. 490–480 Ma (Abati et al., 1999, 2007) and, as in the lower sheet, has been interpreted as related to the earlier dynamics of the peri-Gondwanan arc. The generation of granulitic shear zones that affect the large gabbroic massifs at the base of this sheet has been linked to this event (Abati et al., 2007). In this intermediate-pressure upper unit, it is often difficult to recognize the significance of the tectonothermal evolution subsequent to the development of the dominant regional fabrics, including events associated with the accretion of the arc to Laurussia and those that came later, during the Variscan. As a result, these uppermost units afford an excellent opportunity to investigate the role of the early dynamics of the peri-Gondwanan magmatic arc.

The metagreywacke series, which occupies the uppermost structural levels, is particularly well exposed on the coastline, where it outcrops a schistose formation with frequent recumbent folds, intruded by a swarm of diabasic dykes that, in most cases, clearly cut the regional fabrics. The features and internal structure of this metagreywacke formation were first described by Matte and Capdevila (1978), who identified the presence of large recumbent folds. These folds make it difficult to create detailed stratigraphic columns of the greywacke formation or estimate its true thickness.

3. Lithological and sedimentological features of the top greywacke series

The uppermost series in the intermediate-pressure upper units occupies the central part of the Órdenes Complex (Fig. 3) and is exclusively composed of metasediments intruded by minor gabbroic and diabasic dykes. Intense polyphase deformation precludes precise determination of thickness, but it is roughly estimated to be a maximum of 3 km (Fig. 4). The lower half of this series contains a strong penetrative crenulation cleavage (S_2), with syntectonic garnet and biotite porphyroblasts, the paragenesis of which culminates in the

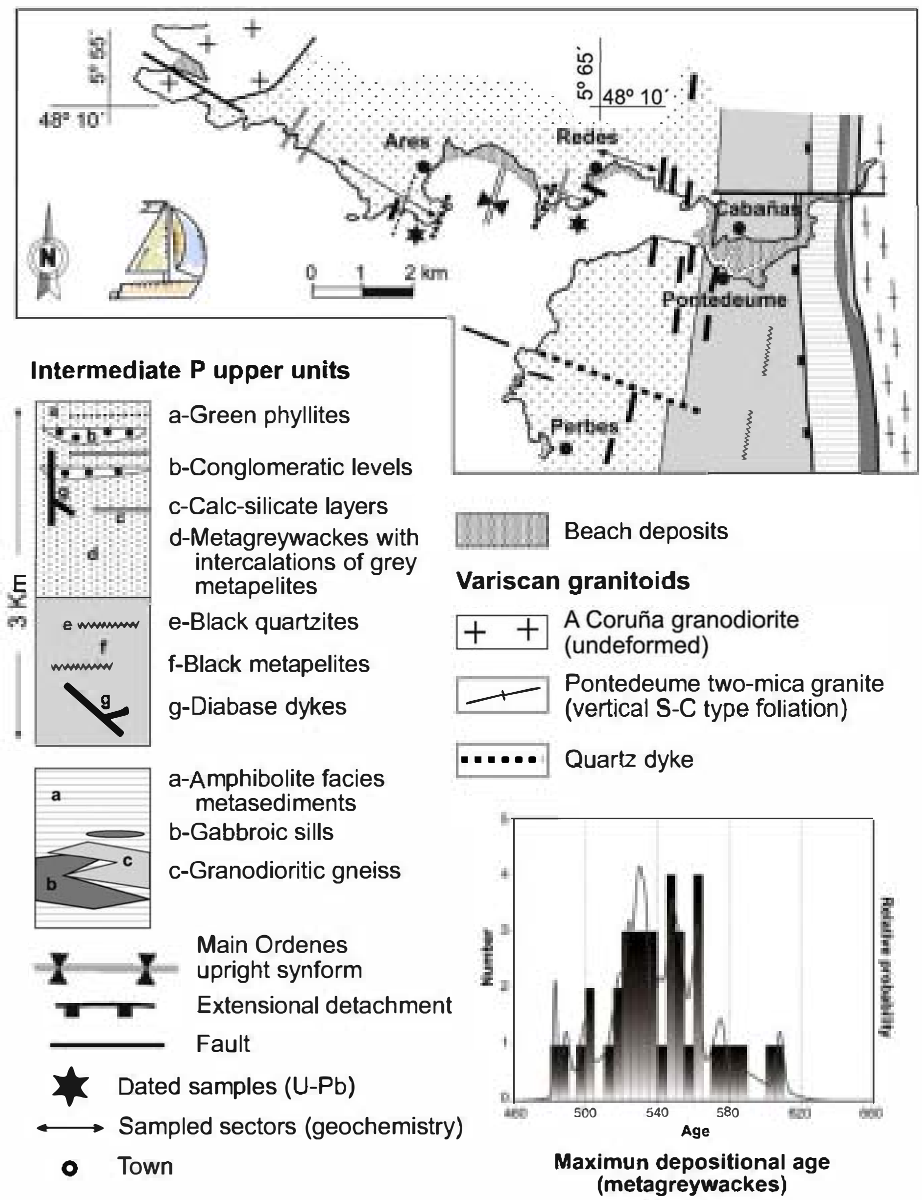

Fig. 4. Sketch showing the geology of the top metagreywackes and related metasediments in the Ares region. A general columnar section of these metasediments is shown, together with the distribution of the most important diabase dykes, the position of the samples dated by U–Pb (detrital zircons in two greywackes; Fernández-Suárez et al., 2003) and the location of the sections sampled for whole rock geochemistry of the metagreywackes. The age diagram used to deduce the maximum sedimentary age of the greywackes is also included (U–Pb ages for the younger group of detrital zircons).

Table 1

Whole rock major and trace element data of the top metagreywackes from the Ördemo Complex

Sample	SO-1	SO-	SO-3	SO-4	SO-5	SO-6	SO-	SO-8	SO-9	SO-10	SO-11	SO-12	SO-13	SO-14	SO-15	SO-16	SO-17	SO-18	SO-19	SO-20
SiO_2	65.54	[illegible]	62.66	65.33	59.77	63.27	60.90	66.30	65.45	[illegible]	66.17	63.14	73.07	75.67	75.74	65.44	64.64	[illegible]	[illegible]	66.69
Al_2O_3	15.28	15.76	16.80	15.70	17.98	17.00	17.48	14.96	16.09	16.51	16.17	17.41	13.09	11.74	11.35	16.65	16.97	17.17	18.08	15.41
Fe_2O_3	5.83	5.67	7.15	5.90	8.02	7.00	7.59	5.75	5.97	5.89	5.66	6.52	3.86	3.73	3.58	5.93	6.20	6.48	6.56	5.68
MnO	0.122	0.106	0.127	0.128	0.128	0.130	0.135	0.149	0.065	0.054	0.055	0.077	0.040	0.060	0.058	0.084	0.087	0.110	0.078	0.081
MgO	2.15	2.22	2.82	2.23	2.89	2.51	2.56	1.97	1.71	1.63	1.52	2.21	1.05	1.03	0.99	1.80	1.95	2.14	2.17	2.21
CaO	2.22	2.51	3.05	2.60	1.17	1.32	1.23	1.94	0.21	0.15	0.25	0.31	0.12	0.49	0.60	0.60	0.84	0.66	1.59	1.41
Na_2O	2.81	3.57	3.71	3.71	2.48	2.46	2.71	2.92	2.97	2.72	3.38	3.21	3.04	3.26	2.81	2.72	3.14	2.86	3.31	3.86
K_2O	2.81	2.30	1.65	1.82	2.79	2.79	2.93	2.12	2.65	2.86	2.42	2.86	2.11	1.97	2.21	3.12	2.86	3.36	3.03	1.53
TiO_2	0.780	0.801	0.856	0.807	0.892	0.866	0.870	0.808	0.753	0.781	0.773	0.824	0.590	0.565	0.543	0.798	0.813	0.835	0.839	0.765
P_2O_5	0.18	0.17	0.18	0.17	0.13	0.16	0.17	0.16	0.14	0.10	0.14	0.17	0.07	0.09	0.09	0.12	0.14	0.13	0.16	0.16
LOI[a]	1.30	1.03	1.46	1.18	3.28	2.63	2.80	1.76	2.88	3.00	2.51	2.92	1.89	1.23	1.35	2.67	2.58	3.09	3.09	2.07
TOTAL	99.03	99.24	100.50	99.57	99.52	100.10	99.36	98.89	98.88	98.76	99.04	99.65	98.92	99.82	99.31	99.92	100.20	99.00	100.10	99.85
Sc	15	15	19	16	22	19	19	15	15	[illegible]	15	18	10	9	8	16	17	[illegible]	18	15
V	111	111	116	111	127	121	154	120	138	137	134	144	[illegible]	77	73	135	139	160	145	110
Cr	50	50	50	50	50	50	60	50	40	50	40	50	30	30	30	50	50	50	60	50
Co	13	11	15	12	17	13	14	7	6	6	11	14	5	7	7	8	13	11	12	12
Ni	30	30	30	30	40	30	40	<20	20	30	30	30	<20	20	20	30	40	30	30	20
Cu	10	30	40	20	50	30	20	30	30	40	20	30	10	10	10	30	30	30	20	20
Zn	90	90	110	80	120	120	110	90	110	130	110	130	70	70	70	110	130	130	120	80
Ga	19	19	21	19	23	21	22	18	20	21	20	22	15	13	13	21	22	22	23	18
Rb	84	70	47	53	85	92	88	80	88	87	78	93	65	58	68	98	99	100	96	44
Sr	169	252	289	246	217	172	205	231	117	131	145	156	129	139	123	112	138	137	160	295
Y	28.0	20.7	25.3	23.2	34.2	25.0	26.4	19.1	30.0	32.5	31.5	36.7	22.7	21.9	20.7	23.3	34.7	30.3	40.0	23.4
Zr	160	184	180	193	173	171	175	166	194	[illegible]	220	195	[illegible]	172	164	222	198	[illegible]	[illegible]	168
Nb	7.5	7.9	10.5	8.2	10.3	10.5	10.1	8.1	9.2	9.7	9.1	10.2	7.0	6.5	6.3	10.0	10.8	10.3	11.7	6.9
Cs	4.8	5.0	3.1	3.5	3.3	4.1	3.9	4.7	4.6	4.5	3.8	4.1	3.5	4.8	6.1	2.7	3.4	3.3	3.4	1.3
Ba	617	758	428	519	689	513	565	468	637	647	574	721	[illegible]	573	615	547	597	[illegible]	651	449
Hf	4.8	5.3	5.2	5.5	5.1	4.9	5.1	4.5	5.5	5.9	6.2	5.6	4.8	4.7	4.4	6.2	5.8	5.7	6.2	4.5
Ta	0.66	0.70	0.89	0.79	0.92	0.90	0.87	0.68	0.84	0.87	0.85	0.96	0.66	0.64	0.60	0.90	0.95	0.94	0.97	0.60
Pb	15	13	13	13	14	13	11	16	17	17	12	15	13	8	9	14	16	[illegible]	9	9
Th	6.63	7.27	8.92	6.81	8.90	7.95	8.70	7.87	8.19	8.79	8.52	9.11	6.44	5.95	5.79	8.60	9.16	8.24	8.96	5.34
U	2.09	2.21	2.91	2.14	2.00	2.10	2.66	2.09	3.33	3.51	3.44	2.96	2.30	1.73	1.93	3.09	3.37	3.17	3.11	1.31
Rb/Sr	0.50	0.28	0.16	0.22	0.39	0.53	0.43	0.35	0.75	0.80	0.54	0.60	0.49	0.42	0.55	0.88	0.72	0.73	0.53	0.15
Ti/Zr	26	26	29	25	31	30	30	29	23	23	21	25	20	20	20	22	25	25	24	27
La/Sc	1.63	1.24	1.35	1.36	1.18	0.83	1.22	1.79	1.62	1.81	1.75	1.74	2.11	2.43	2.24	0.81	1.95	1.27	1.92	1.57
La/Y	0.87	0.90	1.02	0.94	0.76	0.63	0.88	1.41	0.81	0.89	0.83	0.85	0.93	1.00	0.86	0.55	0.95	0.58	0.87	1.01
La/Th	3.68	2.56	2.88	3.20	2.92	1.97	2.67	3.42	2.97	3.30	3.09	3.44	3.28	3.68	3.09	1.50	3.61	2.47	3.86	4.42
Sc/Cr	0.30	0.30	0.38	0.32	0.44	0.38	0.32	0.30	0.58	0.32	0.38	0.36	0.33	0.30	0.27	0.32	0.34	0.36	0.30	0.30
Th/Sc	0.44	0.48	0.47	0.43	0.40	0.42	0.46	0.52	0.55	0.55	0.57	0.51	0.64	0.66	0.72	0.54	0.54	0.51	0.50	0.36

Oxides are in weight percent (wt%). Trace elements are in parts per million (ppm).
The element concentrations expressed with the < sign are below detection limit.
[a] Loss on ignition.

development of the basal Ponte Carreira detachment (PCD; Fig. 3). This basal extensional detachment prevents the identification of original relationships with the underlying part of the intermediate-pressure upper units.

From a lithological point of view the uppermost terrigenous series can be divided into two members: (1) a lower member with a maximum thickness of c. 1 km consisting of black metapelites with intercalations of grey to black quartzites and lydites of variable thickness; and (2) an upper member, c. 2 km thick, that has a flyschoid appearance and consists of alternations of metagreywackes and grey to black metapelites with conglomeratic intervals and minor green phyllites and calcsilicate layers. The entire succession appears to represent an upward shoaling megasequence. Two detailed partial stratigraphic columns were previously measured and studied by Gutiérrez Alonso et al. (2000), who identified facies indicating various settings within a deep submarine fan model (mainly lower-middle fan and upper fan, with a few facies representing the slope). The identified facies' association suggests a type II turbiditic system (Mutti, 1985), mostly formed by channel and sand lobe complexes.

Conglomeratic levels consist of pebbles of granitic rocks, quartz and greywacke intraclasts. Most of the sandstones can be classified as feldespathic greywackes with a framework of quartz and weakly altered plagioclase. Rock fragments of vitric and microgranular texture are common in polymictic conglomerates and coarse-grained greywackes, together with slates, cherts and bipyramidal volcanic quartz fragments. Although recrystallization under greenschist facies conditions in the chlorite and biotite zones and the presence of two cleavages hinder detailed textural analysis, the sandstones are typical immature, first-cycle sandstones with angular to subangular, poorly sorted grains in a muddy matrix. Heavy minerals are dominated by unabraded zircons and less abundant epidote and rutile.

Detrital zircons of two metagreywacke samples collected near Ares and Redes (Fig. 4) were studied by Fernández-Suárez et al. (2003) in order to constrain the provenance of the greywacke series and its maximum depositional age. The age groups of the zircons (480–610 Ma, 1900–2100 Ma and 2400-2500 Ma) and the absence of Mesoproterozoic zircons suggest an origin in a Neoproterozoic–Early Palaeozoic peri-Gondwanan realm along the periphery of the West African Craton. The maximum depositional age of the greywackes, initially thought to be c. 480 Ma (Early Ordovician), was reassessed in this study. Using only analyses with < 10% discordance (shown in Fig. 4 for the youngest group of detrital zircons), the maximum depositional age can be estimated at c. 530 Ma, based on the average age of the largest group of youngest zircons (Elliot and Fanning, 2008). However, it is possible that the age of the youngest zircon in this group is significant, in which case the maximum age of deposition could be as young as 510–520 Ma.

4. Whole rock geochemistry

The chemical composition of sedimentary rocks depends on numerous factors, including the nature of the source areas, and the subsequent processes, such as weathering, diagenesis or metamorphism. Likewise, the tectonic setting in which the sedimentary basin developed also exerts a significant control over the final composition of the resulting rocks (Bathia, 1983; Bathia and Crook, 1986; Ranjan and Banerjee, 2009; Hegde and Chavadi, 2009). The abundance of some elements, such as rare earth elements (REE), Hf, Ti, Cr, Co, Zr, Nb, Y, Th and Sc, is preserved in sedimentary rocks through the weathering processes. These elements have very low residence times in oceanic waters, being transferred almost quantitatively to sedimentary rocks. Thus, they provide excellent discriminating factors for determining the provenance and tectonic setting of sedimentary rocks in both ancient successions and far travelled terranes.

Twenty metagreywacke samples from the sedimentary series that constitutes the upper levels of the Órdenes Complex (intermediate-

Table 2
Whole rock rare earth element data of the top metagreywackes from the Órdenes Complex.

Sample	SO-1	SO-2	SO-3	SO-4	SO-5	SO-6	SO-7	SO-8	SO-9	SO-10
La	24.4	18.6	25.7	21.8	26.0	15.7	23.2	26.9	24.3	29.0
Ce	50.1	35.2	56.6	41.5	79.6	36.3	49.0	54.9	50.3	61.7
Pr	6.05	50.70	6.51	5.51	6.68	4.44	5.80	6.05	6.12	7.06
Nd	24.5	20.1	25.2	22.1	27.0	17.2	22.6	23.2	24.1	28.2
Sm	5.09	4.18	5.32	4.55	5.84	3.67	4.62	4.53	5.08	5.62
Eu	1.38	1.19	1.29	1.28	1.48	0.99	1.22	1.20	1.21	1.41
Gd	4.72	3.49	4.52	3.95	5.52	3.23	3.84	3.92	4.77	5.20
Tb	0.82	0.62	0.80	0.67	0.98	0.61	0.66	0.67	0.85	0.93
Dy	4.96	3.88	4.85	4.07	5.99	4.04	4.30	3.80	5.25	5.40
Ho	0.98	0.77	0.91	0.80	1.19	0.87	0.90	0.72	1.03	1.07
Er	2.90	2.37	2.79	2.40	3.61	2.74	2.83	2.08	3.11	3.21
Tm	0.446	0.386	0.455	0.380	0.569	0.449	0.471	0.333	0.482	0.513
Yb	2.92	2.67	3.11	2.59	3.71	3.05	3.18	2.23	3.17	3.40
Lu	0.45	0.42	0.5	0.4	0.57	0.48	0.49	0.34	0.51	0.52
Σ REE	130	99	139	112	169	94	123	131	130	154
Eu/Eu*	0.87	0.96	0.81	0.93	0.80	0.88	0.89	0.88	0.76	0.79
$(La/Sm)_N$	2.96	2.75	2.98	2.96	2.75	2.64	3.10	3.66	2.95	3.07
$(Gd/Yb)_N$	1.29	1.04	1.16	1.22	1.19	0.84	0.96	1.40	1.20	1.22
$(La/Yb)_N$	5.59	4.66	5.53	5.63	4.69	3.44	4.88	8.07	5.13	5.7

Sample	SO-11	SO-12	SO-13	SO-14	SO-15	SO-16	SO-17	SO-18	SO-19	SO-20
La	26.3	31.3	21.1	21.9	17.9	12.9	33.1	22.8	34.6	23.6
Ce	57.2	62.4	43.4	40.2	35.1	29.0	50.6	34.1	49.9	43.6
Pr	6.62	7.40	4.96	5.26	4.35	3.50	8.51	6.30	8.20	5.67
Nd	25.9	29.7	19.1	20.6	17.3	14.1	33.0	25.2	31.4	22.1
Sm	5.45	6.12	3.97	4.00	3.62	3.26	6.88	5.72	6.49	4.53
Eu	1.32	1.59	1.05	1.04	0.94	0.87	1.74	1.50	1.75	1.30
Gd	4.87	5.84	3.51	3.59	3.30	3.05	6.43	5.81	6.31	4.04
Tb	0.90	1.06	0.65	0.62	0.59	0.62	1.11	1.08	1.12	0.71
Dy	5.39	6.22	4.00	3.75	3.51	4.13	6.74	6.86	6.92	4.32
Ho	1.05	1.22	0.78	0.72	0.69	0.85	1.26	1.39	1.36	0.85
Er	3.18	3.64	2.37	2.20	2.13	2.76	3.78	4.22	4.02	2.56
Tm	0.502	0.558	0.370	0.339	0.345	0.484	0.597	0.686	0.602	0.395
Yb	3.32	3.70	2.44	2.30	2.30	3.33	3.91	4.54	3.89	2.63
Lu	0.516	0.589	0.374	0.358	0.348	0.523	0.850	0.670	0.596	0.380
Σ REE	143	161	108	107	92	79	158	121	157	117
Eu/Eu*	0.79	0.82	0.86	0.84	0.84	0.85	0.80	0.80	0.84	0.93
$(La/Sm)_N$	2.98	3.16	3.28	3.38	3.05	2.44	2.97	2.46	3.29	3.21
$(Gd/Yb)_N$	1.17	1.26	1.15	1.24	1.14	0.73	1.31	1.02	1.29	1.22
$(La/Yb)_N$	5.30	5.66	5.78	6.37	5.20	2.59	5.66	3.36	5.95	6.00

Rare earth element data in parts per million (ppm).

pressure upper units) were collected in order to study their geochemistry, provenance and tectonic setting. Samples were collected along three sections on the coastline surrounding Redes and Ares (Fig. 4). Sample preparation was carried out at Universidad Complutense de Madrid, and whole rock major and trace elements analyses were performed at Activation Laboratories Ltd. (Actlabs) in Canada. The method used for sample digestion was fusion with lithium metaborate/tetraborate, and the analytical techniques for major and trace element determination were ICP-OES and ICP-MS, respectively. The chemical analyses of the greywackes are shown in Tables 1 and 2.

4.1. Composition and classification

The analysed greywackes are characterized by variable SiO_2 contents (59.8–75.7 wt.%), with an average of 65.7 wt.%. Only three samples have SiO_2 contents higher than 70 wt.% (SO-13 to SO-15). The grewackes have relatively high, homogeneous Na_2O contents (2.5–3.9 wt.%), with an average of 3.1 wt.%, and relatively low and variable contents in CaO (0.1–3.1 wt.%) and K_2O (1.5–3.4 wt.%), with averages of 1.1 and 2.5 wt.%, respectively. The compositional ranges of the remaining major elements are Al_2O_3 (11.4–18.1 wt.%), Fe_2O_3 (3.6–8.0 wt.%), MnO (0.04–0.15 wt.%), MgO (1.0–2.9 wt.%), TiO_2 (0.54–0.89 wt.%) and P_2O_5 (0.07–0.18 wt.%). Based on the SiO_2 contents and the K_2O/Na_2O ratio (0.4–1.2), most of the greywackes are quartz-intermediate (Crook, 1974). A negative correlation exists between SiO_2 and Fe_2O_3, MgO, MnO, CaO and TiO_2, whereas a positive correlation exists between TiO_2 and Al_2O_3. There is also significant scatter in the SiO_2/K_2O and SiO_2/Na_2O ratios due to the high mobility of Na and K during alteration processes.

The chemical classification of sedimentary rocks differentiates between mature and immature sediments. One of the most widely used parameters is the Fe_2O_3/K_2O ratio (Herron, 1988), which is especially applicable to arkoses. This ratio is better than the Na_2O/K_2O ratio used by Pettijohn et al. (1972), and can be applied to unconsolidated fine- to coarse-grained sediments. Based on the chemical classification diagram by Herron (1988), most of the analysed samples cluster in the greywacke field (Fig. 5a). Only samples SO-14 and SO-15 fall in the field oflitharenites. The SiO_2/Al_2O_3 ratio of the samples is low (3.3–6.7), which is indicative of immaturity. The variable K_2O/Na_2O ratio (0.4–1.2) and average value of0.8, can be interpreted in the same way (Asiedu et al., 2004; Spalletti et al., 2008). The Rb/Sr ratio, which also reflects recycling processes, varies between 0.15 and 0.88, with an average value of 0.5. Weathering processes and, in some cases, diagenesis can lead to an important increase of the Rb/Sr ratio, due largely to Sr loss during plagioclase alteration. Values higher than 0.5 are interpreted by McLennan et al. (1993) as a weathering and sedimentary recycling index. An average value of 0.5 in the greywackes indicates a certain increase relative to the average value of the Rb/Sr ratio in the upper crust (0.32; Taylor and McLennan, 1985). This, in turn, suggests that alteration processes during the sedimentary history of the greywackes were minor.

The effects of homogenization in sedimentary processes result in a relatively uniform distribution of REE in detrital rocks, the pattern reflecting the abundance of REE in the upper crust. REE are generally considered to be immobile, with only slight changes during sedimentation processes. The results of the REE analysis can be seen in Table 2. The analysed greywackes show little variability in ΣREE, with values ranging between 79 (sample SO-16, with a marked depletion in LREE) and 169 (sample SO-5, with a pronounced positive Ce anomaly). The samples also show similar chondrite-normalized (Nakamura, 1974) fractionation patterns, with slight enrichment in LREE (La–Sm) relative to HREE (Fig. 5b). Likewise, the samples show a weak negative Eu anomaly, which varies from 0.76 to 0.96 (calculated according to Taylor and McLennan, 1985). Eu anomalies are usually interpreted in sedimentary rocks as being inherited from the igneous source rocks. The samples also display an unfractionated HREE

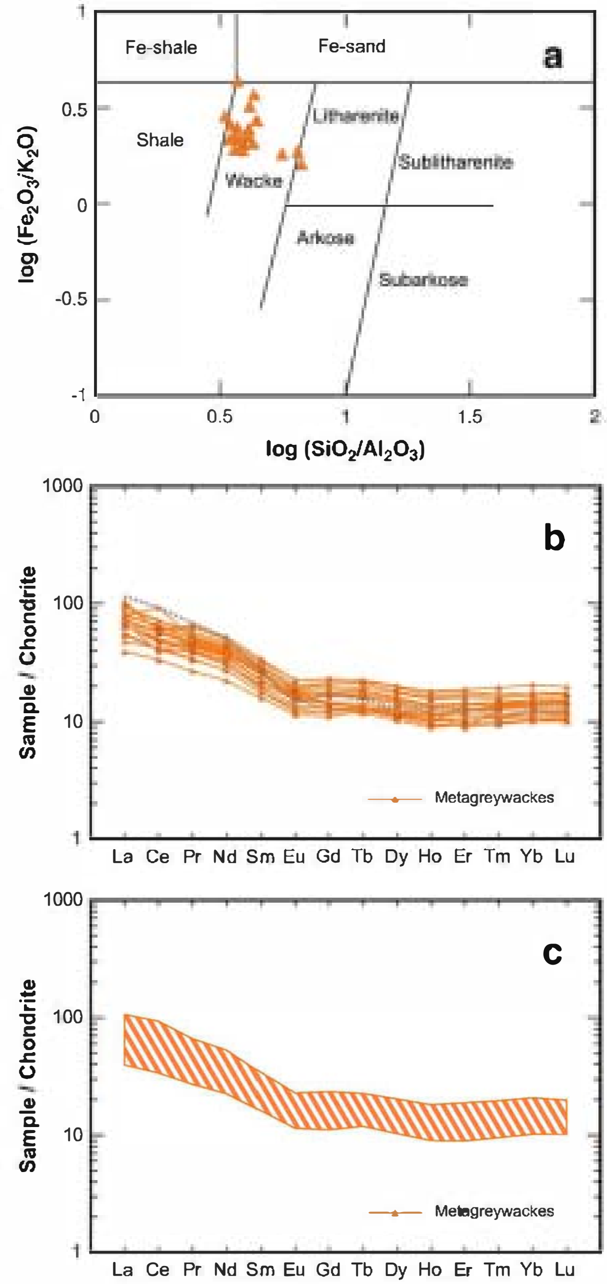

Fig. 5. Chemical diagrams for the metagreywackes from the uppermost levels of the Órdenes Complex. (a) Classification diagram (Herron, 1988). (b) Chondrite-normalized rare earth elements plots; the dotted line corresponds to the PAAS (Post Archean Australian Shale; Taylor and McLennan, 1985). (c) Compositional range of the chondrite-normalized rare earth elements plots.
Normalizing values are from Nakamura (1974).

pattern. As can be seen in Fig. 5b and c, despite some intersample differences in abundance, the REE patterns of the greywackes are similar to those of PAAS (Post Archean Australian Shale; Taylor and McLennan, 1985), which are considered representative of upper continental crust.

The depletion of HREE relative to LREE is usually related to low concentrations of heavy minerals, especially zircon. Here, the low concentration of Zr in the greywackes (average = 187 ppm) is consistent with that interpretation. Almost all the samples have Gd_N/Yb_N values between 1.0 and 2.0 (0.73–1.40) and low Eu/Eu* ratios (0.76–0.96), indicating a provenance from upper continental crust of Post Archean age, based on the similarity of the REE patterns to PAAS. The La_N/Yb_N ratio shows an average value of 5.26 (ranging between 2.59 and 8.07), which is lower than that of PAAS ($La_N/Yb_N = 9.08$) due to a lower La concentration (average La = 24.06 ppm, Yb = 3.12 ppm). The abundance of La agrees with that reported by Bathia and Crook (1986) for igneous terrigenous sediments generated within a volcanic arc built on thinned continental crust, as discussed below.

4.2. Tectonic setting

The geochemistry of major elements has been widely used to establish the tectonic setting of detrital sedimentary rocks (Bathia, 1983; Roser and Korsch 1985, 1986, 1988; Bathia and Crook, 1986; Hegde and Chavadi, 2009). However, diagrams based on the abundance of elements, such as Na or K, must be treated with caution, because of their high mobility during depositional processes. Certain trace elements, such as REE, Cr, Co, Th, Sc, Y, La and Zr, are considered relatively immobile and consequently provide better discrimination of possible tectonic settings (Taylor and McLennan, 1985). Various tectonic discrimination diagrams developed by Bathia and Crook (1986) are shown in Fig. 6. These diagrams allow clear differentiation among the four tectonic settings considered to be the most common sites of greywacke deposition: (A) oceanic island arc, (B) continental island arc, (C) active continental margin, and (D) passive margin. In the Ti/Zr–La/Sc diagram (Fig. 6a), all the samples plot within the continental island arc field. The La/Y–Sc/Cr diagram (Fig. 6b) shows greater scatter due to the variability of the La/Y ratio, the values of which range between 0.55 and 1.41. Nevertheless, all the samples plot in fields related to convergent plate tectonic settings. In the ternary diagrams, La–Th–Sc, Th–Co–Zr and Th–Sc–Zr (Fig. 6c, d and e, respectively), the samples are tightly grouped in the continental island arc fields, with only two samples falling within the field for oceanic island arcs in one of the diagrams. This reflects the low La contents of the two samples relative to the others.

According to Bathia and Crook (1986), the most significant chemical signatures for characterizing greywackes deposited in a continental island arc setting are: La (25 ppm), Th (11 ppm), La/Sc (1.8), Th/Sc (0.85), Ti/Zr (20) and La/Th (2.3). These average values closely match those characteristic of the greywackes of the upper levels of the Órdenes Complex: La (24 ppm), Th (7.86 ppm), La/Sc (1.59), Th/Sc (0.51), Ti/Zr (25) and La/Th (3.1). Hence, according to the concentrations of trace elements with the highest discriminative power, the greywackes were deposited in a sedimentary basin related to a convergent dynamic regime, and in a tectonic setting designated as a continental island arc by Bathia and Crook (1986).

Finally, Fig. 7a and b shows PAAS-normalized plots of the most significant elements for the discrimination of tectonic setting. The figures are plotted according to the criteria of Thompson (1982). The patterns defined by the metagreywackes are very similar to those typical of continental island arcs or active margins (Winchester and Max, 1989). The plots are characterized by depletion in most of the large ion lithophile elements (LILE: Cs, Rb, Th, U, K_2O, La, Ce, and P_2O_5), which deviate slightly from one, whereas the high field strength elements (HSFE: Zr, Hf, HREE, Sm, TiO_2 and Sc)

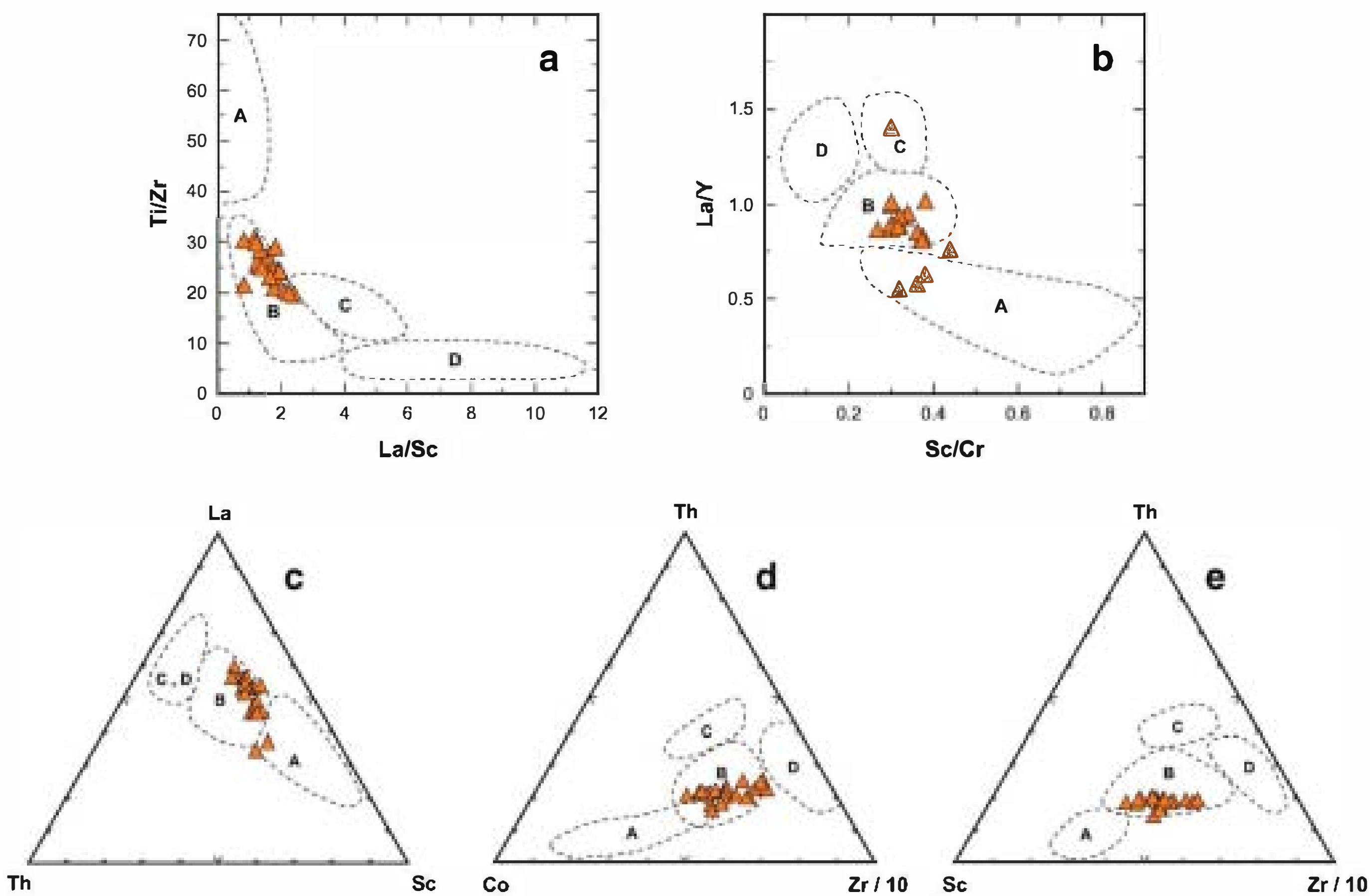

Fig. 6. Trace elements tectonic setting discrimination diagrams for the metagreywackes. A—Oceanic island arc; B—continental island arc; C—active continental margins; D—passive margins.
Diagrams are after Bathia and Crook (1986).

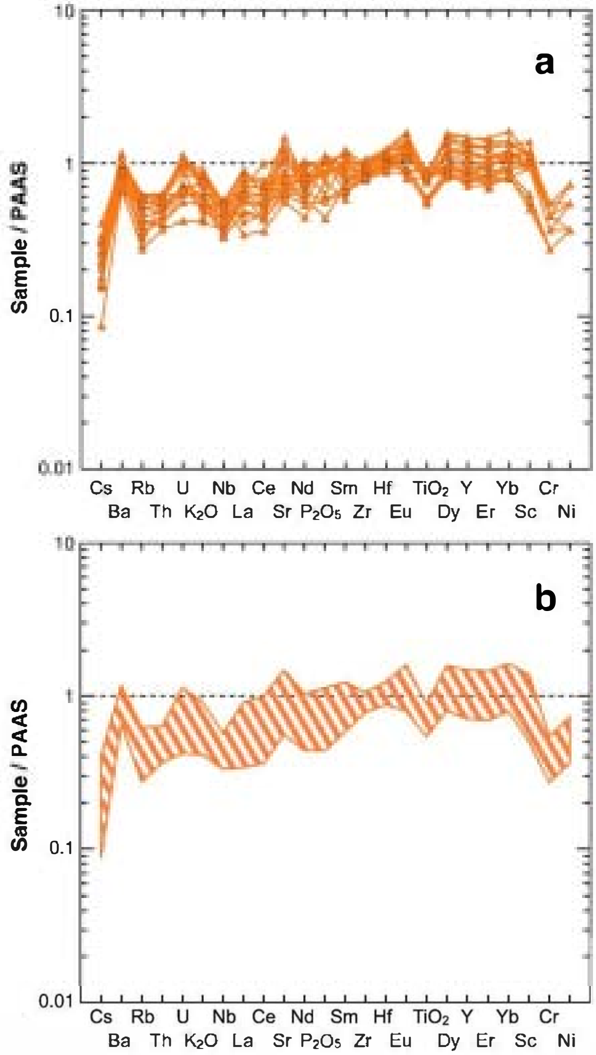

Fig. 7. (a) PAAS-normalized trace elements plots for the metagreywackes. (b) Plot showing the compositional range of the PAAS-normalized trace elements composition of the metagreywackes.
PAAS after Taylor and McLennan, 1985.

Table 3
Whole rock Nd isotope data of the top metagreywackes from the Órdenes Complex.

Muestra	Nd	Sm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	εNd (0)	εNd (500)*	T_{DM} (Ma)[a]
SO-1	22.60	4.93	0.1318	0.512531	3	−2.1	2.0	986
SO-2	18.44	4.22	0.1383	0.512555	4	−1.6	2.1	1017
SO-3	24.49	5.77	0.1425	0.512480	3	−3.1	0.4	1215
SO-4	20.51	4.62	0.1363	0.512633	4	−0.1	3.8	855
SO-5	26.83	5.85	0.1318	0.512456	3	−3.5	0.6	1111
SO-6	16.39	3.78	0.1393	0.512518	3	−2.3	1.3	1098
SO-7	20.64	4.69	0.1373	0.512529	3	−2.1	1.7	1052
SO-8	19.82	4.07	0.1241	0.512589	3	−1.0	3.7	818
SO-9	25.97	4.82	0.1122	0.512482	3	−3.1	2.3	878
SO-10	29.29	6.07	0.1253	0.512497	3	−2.8	1.8	973
SO-11	26.13	5.56	0.1287	0.512518	3	−2.4	2.0	974
SO-12	31.11	6.56	0.1276	0.512537	3	−2.0	2.4	932
SO-13	19.56	4.06	0.1255	0.512587	4	−1.0	3.6	833
SO-14	21.11	4.22	0.1207	0.512636	3	0.0	4.8	720
SO-15	17.66	3.57	0.1224	0.512506	3	−2.6	2.2	930
SO-16	15.76	3.66	0.1402	0.512481	3	−3.1	0.5	1180
SO-17	33.57	7.11	0.1281	0.512427	3	−4.1	0.3	1115
SO-18	26.85	6.20	0.1396	0.512468	3	−3.3	0.3	1194
SO-19	32.82	6.81	0.1254	0.512467	3	−3.3	1.2	1021
SO-20	23.21	4.80	0.1252	0.512476	3	−3.2	1.4	1003

[a] Nd model ages calculated according to DePaolo (1981).
* εNd(t) calculated for 500 Ma.

are generally close to one, with a slight characteristic negative TiO_2 anomaly. In general, a slightly increasing pattern can be observed, culminating in a flat pattern close to one. However, three important differences exist between the diagram for continental island arcs and active margins proposed by Winchester and Max (1989) and that obtained for the analysed greywackes: (1) there is essentially no negative P_2O_5 anomaly, perhaps because of low contents of apatite and monazite; (2) there is a less marked positive Sr anomaly, perhaps as a result of alteration processes; and (3) the Cr and Ni abundances are significantly lower, suggesting an essentially felsic provenance for the greywackes, although the values lie close to the analytical detection limits. The felsic provenance appears to be corroborated by Hf values and La/Th ratio, and is a likely indication of the association of the greywackes with an evolved (mature) volcanic arc.

4.3. Sm–Nd isotope systematics

Isotopic analysis of the greywackes was performed at the Centro de Geocronología y Geoquímica Isotópica at the Universidad Complutense de Madrid. For whole rock Nd isotopic analysis by isotope dilution-thermal ionization mass spectrometry (ID-TIMS), the samples were first dissolved in ultra-pure reagents in order to perform isotope separation by exchange chromatography (Strelow, 1960; Winchester, 1963), and subsequently analysed using a Sector 54 VG-Micromass multicollector spectrometer. The measured $^{143}Nd/^{144}Nd$ isotopic ratios were corrected for possible isobaric interferences from ^{142}Ce and ^{144}Sm (only for samples with $^{147}Sm/^{144}Sm < 0.0001$) and normalized to $^{146}Nd/^{144}Nd = 0.7219$ in order to correct for mass fractionation (Table 3). The La Jolla Nd international isotopic standard was analysed during sample measurement, and gave an average value of $^{143}Nd/^{144}Nd = 0.511859$ for 7 replicas, with an internal precision of ± 0.000015 (2σ). These values were used to correct the measured ratios for possible sample drift. The error estimated for the $^{147}Sm/^{144}Nd$ ratio is 0.1%.

In crustal evolution models based on Nd isotopic composition, the main source of fractionation during the formation and evolution of continental crust takes place during partial melting of lithospheric mantle to generate crustal rocks (McLennan and Hemming, 1992). The εNd model age of a sedimentary rock represents the average age of the extraction of its components from the mantle. In the case of detrital rocks, model ages usually reflect complex mixing based on the different age and provenance of their components. The combined interpretation of model ages and detrital zircon ages has proved to be a powerful tool for investigating the evolution of continental crust, especially in orogenic domains (e.g., Linneman et al., 2004). The Nd model ages calculated for the metagreywackes are included in the εNd vs. the time diagram in Fig. 8. The analysed metagreywackes show $^{147}Sm/^{144}Nd$ ratios <0.145, which is an appropriate ratio for NdT_{DM} calculations. Stern (2002) suggests that a $^{147}Sm/^{144}Nd$ ratio of 0.165 is the upper limit for performing NdT_{DM} calculations. The T_{DM} model ages (DePaolo, 1981) range between 720 and 1215 Ma (Table 3), with an average value of 995 Ma (Fig. 8). εNd (0) values vary from −4.1 to 0, while εNd (500), that is, the εNd value at the time of greywackes sedimentation, ranges between 0.3 and 4.8 (Table 3). A collection of Nd model ages from different regions (Linnemann and Romer, 2002) is also included in Fig. 8. These ages have been divided into two groups according to the age of the dominant source (Grenvillian and post-Grenvillian/pre-Cadomian crust, or pre-Grenvillian, >0.9–1.1 Ga, cratonic crust).

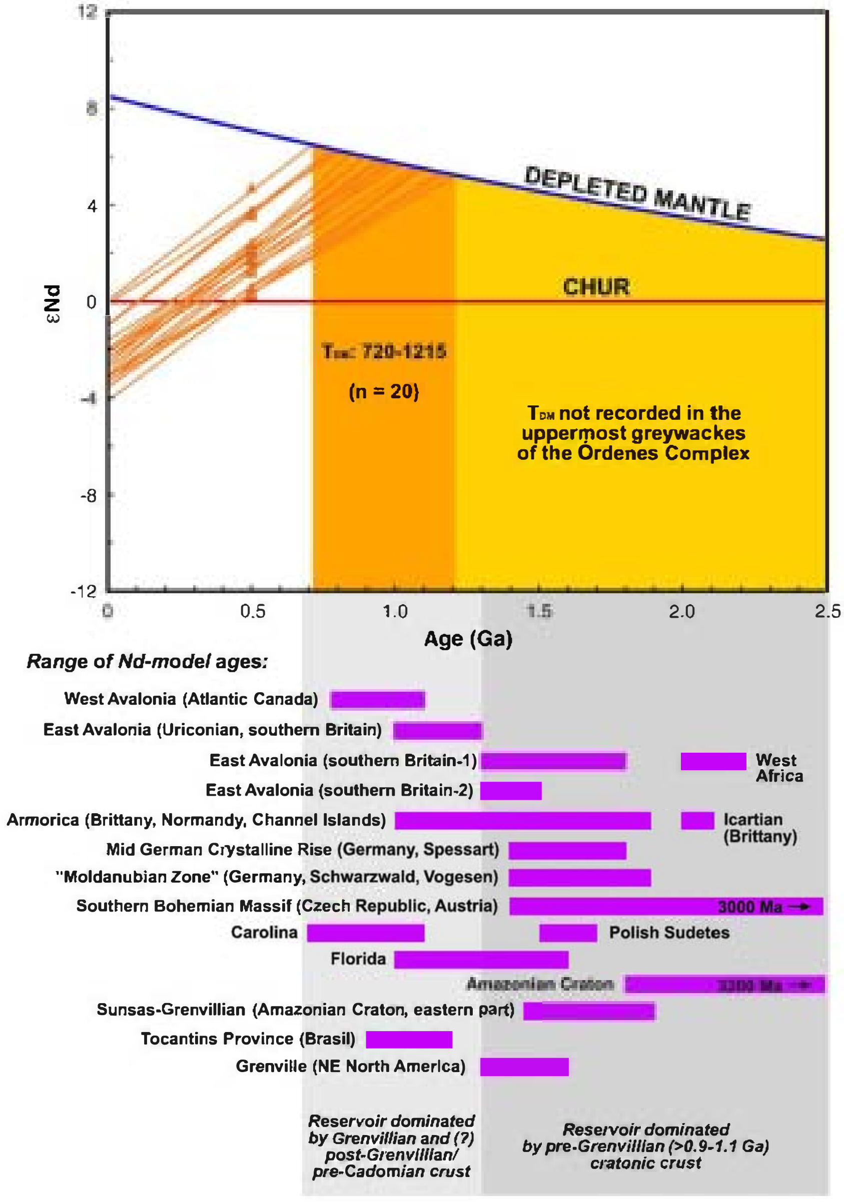

Fig. 8. T_{DM} model ages (DePaolo, 1981) of the top metagreywackes from the Órdenes Complex. Triangles show the εNd values at 500 Ma, a reference age for the deposition of the turbiditic series.
Data source for comparative model ages from different regions taken from Linnemann and Romer (2002).

5. Discussion

According to the age groups recorded by the detrital zircons, the greywackes of the upper levels of the Órdenes Complex have a maximum depositional age of 510–530 Ma (Middle Cambrian). The complete absence of detrital zircons of Mesoproterozoic age (1000–1600 Ma) indicates that the sedimentary basin in which they were deposited was probably located in the peri-Gondwanan realm along the periphery of the West African Craton (Fernández-Suárez et al., 2003). The geochemistry of the greywackes clearly shows that their deposition took place on a convergent margin in a volcanic arc, and specifically (according to the criteria of Bathia and Crook, 1986), in a continental island arc. Within this setting, Bathia and Crook (1986) include sedimentary basins located in the inter-arc, back-arc and fore-arc environments of volcanic arcs developed over thinned continental crust. These arcs have a crystalline continental basement, but lack the thick continental basement of typical arcs generated at active continental margins. The analysed greywackes show very different chemical compositions to those deposited in passive margins or oceanic island arcs. Instead, the geochemical signature of the greywackes indicates deposition in a mature, highly evolved volcanic arc with abundant felsic magmatism.

Pinpointing the location of this sedimentary basin and volcanic arc system turns is more problematic. The similarity in the timing of the greywacke sedimentation (c. 510–530 Ma) and magmatism in the upper units (c. 500-520 Ma; Abati et al., 1999; Fernández Suárez et al., 2007), requires deposition of the turbidites to have taken place during the main phase of volcanic arc activity. Synchronicity of sedimentation with active magmatism is supported by the fact that the greywackes are cross-cut by a coeval diabasic swarm (Díaz-Garcia et al., 2010-this issue). The chemistry of the greywackes also points to the possible presence of thinned continental crust in the root of the arc. Furthermore, the turbiditic series presently forms the upper levels of the arc-derived terrane, and lies structurally above a complex series of high-grade metamorphic rocks (both orthogneisses and paragneisses), the tectonothermal record of which is at least partly

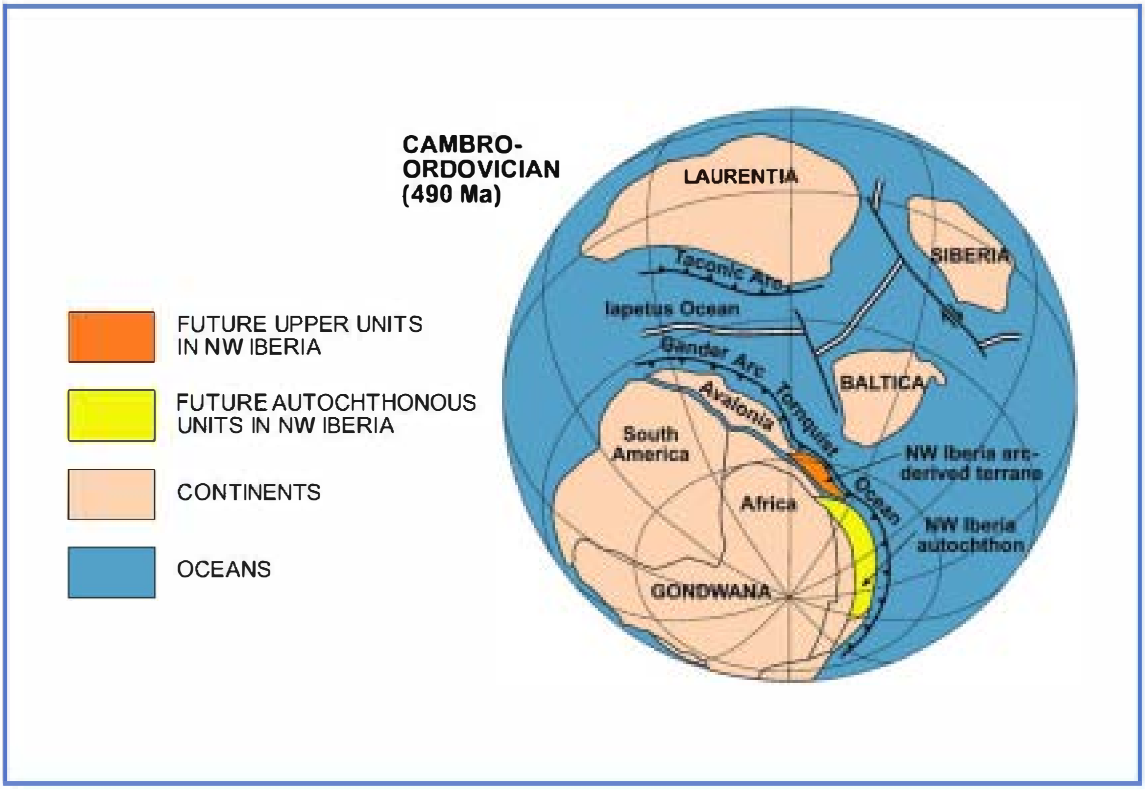

Fig. 9. Paleogeographic reconstruction for the Cambrian–Ordovician limit showing the probable location of the peri-Gondwanan arc where the greywackes were deposited. The figure shows the moment immediately previous to the opening of the Rheic Ocean.
Modified after Arenas et al. (2007).

related to the dynamics of the arc itself. Thus, it is probable that the present position of the turbiditic series partly reflects its primary location (although the contacts with the underlying series are tectonic), and that greywacke deposition took place in an intra-arc basin above thick metamorphic and plutonic complexes and possible pre-arc continental basement, the existence of which has not been investigated in the allochthonous complexes of NW Iberia.

The T_{DM} model ages of the greywackes range from the Middle Neoproterozoic to the Upper Mesoproterozoic (720–1215 Ma, Fig. 8). This, together with the absence of detrital zircons with these ages in the greywackes (Fernández-Suárez et al., 2003), which rules out the presence of Grenvillian terranes in the source area, indicates that the T_{DM} model ages reflect a mixing of components of the Paleoproterozoic and Ediacaran ages. Both sources are represented in the detrital zircon population and are characteristic of the realms bordering the West African Craton.

The presence of Mesoproterozoic basement (1100–1600 Ma) below most of the NW Iberian Massif has been proposed by Murphy et al. (2008). The Paleozoic passive margin sedimentary sequence of the NW Iberian Massif, from the Schistose Domain of the Galicia-Trás-os-Montes Zone to the Cantabrian Zone, may have been deposited on this basement. The combined interpretation of the detrital zircon and Nd model ages from the greywackes of the uppermost levels of the Órdenes Complex, however, indicates a provenance incompatible with the participation of such a basement. If this basement exists, the sedimentary basin in which the greywackes were deposited would have to have been located on a sector of the Gondwanan margin well removed from that represented by the rest of the NW Iberian Massif, although still at the periphery of the West African Craton. A collection of Nd model ages for various terranes of Gondwanan affinity is included in Fig. 8, in addition to the data from the Grenville belt of NE North America (Linnemann and Romer, 2002). Although the ages overlap and the terranes included represent a rather general group, the Nd model ages of the greywackes of the Órdenes Complex compare most closely with those of West Avalonia, Florida and the Carolina terranes, and differ slightly from those of East Avalonia and other terranes, and the domains of the Bohemian Massif. Fig. 9 shows the probable location of the peri-Gondwanan arc immediately prior to the opening of the Rheic Ocean. The opening of this ocean caused the rifting and separation of the external part of the arc, which was transported to the north, carrying with it the sedimentary basin in which the turbiditic series was deposited.

The data obtained from the greywacke provenance of the Órdenes Complex confirm the equivalence of the upper units of the allochthonous complexes of NW Iberia with an arc-derived terrane originally located at the periphery of the West African Craton. This arc was probably generated in the Avalonian peri-Gondwanan realm, in a more westerly position than that occupied by the Lower Paleozoic autochthonous sequence of NW Iberia (Fig. 9). This is consistent with previous data related to the provenance of this allochthonous terrane (Gómez Barreiro et al., 2007). No domain containing the Mesoproterozoic basement was involved in the genesis of the arc. The analysed greywackes were likely deposited adjacent to a mature volcanic arc with abundant felsic magmatism. Although the specific location of the turbidite basin within the volcanic arc is uncertain, the present data suggest deposition in an intra-arc basin generated during the main phase of volcanic arc activity, roughly coincident with the intrusion of the largest plutonic bodies.

Acknowledgements

Financial support for this research has been provided by Spanish project CGL2007-65338-CO2-01/BTE (Ministerio de Ciencia e Innovación). The authors thank Jean Paul Liégeois and an anonymous referee for insightful reviews of the manuscript. This paper is a contribution to IGCP Project 497, "The Rheic Ocean: Origin, evolution and correlatives".

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