A pre-Rodinian ophiolite involved in the Variscan suture of Galicia (Cabo Ortegal Complex, NW Spain)

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U–Pb dating of zircons from a metagabbro of the Purrido amphibolitic unit (Cabo Ortegal Complex, NW Iberian Massif) yielded an age of 1159 ± 39 Ma, interpreted to approximate the crystallization age of the gabbroic protolith. Considering the arc affinity of the metagabbroic rocks, the unit is interpreted as a pre-Rodinian ophiolite developed in a back-arc setting. It is suggested that the ophiolite was obducted over the West African terranes during the assembly of Rodinia. There, this terrane remained tectonically stable and facing an ocean for a long time, and eventually became part of the Gondwanan margin. The ophiolite was finally involved in the Variscan suture of Galicia where it is sandwiched between Palaeozoic rocks. The Purrido unit is so far the only example of a Mesoproterozoic ophiolite in the European Variscan belt, where pre-Neoproterozoic rocks are very scarce and restricted to small exposures.

The Variscan suture of Galicia (allochthonous complexes, Fig. 1) is characterized by the presence of different ophiolitic units located between a lower allochthon representing the most external Gondwanan margin (basal units, Fig. 2), and an arc-derived upper allochthon with polymetamorphic evolution (upper units, Fig. 2) (Arenas *et al.* 1995; Martínez Catalán *et al.* 1996; Abati *et al.* 1999; Gómez-Barreiro *et al.* 2006). Some ophiolitic units previously dated by U–Pb yielded Palaeozoic ages, as in the case of the Careón ophiolite with a Mid-Devonian age of 395 ± 2 Ma (Díaz García *et al.* 1999; Pin *et al.* 2002). Based on this and considering that until now only Palaeozoic ages have been reported in the basal and upper units of the allochthonous complexes, the ophiolitic units involved in the Variscan suture of Galicia have been considered as Palaeozoic (Arenas *et al.* 2006). However, a new U–Pb geochronological study focused on the systematic dating of all the ophiolitic units has provided some surprising results that show an unexpected and complex scenario for the Variscan suture of Galicia.

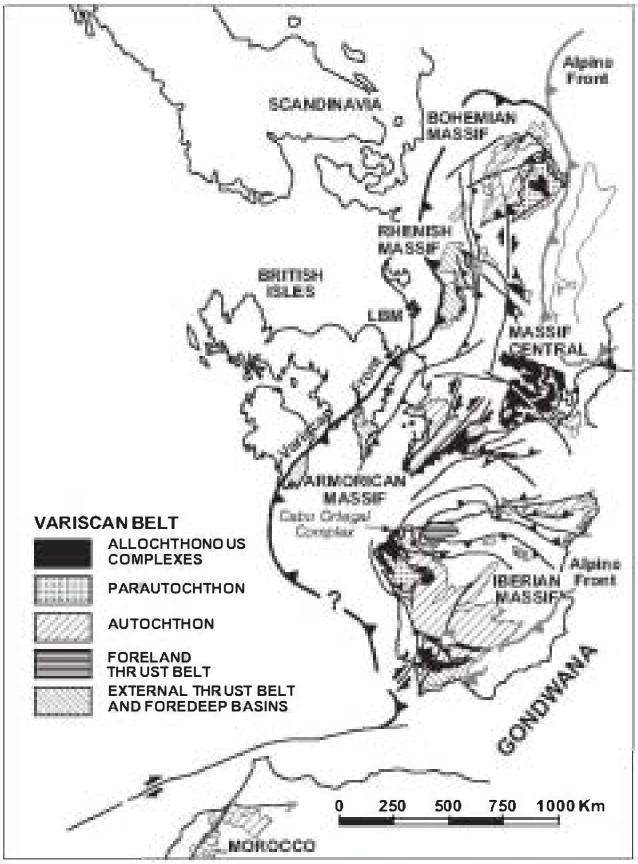

Fig. 1. Location of the Cabo Ortegal Complex in a schematic reconstruction of the Variscan Belt (Martínez Catalán *et al.* 2006). LBM, London–Brabant Massif.

The Purrido amphibolite unit. Excellent exposures of the Purrido amphibolites occur along the cliffs of the western coastline of the Cabo Ortegal Complex, where this unit appears as a 300 m thick, NNE–SSW-striking band underlying the high-*P* and high-*T* upper units (Fig. 2). The Purrido unit has a homogeneous lithological constitution, without significant compositional layering, with medium-grained and well-foliated massive nematoblastic amphibolites, occasionally with garnet-bearing types (hornblende + plagioclase + clinozoisite + quartz + ilmenite + titanite ± garnet ± rutile) (Vogel 1967). These features have been traditionally interpreted in terms of a rather simple history, resulting from a single episode of penetrative deformation and amphibolite-facies metamorphism affecting the massive gabbros. Amphiboles of the prograde nematoblastic fabric of the Purrido amphibolites have been dated at 391 ± 6.6 Ma (^{40}Ar/^{39}Ar in a hornblende concentrate from a garnet-bearing amphibolite; Peucat *et al.* 1990). This age has been considered as evidence for a Variscan tectonothermal evolution.

Geochemically, the Purrido amphibolites can be classified as island-arc tholeiites as illustrated in the Th–Hf–Ta diagram of Figure 3. Additional data are available online at http://www.geol/soc.org.uk/sup18254. A hard copy can be obtained from the Society Library. Therefore it can be suggested that their protoliths were generated in a suprasubduction-zone setting. Considering the homogeneous mafic character of the Purrido unit and its geochemical affinity it can be interpreted as a fragment of the plutonic section of an arc-related ophiolite.

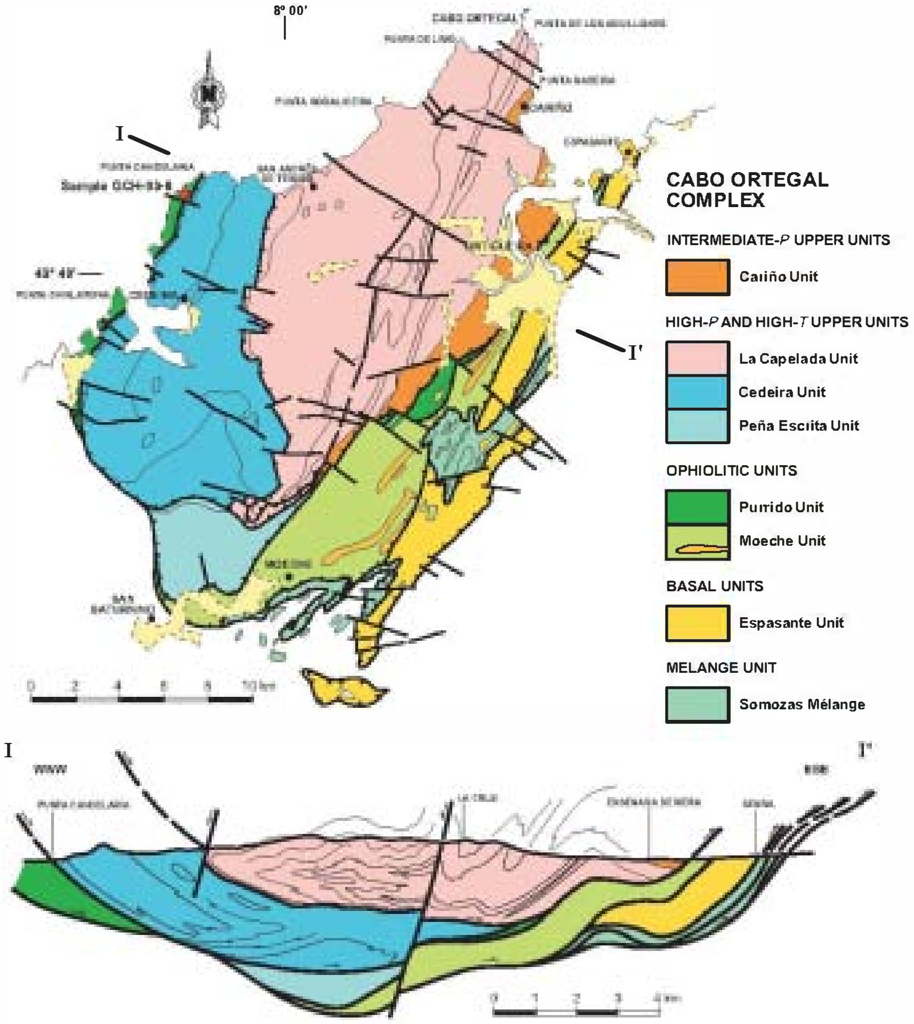

Fig. 2. Sketch map and cross-section of the Cabo Ortegal Complex, in NW Iberia, showing its allochthonous units and main tectonic contacts. The form lines in the cross-section correspond to the main lithological contacts in the upper units and depict the geometry of the main Variscan structures. Location of the Purrido amphibolite sample (GCH-03-8) used for U–Pb dating is also shown.

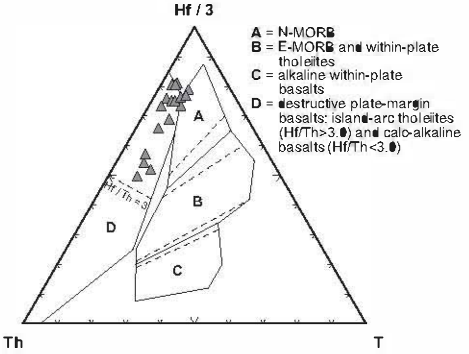

Fig. 3. Th–Hf–Ta diagram (Wood 1980) showing the probable tectonic setting for the Purrido amphibolites. N-MORB, normal mid-ocean ridge basalt; E-MORB, enriched mid-ocean ridge basalt.

U–Pb dating of the Purrido amphibolites.

Analytical techniques. Zircons were separated from sample GCH-03-8 by heavy fraction enrichment on a Wilfley table followed by density separation using di-iodomethane (CH_2I_2) and magnetic separation in a Frantz™ isodynamic separator. Zircon grains representing all sizes and morphological types were selected for laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis. Grains were set in synthetic resin mounts, polished and cleaned in a HNO_3 ultrasonic bath and polished to expose equatorial sections. Analytical instrumentation, analytical protocol and techniques, data reduction, age calculation and common Pb correction are as described by Jeffries *et al.* (2003). In this study, nominal laser-beam diameter was 30 μm. Data were collected in discrete runs of 20 analyses, comprising 12 unknowns bracketed before and after by four analyses of the standard zircon 91500 (Wiedenbeck *et al.* 1995). During the analytical sessions of sample GCH-03-8 the standard 91500 yielded a weighted mean (n = 18) of 1063.1 ± 4 Ma (mean square of weighted deviates (MSWD) $^{206}Pb/^{238}U$ age (certified isotopic dilution thermal ionization mass spectrometry (ID-TIMS) $^{206}Pb/^{238}U$ age 1062.4 ± 0.4 Ma) and a weighted mean of 1064.3 ± 4.3 Ma (MSWD TIMS $^{207}Pb/^{206}Pb$ age: 1065.4 ± 0.3 Ma). Concordia age calculations, and creation of concordia plots, were performed by using Isoplot 3.00 (Ludwig 2003).

Results. Twenty-three analyses were performed on 21 zircon grains from sample GCH-03-8. Of those, three were rejected based on the presence of features such as discordance >25% or high common Pb detected in the U Pb, Th Pb, Pb Pb isotope ratio plots. U Pb and Pb Pb ratios and ages for the 20 selected analyses are given in the Supplementary Publication (see page 737). Within the dataset, there is a statistically coherent group of 10 analyses (based on the robust median algorithm of Ludwig 2003) whose $^{207}Pb/^{206}Pb$ ages range between 1109 ± 18 and

1208 ± 66 Ma. These analyses have consistent Th/U ratios with typical magmatic values mostly between 0.3 and 0.4. The median value of the $^{207}Pb/^{206}Pb$ ages of these 10 analyses is 1159 ± 39 Ma, based on a robust median statistical analysis by means of the TuffZirc algorithm of Ludwig (2003) (Fig. 4a). This group of analyses defines a discordia anchored at 0 Ma with an upper intercept of 1169 ± 16 Ma, within the error of the median value. Two of these analyses (with relatively large errors) overlap each other and the concordia curve, yielding a concordia age of 1121 ± 9 Ma (Fig. 4b). Given that cathodoluminescence assisted laser ablation and examination of isotope-ratio v. time plots ensures that the discordance of the above analyses is not due to mixing of differently aged domains or to instrumental elemental fractionation (Jeffries *et al.* 2003), the most likely source of discordance is recent lead loss. Because the unconstrained discordia has a near-zero lower intercept, the possibility that the $^{207}Pb/^{206}Pb$ ages represent minimum ages (i.e. episodic lead loss at an earlier than zero time) can also be confidently dismissed. Consequently, we argue that the crystallization age of the rock is between *c.* 1120 and 1170 Ma.

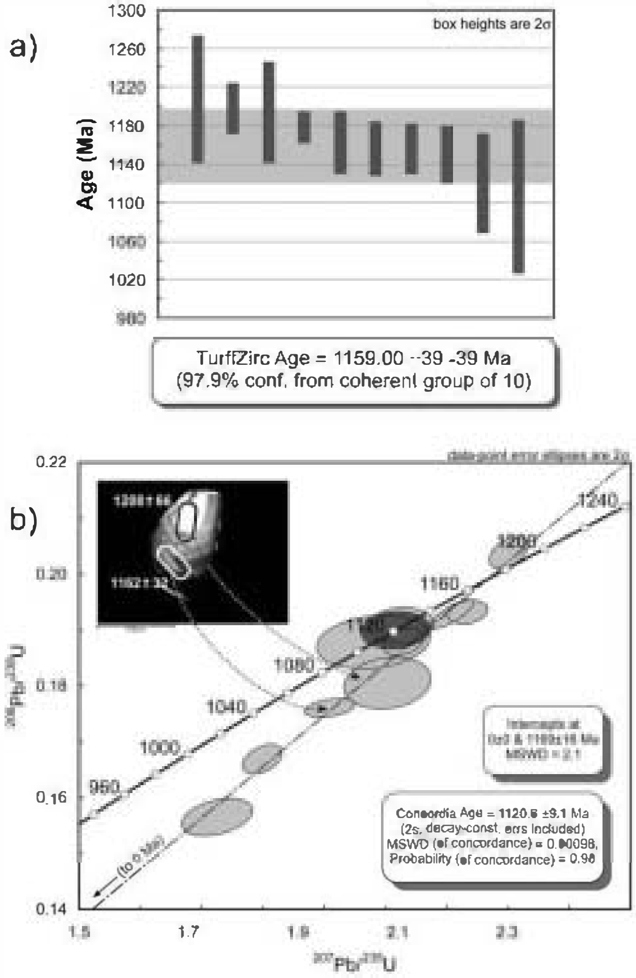

Fig. 4. (a) Robust median statistical analysis of the $^{207}Pb/^{206}Pb$ ages corresponding to a group of 10 analyses of zircons from the Purrido amphibolite sample GCH-03-8 (see text for details). (b) U–Pb concordia diagram showing the results of U–Pb dating of zircon in the sample (GCH-03-8). The dark grey ellipse represents a concordia age calculated from two concordant and overlapping analyses. Errors are given at the 2σ level.

A few analyses yielded older Mesoproterozoic ages ranging from 1265 ± 8 Ma to 1658 ± 32 Ma, and three analyses yielded Variscan–Eovariscan ages between 322 ± 3 and 428 ± 5 Ma. Finally, a single analysis yielded a concordant age of 816 ± 15 Ma. The analyses yielding older Proterozoic ages (see Supplementary Publication, p. 737) are interpreted to represent inherited zircon, indicating that the gabbros were somehow connected with an older Mesoproterozoic crust. This is consistent with the geochemical features of these metabasic rocks, which suggest an arc affinity (see Fig. 3). Regarding the youngest analyses, the 816 Ma concordant zircon may have formed during a yet unconstrained Neoproterozoic event and the three Palaeozoic zircons reflect the tectonothermal reworking of the gabbroic protolith during the Variscan orogeny and are consistent with the $^{40}Ar/^{39}Ar$ ages reported by Dallmeyer *et al.* (1997).

Discussion. The obtained U–Pb age of 1159 ± 39 Ma for the gabbroic protoliths of the Purrido amphibolite allows the identification of this unit as a pre-Rodinian mafic body that we interpret as part of an arc-related ophiolite. This group of ophiolites older than 1100–1000 Ma, the estimated assembly age for the Rodinia supercontinent (Dalziel 1991; Hoffman 1991), is relatively small, as only around 35 cases have been reported so far (Moores 2002). Considering the geochemical affinity of its mafic rocks, the Purrido ophiolite can be assigned to the suprasubduction-zone type and we suggest that it was generated in relation to the activity of a volcanic arc, probably in a back-arc setting. This tectonic setting is also compatible with the presence of inherited zircons with ages ranging between 1265 and 1658 Ma. The Purrido amphibolites are characterized by a rather simple tectonothermal history, mostly of Variscan age. This suggests that the ophiolite was probably incorporated with little deformation into the Variscan orogenic wedge. Therefore it is unlikely that the Purrido unit was involved in the Grenville orogenic belt (developed between 1300 and 1000 Ma), and it can be thus interpreted as a section of peri-arc oceanic lithosphere located away from the realm of this mobile belt.

Probably the most enigmatic aspect in the history of the Purrido unit is its Proterozoic obduction over a continental margin, as this is the only process that can explain the preservation of this oceanic section. This is even a more puzzling issue considering that only Palaeozoic ages have been reported for protoliths in the rest of the units involved in the Variscan suture of Galicia. However, the presence of Palaeo-Proterozoic or even Archaean continental basement in the Variscan belt of Western Europe was described a long time ago. This is respectively the case for the Icart gneisses (Channel Islands; Samson & D'Lemos 1998) and the granulites of the Bay of Biscay (Guerrot *et al.* 1989), which are both interpreted as remnants of the West African craton. Considering the new information provided in this work, it is clear that the basement of the Variscan belt also includes Mesoproterozoic mafic sections with oceanic affinity, such as the Purrido unit, which probably were obducted over a continental margin during the Rodinia assembly. Alternative hypotheses such as ophiolite obduction during continent dispersal following the break-up of Rodinia are less probable, as they would imply that the oceanic domain recorded by the ophiolite existed longer than 400 Ma (the break-up of Rodinia began at around 750 Ma; Torsvik 2003).

Taking into account widely accepted palaeogeographical reconstructions of the continents immediately before the assembly of Rodinia, it seems that at *c.* 1100 Ma Amazonia and West Africa defined a single continental domain located between the equator and latitude 40°S (Pisarevsky *et al.* 2003). Present data

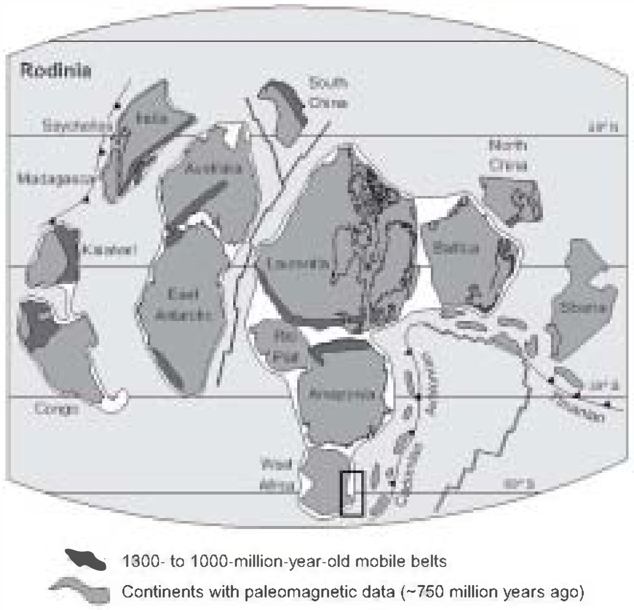

Fig. 5. Suggested location of Purrido ophiolite (framed region) in the Rodinia reconstruction at *c.*750 Ma of Torsvik (2003).

for the Purrido unit, especially the geochemistry of mafic rocks, suggest that this ophiolite could have been generated in relation to an active arc system in the eastern margin of Amazonia West Africa. The ophiolite was obducted later with little internal deformation over the external margin of West Africa, probably during the main phases of Rodinia assembly. Rodinia remained assembled between 1000 and 750 Ma. Figure 5 shows the suggested location for the Purrido ophiolite (Rodinia reconstruction at *c.* 750 Ma; Torsvik 2003). The ophiolite would have been mainly stable in this position and facing an arc system (Avalonia Cadomia) during the Rodinia breakup, and was later incorporated to the northern margin of the new Gondwana supercontinent, finally assembled at *c.*530 Ma (Cawood 2005).

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References

Abati, J., Dunning, G.R., Arenas, R., Díaz García, F., González Cuadra, P., Martínez Catalán, J.R. & Andonaegui, P. 1999. Early orogenic event in Galicia (NW Spain): evidence from U–Pb ages in the uppermost unit of the Órdenes Complex. *Earth and Planetary Science Letters*, **165**, 213–228.

Arenas, R., Rubio Pascual, F.J., Díaz García, F. & Martínez Catalán, J.R. 1995. High-pressure micro-inclusions and development of an inverted metamorphic gradient in the Santiago Schists (Órdenes Complex, NW Iberian Massif, Spain): evidence of subduction and syncollisional decompression. *Journal of Metamorphic Geology*, **13**, 141–164.

Arenas, R., Martínez Catalán, J.R. & Sánchez Martínez, S. *et al.* 2006. Paleozoic ophiolites in the Variscan suture of Galicia (northwest Spain): distribution, characteristics and meaning. *In:* Hatcher, R.D. *et al.* (ed.) *4-D Framework of Continental Crust.* Geological Society of America Memoir, in press.

Cawood, P.A. 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. *Earth-Science Reviews*, **69**, 249–279.

Dallmeyer, R.D., Martínez Catalán, J.R. & Arenas, R. *et al.* 1997. Diachronous Variscan tectonothermal activity in the NW Iberian Massif: evidence from ^{40}Ar/^{39}Ar dating of regional fabrics. *Tectonophysics*, **277**, 307–337.

Dalziel, I.W.D. 1991. Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. *Geology*, **19**, 598–601.

Díaz García, F., Arenas, R., Martínez Catalán, J.R., González del Tánago, J. & Dunning, G.R. 1999. Tectonic evolution of the Careón Ophiolite (Northwest Spain): a remnant of oceanic lithosphere in the Variscan Belt. *Journal of Geology*, **107**, 587–605.

Gómez-Barreiro, J., Wijbrans, J.R., Castiñeiras, P., Martínez Catalán, J.R., Arenas, R., Díaz García, F. & Abati, J. 2006. ^{40}Ar/^{39}Ar laserprobe dating of mylonitic fabrics in a polyorogenic terrane of NW Iberia. *Journal of the Geological Society, London*, **163**, 61–73.

Guerrot, C., Peucat, J.J., Capdevila, R. & Dosso, L. 1989. Archean protoliths within Early Proterozoic granulitic crust of the west European Hercynian belt: possible relics of the west African craton. *Geology*, **17**, 241–244.

Hoffman, P.F. 1991. Did the breakout of Laurentia turn Gondwana inside-out? *Science*, **252**, 1409–1412.

Jeffries, T., Fernández-Suárez, J., Corfu, F. & Gutiérrez-Alonso, G. 2003. Advances in U–Pb geochronology using a frequency quintupled Nd:YAG based laser ablation system (lambda = 213nm) and quadrupole based ICP-MS. *Journal of Analytical Atomic Spectrometry*, **18**, 847–855.

Ludwig, K.R. 2003. *User's Manual for Isoplot 3.00*. Berkeley Geochronology Center Special Publications, **4**.

Martínez Catalán, J.R., Arenas, R., Díaz García, F., Rubio Pascual, F.J., Abati, J. & Marquínez, J. 1996. Variscan exhumation of a subducted Paleozoic continental margin. The basal units of the Órdenes Complex, Galicia, NW Spain. *Tectonics*, **15**, 106–121.

Martínez Catalán, J.R., Arenas, R. & Díaz García, F. *et al.* 2006. Space and time in the tectonic evolution of the northwestern Iberian Massif. Implications for the comprehension of the Variscan belt. *In:* Hatcher, R.D. *et al.* (ed.) *4-D Framework of Continental Crust.* Geological Society of America, Memoirs, in press.

Moores, E.M. 2002. Pre-1 Ga (pre-Rodinian) ophiolites: their tectonic and environmental implications. *Geological Society of America Bulletin*, **114**, 80–95.

Peucat, J.J., Bernard-Griffiths, J., Gil Ibarguchi, J.I., Dallmeyer, R.D., Menot, R.P., Cornichet, J. & Iglesias Ponce de León, M. 1990. Geochemical and geochronological cross section of the deep Variscan crust: the Cabo Ortegal high-pressure nappe (northwest Spain). *Tectonophysics*, **177**, 263–292.

Pin, C., Paquette, J.L., Santos Zalduegui, J.F. & Gil Ibarguchi, J.I. 2002. An Early Devonian supra-subduction zone ophiolite related to incipient collisional processes in the Western Variscan Belt: the Sierra de Careón Unit, Órdenes Complex, Galicia. *In:* Martínez Catalán, J.R., Hatcher, R.D. Jr, Arenas, R. & Díaz García, F. (eds) *Variscan–Appalachian Dynamics: the Building of the Late Paleozoic Basement.* Geological Society of America, Special Papers, **364**, 57–71.

Pisarevsky, S.A., Wingate, M.T.D., Powell, C.McA., Johnson, S.P. & Evans, D.A.D. 2003. Models of Rodinia assembly and fragmentation. *In:* Yoshida, M., Windley, B.F. & Dasgupta, S. (eds) *Proterozoic East Gondwana: Supercontinent Assembly and Break-up.* Geological Society of London, Special Publications, **206**, 35–55.

Samson, S.D. & D'Lemos, R. 1998. U–Pb geochronology and Sm–Nd isotopic composition of Proterozoic gneisses, Channel Islands, UK. *Journal of the Geological Society, London*, **155**, 609–618.

Torsvik, T.H. 2003. The Rodinia jigsaw puzzle. *Science*, **300**, 1379–1381.

Vogel, D.E. 1967. Petrology of an eclogite- and pyrigarnite-bearing polymetamorphic rock Complex at Cabo Ortegal, NW Spain. *Leidse Geologische Mededelingen*, **40**, 121–213.

Wiedenbeck, M., Allé, P. & Corfu, F. *et al.* 1995. Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. *Geostandards Newsletter*, **19**, 1–23.

Wood, D.A. 1980. The application of a Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary Volcanic Province. *Earth and Planetary Science Letters*, **50**, 11–30.