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Peridotites and mafic igneous rocks at the foot of the Galicia Margin: an oceanic or continental lithosphere? A discussion

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ABSTRACT

An ultramafic/mafic complex is exposed on the seafloor at the foot of the Galicia Margin (Spain and Portugal). It comprises various types of peridotites and pyroxenites, as well as amphibole-diorites, gabbros, dolerites and basalts. For chronological and structural reasons (gabbros were emplaced within peridotites before the continental break-up) this unit cannot be assigned to the Atlantic oceanic crust. The compilation of all available petrological and geochemical data suggests that peridotites are derived from the sub-continental lithospheric mantle, deeply transformed during Cretaceous rifting. Thus, websterite dykes extracted from the depleted MORB mantle reservoir (DMM), were emplaced early within the lithospheric harzburgites; subsequent boudinage and tectonic dispersion of these dykes in the peridotites, during deformation stages at the beginning of rifting, resulted in the formation of fertile but isotopically depleted lherzolites. Sterile but isotopically enriched websterites, would represent melting residues in the peridotites, after significant partial melting and melt extraction related to the thermal erosion of the lithosphere. The latter melts are probably the source of brown amphibole metasomatic crystallization in some peridotites, as well as of the emplacement of amphibole-diorite dykes. Melts directly extracted from the asthenosphere were emplaced as gabbro within the sub-continental mantle. Mixing these DMM melts together with the enriched melts extracted from the lithosphere, provided the intermediate isotopic melt-compositions - in between the DMM and Oceanic Islands Basalts reservoir - observed for the dolerites and basalts, none of which are characterized by a genuine N-MORB signature. An enriched lithospheric mantle, present prior to rifting of the Galicia margin, is in good agreement with data from the Messejana dyke (Portugal) and more generally, with those of all continental tholeiites of the Central Atlantic Magmatic Province (CAMP).

Key words: Galicia Margin, ocean-continent transition, rifting, lithospheric mantle, mantle contamination

Peridotitas y magmatitas máficas al pie del Margen de Galicia: ¿Litosfera oceánica o continental? Una discusión

RESUMEN

En el fondo marino al pie del Margen de Galicia (latitudes correspondientes a España y Portugal) aflora un complejo ultramáfico / máfico, compuesto por varios tipos de peridotitas y piroxenitas, así como dioritas anfibólicas, gabros, doleritas y basaltos. Por razones cronológicas y estructurales (gabros emplazados dentro de peridotitas antes de la fractura continental) esta unidad no se puede asignar a la corteza oceánica del Atlántico. La recopilación de todos los datos petrológicos y geoquímicos disponibles sugiere que las peridotitas se derivan del manto litosférico subcontinental, profundamente transformado durante el "rifting" cretácico. Así, en las harzburgitas litosféricas se emplazaron tempranamente diques de websterita extraídos del reservorio mantélico MORB empobrecido (DMM); ulteriores procesos de deformación (boudinage) y dispersión tectónica de estos diques en las peridotitas, durante las etapas de deformación iniciales del rifting, dieron lugar a la formación de lherzolitas fértiles pero isotópicamente empobrecidas. Las websteritas *estériles pero isotópicamente enriquecidas podrían representar residuos de fusión en las peridotitas, tras una significativa fusión parcial y extracción del fundido, en relación con la erosión térmica de la litosfera. Estos últimos fundidos son probablemente la fuente de la cristalización metasomática de anfíbol marrón en algunas peridotitas, así como del emplazamiento de diques de diorita anfibólica. Los fundidos extraídos directamente de la astenosfera se emplazaron como gabros en el interior del manto subcontinental. La mezcla de estos fundidos DMM con los fundidos enriquecidos extraídos de la litosfera dio lugar a las composiciones isotópicas intermedias -entre DMM y el reservorio OIB o basaltos de isla oceánica- observadas en doleritas y basaltos, ninguno de los cuales se caracteriza por una típica firma N-MORB. Un manto litosférico enriquecido, presente antes de la dislocación del margen de Galicia, concuerda bien con los datos del dique Messejana (Portugal) y, en general, con los de todas los toleitas continentales de la Provincia Magmática del Atlántico Central (CAMP).*

Palabras clave: Margen de Galicia, transición Océano-Continente, rifting, manto litosférico, contaminación mantélica

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

Las relaciones entre manto litosférico sub-continental y astenosfera no se han tenido en cuenta, en general, de forma seria en los modelos de rifting y de apertura oceánica. La existencia de peridotitas y de rocas ígneas al pie del margen de Galicia (España y Portugal) brinda la oportunidad de estudiar una zona de transición entre continente europeo y océano Atlántico: se trata de la litosfera oceánica, de la litosfera continental, o bien de un dominio intermedio? El examen del conjunto de datos petrológicos y geoquímicos permite proponer un modelo coherente, aunque reposa todavía sobre varias hipótesis.

Recopilación de datos

La localización y los principales estadios de la evolución estructural del margen de Galicia se representan en las figuras 1 y 3. Las rocas muestreadas son peridotitas serpentinizadas, piroxenitas (websteritas y clinopiroxenita), dioritas anfibólicas, gabros, doleritas y basaltos (Fig. 2).

1) Las peridotitas serpentinizadas

Se trata de lherzolitas y harzburgitas con espinela y espinela + plagioclasa. El clinopiroxeno (CPX) aparece a veces sustituído metasomáticamente por anfíbol marrón (AMP). Las peridotitas han sufrido varias fases de deformación a alta (900 ° C) y baja temperatura (milonitización) y son heterogéneas desde los puntos de vista mineralógico y geoquímico. En las lherzolitas del Banco de Galicia (GB), el CPX es rico en Na, mientras que es muy pobre en Na en las harzburgitas en la llanura abisal ibérica (IAP); entre los dos (colina 5 100 = 5 100H), las concentraciones de Na son intermedias (Fig. 4). Los perfiles de Tierras Raras de los CPX están empobrecidos en tierras raras ligeras, LREE, pero no tanto como los de los CPX de las peridotitas abisales. Las relaciones isotópicas Sr-Nd muestran que los CPX de las lherzolitas están fuertemente deprimidos isotópicamente, mientras que las del CPX de 5 100H CPX y las de los AMP metasomáticos muestran, en cambio, un relativo enriquecimiento (Fig. 5).

2) Websteritas y clinopiroxenita

Estas rocas forman raras intercalaciones en las lherzolitas (GB) y en las harzburgitas (IAP). Sus CPX tienen composiciones idénticas (pero menos cromíferas) a las de los CPX de las peridotitas encajantes (Fig. 4). Todos los perfiles de REE están deprimidos en tierras raras ligeras en comparación con las condritas. Mientras que los CPX GB están empobrecidos isotópicamente, los de las websterites IAP están en cambio muy enriquecidos, con relaciones de Sr-Nd cercanas a las de las fuentes mantélicas EM1-EM2 (Fig. 5).

3) Las dioritas anfibólicas

Se presentan en vetas inyectadas en las peridotitas con AMP, tardíamente con respecto a la deformación HT. El AMP de las dioritas se ha datado en 122 ± 0.6 Ma (^{39}Ar-^{40}Ar), edad que corresponde también, por tanto, al *fin de la deformación HT. Los espectros de los AMP son planos, altamente enriquecido en comparación con las condritas y en comparación con los de los AMP de las peridotitas encajantes. Las relaciones isotópicas Sr-Nb son intermedias (entre DMM y EM1-EM2), análogas a las de los AMP de las peridotitas (Fig. 5).*

4) Los Gabros

Se observaron gabros deformados a temperaturas moderadas tanto en el norte (GB) como en el Sur (IAP). Se han determinado en gabros milonitizados ricos en circón edades U-Pb de 122.3 ± 0.3 y 121.7 ± 0.4 Ma, anteriores a la ruptura continental. El CPX de algunos gabros GB se caracteriza por relaciones isotópicas Sr-Nd intermedias. En cambio, los datos sobre los gabros IAP indican relaciones isotópicas ^{143}Nd/^{144}Nd elevadas, lo que sugiere que fueron extraídos directamente de la astenosfera. Del mismo modo, el sistema ^{167}Lu-^{177}Hf indica un origen astenosférico para los circones de los gabros milonitizados.

5) Doleritas y basaltos

Se obtuvieron muestras de doleritas y basaltos en filones y en coladas (GB), así como en depósitos de avalancha (IAP). Las doleritas están ligeramente deformadas; no así los basaltos. La forma de los espectros de tierras raras varía, evolucionando desde términos enriquecidos en LREE hasta términos deprimidos, pero nunca tan deprimidos como los de los N-MORB. Todas las relaciones isotópicas de Sr y Nd se sitúan en el dominio intermedio del «mantle array» (Fig. 5).

Interpretación de los datos

1) Las lherzolitas del Banco de Galicia (GB) : manto litosférico sub-continental contaminado por líquidos emanados de la astenosfera

Los CPX de las lherzolitas GB y de las websteritas asociadas tienen características contradictorias: son ricos en Na y, por tanto, fértiles (lo que las aleja de las peridotitas abisales estériles de la litosfera oceánica), al tiempo que isotópicamente empobrecidos (lo que las aproxima al manto empobrecido fuente de los MORB, DMM). La evolución temporal de la relación isotópica del Nd de una websterita corta el dominio del DMM, definiendo una «edad modelo» comprendida entre 80 y 350 Ma. Se propone la hipótesis de que los líquidos originales de las websteritas GB fueron extraídos del reservorio DMM en el momento del rifting, hacia 130-135 Ma (Fig. 8). Después de su emplazamiento, las websteritas fueron estiradas por la deformación HT. La dispersión tectónica del CPX en las peridotitas condujo a la formación de las lherzolitas GB, cuyo CPX, químicamente muy similar al de las websteritas, está sin embargo re-equilibrado con la paragénesis de espinela cromífera.

2) Las harzburgitas y las websteritas de la Llanura Abisal Ibérica (IAP): un manto litosférico sub-continental afectado por fusión parcial y extracción de líquido

Los CPX de las harzburgitas IPA y de las piroxenitas asociadas son muy pobres en Na y están fuertemente empobrecidos en LREE. Los CPX de las websteritas y de una clinopiroxenita, por el contrario, están isotópicamente enriquecidos. Esta característica se encuentra generalmente en los CPX de xenolitos de basaltos alcalinos continentales, correspondientes al manto litosférico sub-continental, pero generalmente ricos en Na. Por tanto, las piroxenitas IAP habrían pertenecido, antes del rifting, al manto litosférico sub-continental enriquecido; la fusión parcial de éste, en el curso de la erosión térmica de la litosfera, habría provocado su empobrecimiento en elementos incompatibles, mientras que sus relaciones isotópicas se mantuvieron sin cambios.

3) Las rocas ígneas del margen de Galicia: inyección directa desde la astenosfera y mezcla de magmas

La edad modelo Nd indica que las websteritas podrían haberse emplazado en las peridotitas GB, a partir del reservorio DMM, desde el comienzo del rifting. Los gabros procedentes de la astenosfera se inyectaron *después de la deformación HT pero antes de la ruptura continental. Las dioritas anfibólicas, acompañadas de un metasomatismo modal en las peridotitas vecinas, muestran la intervención de un componente magmático enriquecido en isótopos radiogénicos al final de la deformación HT; la contribución de este componente continúa con el emplazamiento de algunos gabros GB, de las doleritas y de los basaltos. La composición de las rocas ígneas del margen de Galicia implica, pues, la participación de (¡al menos !) dos fuentes distintas: una fuente empobrecida de tipo DMM y una fuente enriquecida.*

4) ¿De dónde procede el componente enriquecido?

En lugar de invocar una fuente del tipo OIB, es más fácil admitir que la fuente enriquecida es simplemente la litosfera subcontinental, tal como se la conoce por las peridotitas y websteritas de la Llanura Abisal Ibérica (IPA). La hibridación de los líquidos extraídos de las websteritas IAP durante el rifting, con líquidos procedentes del reservorio DMM, puede dar cuenta de las composiciones isotópicas de las diversas rocas ígneas observadas en el margen de Galicia. Esta interpretación es coherente con las características de las rocas ígneas emplazadas en la Península Ibérica desde mucho antes del rifting (dique de Messejana y ofitas de los Pirineos, al final del Triásico o al principio del Jurásico), y en general de todas las que pertenecen a la provincia magmática del Atlántico central (CAMP). Efectivamente, se considera que todas resultan de la fusión parcial del manto superior litosférico enriquecido de Pangea.

Conclusiones

Las peridotitas del margen de Galicia han sido intruídas por gabros antes de la ruptura continental. Queda pues excluído, por razones estructurales, que puedan pertenecer a la litosfera oceánica. Algunas fueron fertilizadas por líquidos procedentes de la astenosfera; otras sufrieron fusión parcial. Estas rocas parecen representar, por tanto, diferentes zonas del manto litosférico superior sub-continental que han experimentado transformaciones importantes, pero diversificadas, durante el rifting. Las rocas ígneas asociadas a las peridotitas proceden, en algunos casos, directamente del reservorio DMM; las otras, particularmente las doleritas y los basaltos, resultarían de la hibridación de líquidos DMM y de líquidos enriquecidos resultantes de la fusión parcial del manto subcontinental. Las características isotópicas de este último son compatibles con las de la litosfera continental de Pangea, cuya fusión parcial generó, en el Triásico-Liásico, las toleítas continentales de la provincia magmática del Atlántico central (CAMP).

Introduction

Since the early 1950s, the multiplication of oceanographic vessels has led to detailed studies of continental passive margins - especially in the Atlantic Ocean - for both economic and scientific purposes. Oil companies and academic researchers have conducted a number of surveys at sea (bathymetry, seismic reflection, gravimetry, magnetism, etc), whilst the DSDP and ODP programmes, involving the *Glomar Challenger* and then the *Joides Resolution*, recovered miles of cores and loggings. This large amount of new data has allowed researchers to understand the structure of continental margins by identifying pre-, syn- and post-rift terranes, as well as the form and timing of related faulting (Burk and Drake, 1974). In most cases, however, these data relate only to relatively shallow terranes, as the drillings rarely exceeded depths of more than a few kilometres, whilst seismic data recognize all the units beneath the sediments as the « acoustic basement », without any discrimination. But extension mechanisms leading to continental break-up involve the whole lithosphere and underlying asthenosphere. Therefore, both analog and digital modelling were required in the study of rifting and continental break-up mechanisms. The famous model of Wernicke (1985) is based on a large detachment fault associated with an asymmetric bulge of the asthenosphere. In this model, as in the following (see review in Boillot and Coulon, 1998), neither the discrimination between continental and oceanic lithosphere, nor the transformations experienced by the lithospheric mantle during rifting are really taken into consideration.

Since the discovery of serpentinized and weathered peridotites at the foot of the Galicia Bank (Boillot *et al.*, 1980), several surveys at sea have been devoted to this transition, occurring in the area between the European continent and Atlantic Ocean (e.g. Boillot and Winterer, 1988; Boillot *et al.*, 1989; Boillot *et al.*, 1995a; Boillot and Froitzheim, 2001; Malod *et al.*, 1993; Manatschal and Bernoulli, 1999; Whitmarsh, R. B. and Wallace, 2001). Geophysical investigations have identified an ultramafic ridge along the Iberian

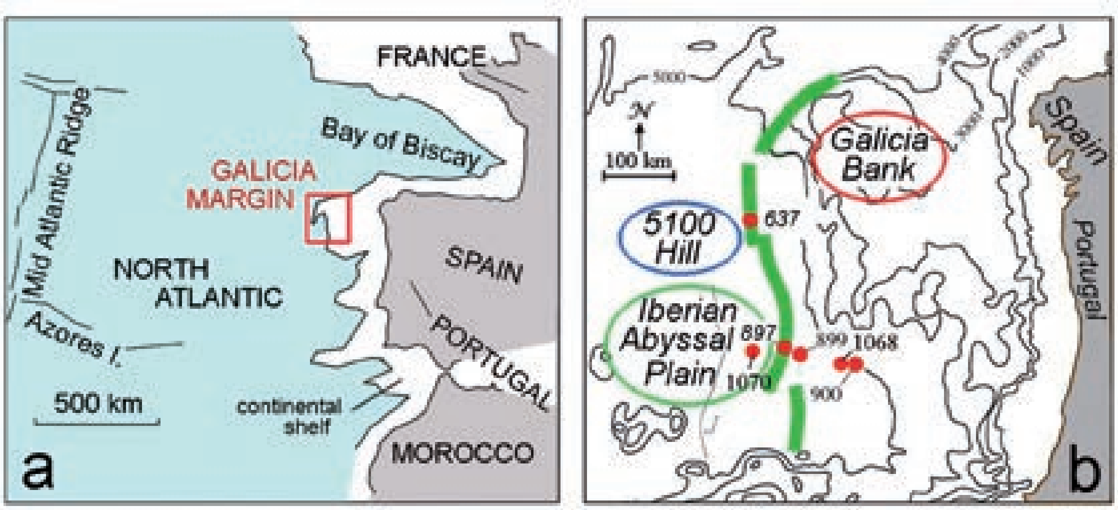

Figure 1. Situation of the Galicia margin: a) In the North Atlantic Ocean; b) Off the Iberian Peninsula. Areas described in this paper are surrounded by circles, the colors of which (red: Galicia Bank = GB; blue: 5 100 Hill; green: Iberian Abyssal Plain = IAP) characterize each sampling sites in the following diagrams. The wide green band is the ultramafic ridge, which, in the Iberian Abyssal Plain (IAP) at least, actually extends eastwards for several tens of km. Red dots: ODP sites. J = J magnetic anomaly.

Figura 1. *Situación del margen de Galicia: a) En el Océano Atlántico Norte; b) En relación con la Península Ibérica. Las áreas descritas en este artículo están rodeadas por círculos cuyos colores (rojo: Banco de Galicia = GB; azul: Colina 5 100; verde: Llanura Abisal Ibérica = IAP) caracterizan cada punto de muestreo en los siguientes diagramas. La banda ancha verde es la cresta ultramáfica, la cual en realidad, al menos en la Llanura Abisal Ibérica (IAP), se extiende hacia el este por varias decenas de km. Puntos rojos: sondeos ODP. J = anomalía magnética J.*

passive margin, which extends from north to south over more than 500 km (Fig. 1b). Several ODP drillings and two diving cruises with the submersible *Nautile* have shown that this ultramafic ridge also includes a variety of igneous rocks intruded within the peridotites or having flowed over them (Fig. 2). On the basis of all the available data about these rocks, this paper tries to build a consistent model of lithospheric mantle evolution during rifting and continental break-up.

Main features of geology, petrology and geochemistry

The Galicia Margin history started about 140 Ma ago with the beginning of the North Atlantic rifting (e.g. Boillot and Winterer *et al.*, 1988). Figure 3 summarizes the main stages of its edification. Together with the serpentinized peridotites, the ultramafic ridge allowed researchers to sample websterites, amphibole-diorites, gabbros, dolerites and basalts (Fig. 3). Descriptions of these rocks have already been presented in several papers acknowledged throughout this article; only the main features, useful for a general interpretation, are highlighted in this section. From north to south, the sampling sites are referenced as follows (Fig. 1): Galicia Bank = GB; 5 100 Hill = 5 100H; Iberian abyssal plain = IAP.

Serpentinized peridotites

These rocks are strongly foliated and have experienced one or more deformation stages at high temperatures (ca 900°C). They have locally been mylonitized later, at lower temperatures (Evans and

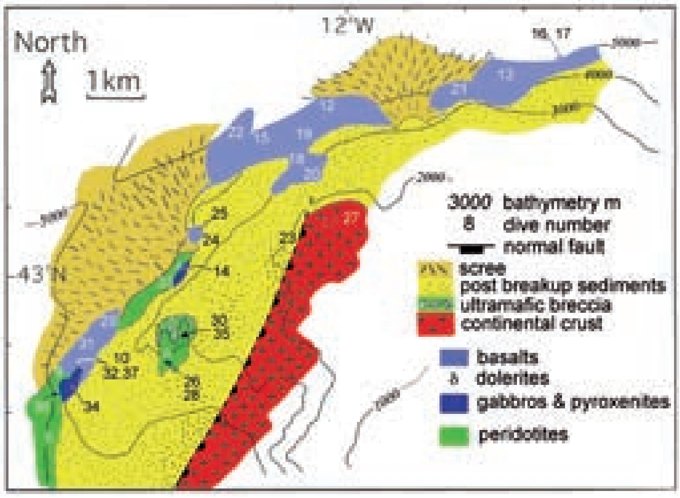

Figure 2. Geological sketch of the Galicia Bank (IFREMER Galinaute cruises I and II).

Figura 2*. Esquema geológico del Banco de Galicia (cruceros IFREMER Galinaute I y II).*

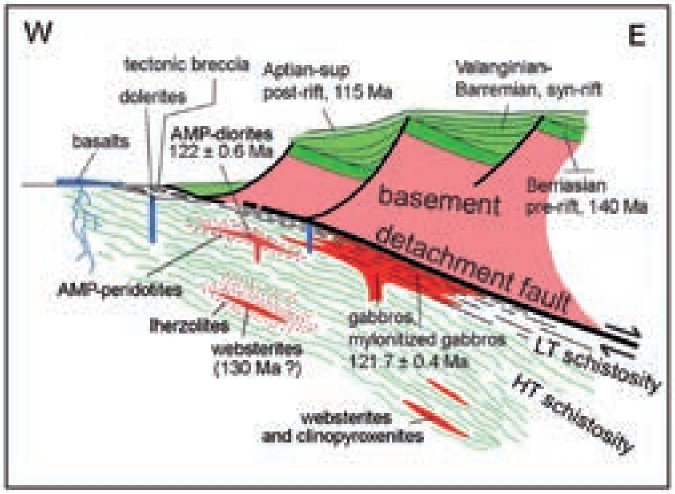

Figure 3. Structural evolution of the Galicia Margin (modified from Boillot et al., 1995b). The rifting occurred between 140 and 115 Ma. AMP = amphibole; HT and LT: high and low temperature, respectively. Gabbro U-Pb age: Schärer et al., 2000. AMP-diorite K-Ar age: Féraud et al., 1988). Websterite model age: Chazot et al., 2005.

***Figura 3**. Evolución estructural del Margen de Galicia (modificada a partir de Boillot et al, 1995b). El "rifting" ocurrió entre 140 y 115 Ma. AMP = anfíboles; HT y LT: alta y baja temperatura, respectivamente. Edad U-Pb gabro: Schärer et al, 2000. Edad K-Ar diorita AMP: Féraud et al., 1988). Edad modelo de websterita: Chazot et al., 2005.*

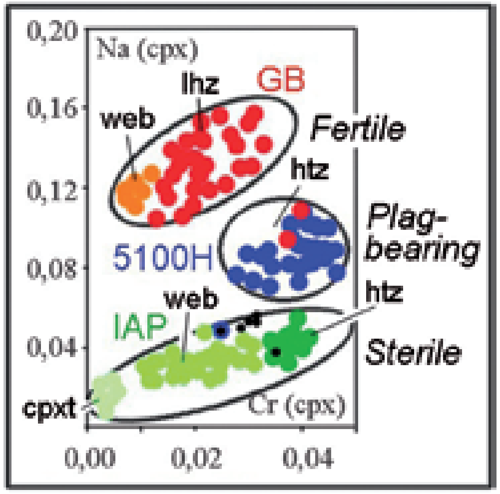

Figure 4. Na vs Cr in CPX from peridotites (cations per formula unit on 6 oxygens). See text for explanation. lhz: lherzolites; web: websterites; htz: harzburgites; cpxt: clinopyroxenite; plag: plagioclase. Black dots: data from holes 1068A and 1070A (Abe, 2001). Modified from Kornprobst et al., 1981.

***Figura 4.** Na vs Cr en CPX de peridotitas (cationes por unidad de fórmula con 6 oxígenos). Véase el texto para explicación. lhz: lherzolita; web: websteritas; htz: harzburgitas; cpxt: clinopyroxenita; plag: plagioclasa. Puntos negros: datos de sondeos 1068A y 1070A (Abe, 2001). Modificado de Kornprobst et al., 1981.*

Girardeau, 1988; Girardeau *et al.,* 1988; Beslier *et al.,* 1988; 1990; 1996). The peridotites are highly serpentinized. These are spinel and spinel + plagioclase harzburgites and lherzolites (Boillot *et al*., 1980; Evans and Girardeau, 1988; Girardeau *et al*., 1988; Kornprobst and Tabit, 1988; Cornen *et al*., 1996a; 1999; Chazot *et al*., 2005). When present, the plagioclase (PL) is mainly the product of the destabilization of the primary assemblage orthopyroxene (OPX) + clinopyroxene (CPX) + spinel (SP) at lower pressure. Brown amphibole (AMP) occurs in several samples (GB) where it has metasomatically replaced the CPX.

CPX composition (note that all the data are available in the publications referenced below) varies widely, depending on the sampling site (Fig. 4) and is especially Na-rich in the lherzolites to the north of the ultramafic ridge (GB), whilst this mineral is very poor in Na southwards (IAP); it has intermediate Na-concentrations at 5100 H, in between GB and IAP. On the basis of a compilation of CPX compositions in the peridotites (Kornprobst *et al*., 1981), the GB lherzolites should be considered as part of the fertile sub-continental mantle (i.e. rich enough in incompatible elements to provide a significant amount of melt due to partial melting). On the contrary, the IAP harzburgites are sterile or nearly sterile. Therefore, they have been inferred to come from the oceanic lithosphere which was partially molten during its history (Cornen *et al*., 1996a; 1999). The intermediate composition of harzburgite CPX (5100H) may be related to the preferential entry of Na in the plagioclase lattice during late secondary crystallization of this mineral (Kornprobst and Tabit, 1988). The following sections show that the reality is more complex.

All REE patterns drawn from CPX extracted from the peridotites are depleted in LREE with respect to chondrites. But none have achieved the degree of depletion (based on the La/Sm ratio for example) reported for the abyssal peridotites that represent the oceanic neolithosphere (Chazot *et al*., 2005). Isotope geochemistry of Nd and Sr shows quite surprising results (Fig. 5). The fertile CPX (GB) is depleted in ^{87}Sr and strongly radiogenic in ^{143}Nd, even more than the NMORB average. Amphibole in peridotites (GB) has rather flat REE patterns, whereas their isotopic ratios Sr/Nd are shifted towards the enriched side of the mantle array. Such a significant isotopic disequilibrium between minerals in adjacent rocks supports the metasomatic origin of the amphibole. The CPX isotopic ratio in harzburgite 5100H is also plotted within the enriched side of the mantle array (Fig. 5).

The websterites and one clinopyroxenite

These two-pyroxenes + spinel rocks, as well as a single clinopyroxenite, were observed in two occurrences (GB and IAP) as thin layers (several cm thick) within the peridotites. These layers are stretched and have experienced boudinage; the texture is porphyroclastic, without penetrative deformation. The CPX composition is similar - but less chromiferous – compared to that of the CPX in surrounding peridotites (Fig. 4). Similarly to the « ariégites » in the French Pyrenees or in other ultramafic massifs, these rocks are considered as cumulates extracted from melts having been injected within the peridotites before HT deformation (Kornprobst, 1969).

The REE patterns of CPX from the websterites GB and IAP are all together LREE depleted with respect to the chondrites, and are similar in shape to the profiles observed from the CPX in the peridotites. However, the isotopic ratios Sr-Nd vary radically from one occurrence to the other. The GB websterite, like the lherzolite into which it was injected, is very rich in ^{143}Nd and rather poor in radiogenic ^{87}Sr (Fig. 5a). Therefore, the melt from which the GB websterite has crystallized had great affinities with the N-MORB mantle reservoir (depleted MORB mantle = DMM) and certainly was directly injected from the asthenosphere. On the contrary, the sterile CPX from the IAP websterites are enriched in radiogenic ^{87}Sr and depleted in ^{143}Nd; their isotopic composition is therefore close to the composition of the mantle source EM1 and EM2 (Fig. 5b) that, generally, is related to the generation of the oceanic islands basalts (OIB; e.g. Workman *et al*., 2004; Willbold & Stracke, 2010).

The amphibole diorites

These rocks occur as veins (a few cm thick) observed in several sites of the Galicia Bank, generally associated with amphibole-bearing peridotites. Mainly composed of plagioclase, amphibole and ilmenite, the veins were emplaced later into the peridotites, with respect to the formation of the main HT foliation (Beslier *et al*., 1988). Therefore, the ^{39}Ar-^{40}Ar dating results performed on amphibole (122.0 ± 0.6 Ma) all together provide the age of the injection as well as the age of the end of the HT deformation (Féraud *et al*., 1988).

Amphiboles from the diorites have rather flat REE patterns, significantly enriched with respect to chondrites, and also significantly enriched with respect to the AMP of the amphibole-bearing peridotites. Note the great similarity of the isotopic ratios Nd/Sr of these amphiboles with that from AMP in amphibole-bearing peridotites, all being plotted in the intermediate field on the mantle array (Fig. 5b).

The gabbros

Two outcrops of gabbro were observed on the Galicia Bank (dives 14 and 34 from the *Nautile*), both in the same structural position, just above the peridotites (Fig. 3). The first one is a layered cumulate of CPX with some orthopyroxene and interstitial plagioclase. The other, 600 m thick, is essentially made up of CPX and PL. The rocks have granoblastic, sometimes porphyroclastic textures related to a rough schistosity, which reflects a moderate temperature deformation; however, the initial granular igneous texture can generally be recognized. Two other cross-sections (dives 10 and 32) have shown chloritic schists (more than 100 m thick), also located just above the peridotites; some of these schists are rich in zircon crystals. These were considered as ultra-mylonitized gabbros, having been crushed along the main detachment fault of the rifting (Beslier *et al*., 1990). Zircons were dated by the U-Pb method, at 122.3 ± 0.3 and 121.7 ± 0.4 Ma (Schärer *et al*., 1995; 2000), in good agreement with the ^{40}Ar/^{39}Ar age provided by the amphibole from diorites. It is essential to note that these ages are older by at least 5 Ma than the continental break-up of the Galicia Margin (Schärer *et al*., 2000).

In the Iberian Abyssal Plain, a gabbro was drilled at about 50 m above the bottom of site 900A of Leg 149, directly beneath the Paleocene sediments (Seifert *et al*., 1996). The floor has not been identified and, as a result, the structural situation of the gabbros (above or across ?) is not known with respect to the peridotites. The primary igneous mineralogy involves CPX and PL. When poorly deformed, the rocks are very similar to the gabbros from the Galicia Bank. In other instances, the gabbro is extremely stretched and recrystallized, looking like an amphibole « flaser-gabbro » (Cornen *et al*., 1996b). According to Seifert *et al.* (1996), such heterogeneous deformation would have been acquired within the oceanic crust.

CPX of the gabbroic cumulate from dive 14 have Nd and Sr isotopic ratios similar to those of the Galicia Bank amphiboles (Fig. 5b), i.e. intermediate between DMM and EM1-EM2. On the other hand, 3 samples of gabbro from site 900A, have Nd isotopic ratios in between 0.5130 and 0.5133 (Seifert *et al*., 1997) that lead us to believe that these rocks were extracted from the DMM reservoir (Fig. 5b). On the other hand, zircons from the chloritic schists (dives 10 and 32) considered as crushed gabbros, have provided εHf values at

121 Ma corresponding to those of the DMM reservoir at the same time (Schärer *et al.*, 2000).

Dolerites and basalts

On the Galicia Bank side, several outcrops of dolerites and basalts were identified and sampled. For example, dive 14 allowed us to observe a 2 m thick doleritic dyke that cross cuts the peridotites. Dives 14, 28 and 33 have shown large outcrops of dolerites, whose mode of occurrence - most probably dykes - has not been directly observed. Basalts appear in several large pillowed lava-flows. On the Iberian Abyssal Plain side, basalts and dolerites were recovered by the 899B drilling of Leg 149, within breccias considered as mass flows (Cornen *et al.*, 1996b).

Textures and mineralogical compositions of these igneous rocks have been previously described in several papers (Kornprobst *et al.*, 1988; Cornen *et al.*, 1996b; Seifert *et al.*, 1997; Charpentier *et al.*, 1998). It must be recalled that on Galicia Bank at least, the dolerites are slightly deformed (crystals in thin section show ondulose extinction) whilst the basalts are not. This means that the doleritic dyke emplacement

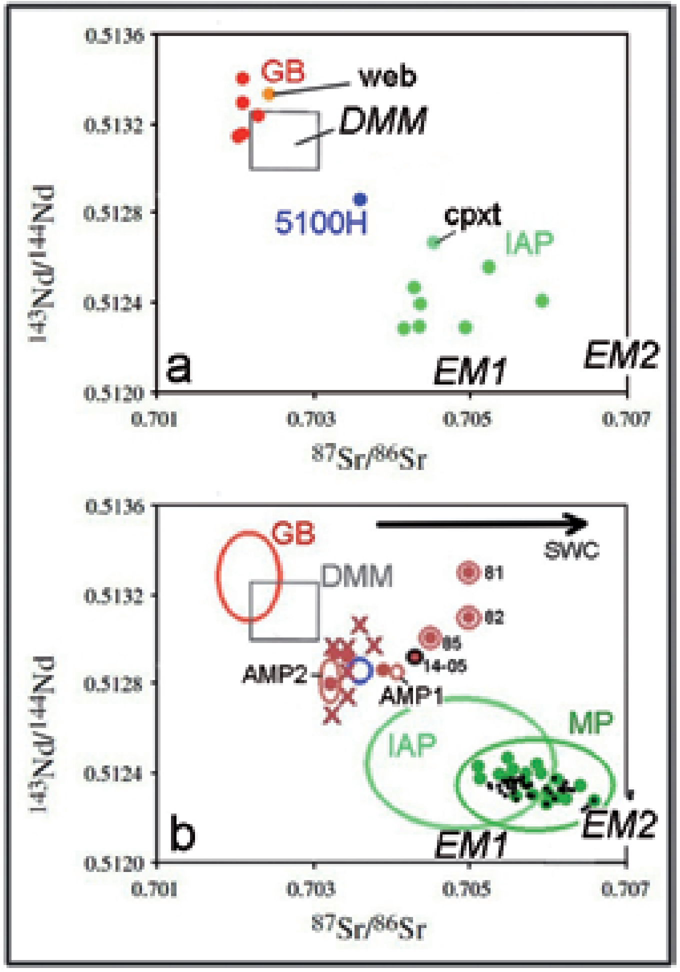

Figure 5. Sr-Nd isotopic compositions of ultramafic and igneous rocks from the Galicia margin (modified from Chazot et al., 2005). See text for explanation. a) CPX from the ultramafic rocks; b) Igneous rocks. DMM = depleted MORB mantle average; EM1 and EM2 = enriched mantle sources; web = GB websterite; cpxt = clinopyroxenite; AMP1 and AMP2 = amphiboles from peridotites and diorites, respectively; 14-05 = CPX from the GB gabbro; 81, 82 and 85 = IAP gabbros (Seifert et al., 1997); brown dots and crosses = GB dolerites and basalts, respectively; MP = Messejana-Placensia dolerites and Pyrenean ophites (green spots: Cebria et al., 2003; black dots: Callegaro et al., 2014). SWC = sea-water contamination. The CPX from the 5100H harzburgite, already plotted in Figure 5a, is also reported in Figure 5b (blue circle) for comparison.

Figura 5*. Composiciones isotópicas Sr-Nd de las rocas ultramáficas e ígneas del margen de Galicia (modificada a partir de Chazot et al, 2005). Véase el texto para explicación. a) CPX de las rocas ultramáficas; b) Rocas ígneas. DMM = media del manto MORB empobrecido; EM1 y EM2 = fuentes del manto enriquecido; web = websterita GB; cpxt = clinopyroxenita; AMP1 y AMP2 = anfíboles de peridotitas y dioritas, respectivamente; 14-05 = CPX del gabro GB; 81, 82 y 85 = gabros IAP (Seifert et al., 1997); puntos marrones y cruces = doleritas y basaltos GB, respectivamente; MP = doleritas Messejana-Plasencia y ofitas pirenaicas (manchas verdes: Cebria et al, 2003; puntos negros: Callegaro et al, 2014). SWC = contaminación del agua de mar. El CPX de la harzburgita 5100H, ya representado en la Fig. 5a, también se sitúa en la Fig. 5b (círculo azul) para comparación.*

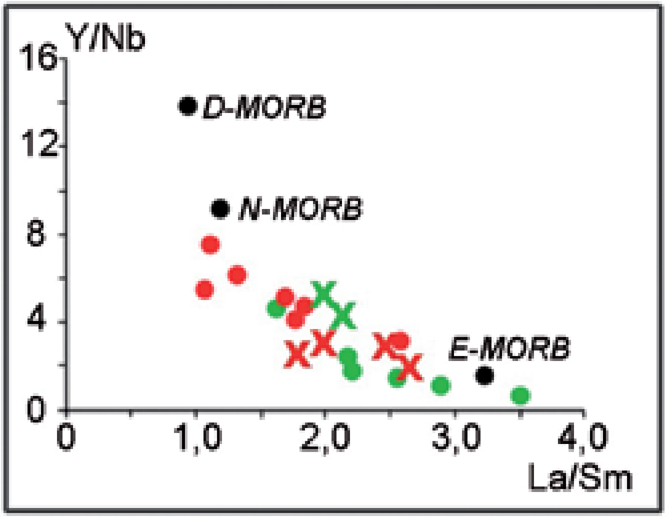

Figure 6. Y/Nb vs La/Sm for the igneous rocks of the Galicia Margin. Red symbols: GB; green symbols: IAP (Cornen et al., 1996b; Seifert et al., 1997); crosses: dolerites; dots: basalts. Black dots: average compositions for D-MORB (depleted MORB), N-MORB (normal MORB) and E-MORB (enriched MORB), according to Gale et al. (2013).

Figura 6*. Diagrama Y/Nb vs La/Sm de las rocas ígneas del margen de Galicia. Símbolos rojos: GB; símbolos verdes: IAP (Cornen et al, 1996b; Seifert et al., 1997). Cruces: doleritas; puntos: basaltos. Puntos negros: composiciones medias de D-MORB (MORB empobrecido), N-MORB (MORB normal) y E-MORB (MORB enriquecido), según Gale et al. (2013).*

took place before the outpouring of lava-flows. All these rocks have experienced hydrothermal recrystallisations.

The REE patterns of dolerites and basalts range from LREE-rich to moderately depleted compositions. No composition is depleted enough in LREE to be considered to have been extracted from the DMM reservoir. The same is true if we consider the ratios Y/Nb and La/Sm (Fig. 6): indeed, all compositions are on the enriched side of the MORB repartition curve (Gale *et al*., 2013). Some GB basalt compositions are quite close to those of N-MORB, whilst all the basalts and dolerites from IAP have E-MORB compositions.

Nd and Sr isotopic data are only available for the Galicia Bank basalts and dolerites. All the compositions are plotted on the mantle array, in the field located in between DMM and EM1-EM2 (Fig. 5b).

Interpretation of data

The petrological and geochemical data from the rocks of the Galicia Margin are actually rather dispersed if we consider the large area from which they have been collected. Furthermore, neither the structural relationships, nor the relative proportions of the various rock-types are really known. On the other hand, the very low concentration of lead in CPX did not allow the characterization of the Pb isotopic ratios. However, we have tried to provide a consistent interpretation of all the data below.

The Galicia Bank lherzolites: sub-continental lithospheric mantle contaminated by melts from the asthenosphere

The Galicia Bank lherzolites have CPX very rich in Na, much richer than in any abyssal peridotite; such a mineral composition does not reflect either significant partial melting, or significant melt extraction. On the other hand, CPX in the Galicia Bank lherzolites has very high ^{143}Nd/^{144}Nd ratios, even higher than those for the DMM asthenospheric reservoir (Fig. 5a). Although less chromiferous, CPX in the Galicia Bank websterite rigorously presents the same geochemical characteristics. The temporal evolution of the ^{143}Nd/^{144}Nd ratio in CPX of the Galicia Bank websterite intersects the DMM compositions in between 90 and 350 Ma (Fig. 7); therefore, the melt from which the websterite precipitated was extracted from the asthenosphere and injected into the surrounding peridotites within the same time interval. Taking into account the dynamics of this area during the lower Cretaceous, we suggest that this melt has been generated during the adiabatic decompression of an asthenospheric bulge, at the beginning of the rifting process, around 135-130 Ma ago (Fig. 8a).

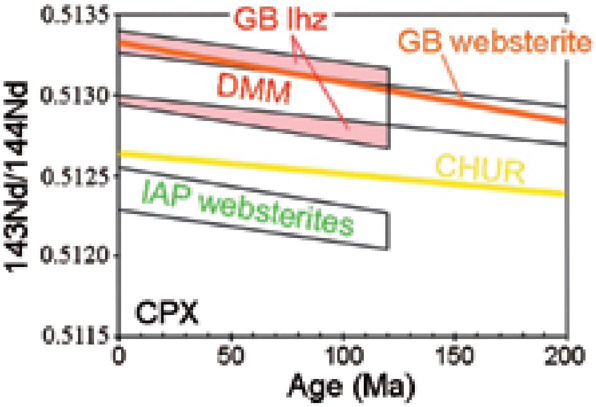

Figure 7. Temporal evolution of the ^{143}Nd/^{144}Nd ratio for the CPX from the GB websterite (orange line). The line intersects the DMM field (Sue and Langmuir, 2003; Workmann et al. Hart, 2005) between 80 and 350 Ma. The CHUR line (Chondritic Uniform Reservoir) and boxes for the GB and IAP CPX have been drawn for comparison.

Figura 7. *Evolución temporal de la relación* ^{143}*Nd/*^{144}*Nd para el CPX de la websterita GB (línea naranja). La línea intersecta el campo DMM (Sue y Langmuir, 2003; Workmann y Hart, 2005) entre 80 y 350 mA. Para comparación, se han representado la línea CHUR (reservorio condrítico uniforme) y las cajas correspondientes a GB y a IAP -CPX.*

The great geochemical similarities between CPX in websterite and CPX in the surrounding lherzolites, suggest that the latter originated from the tectonic dispersion of websterite dykes within the peridotites. The difference in Cr-concentration between CPX in lherzolite and CPX in websterite simply results from the reequilibration of the latter with the chromite-rich spinel from peridotite. Such a stirring mechanism is quite efficient for a refertilization of peridotites (Kornprobst, 1966; Tabit *et al*., 1997). It could have taken place during the HT deformations at the time of the rifting (Fig. 8b). Other fertilization mechanisms may have played their part, as melt percolation through the lithospheric mantle (e.g. Lenoir *et al*., 2001), but this interpretation is not so far supported by observations in this particular locality.

The Iberian Abyssal Plain peridotites and websterites: partially molten sub-continental lithospheric mantle

CPX of the Iberian Abyssal Plain harzburgite and associated pyroxenites are very Na poor and strongly depleted in LREE. These characteristics are those of CPX from ultramafic rocks that have experienced

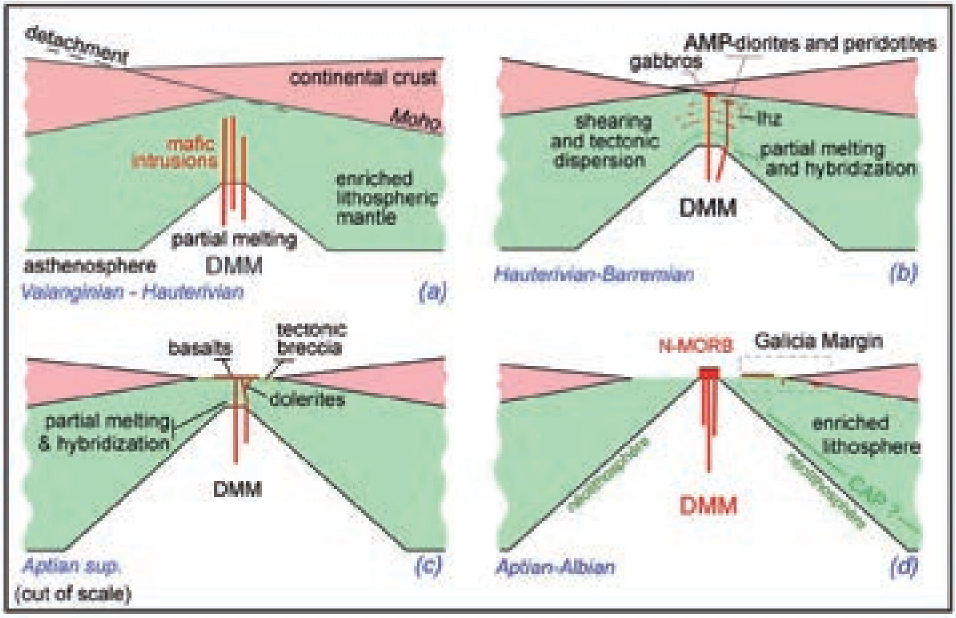

Figure 8. Evolution of the Galicia margin during rifting. a) Beginning of rifting and partial melting of the asthenospheric bulge (DMM); emplacement of the GB websterites within the lithospheric subcontinental mantle. b) Shearing of the lithosphere and development of HT schistosity in the peridotites; tectonic dispersion of the websterites and lherzolite formation; partial melting of the enriched lithosphere (EM1-EM2); metasomatic AMP crystallization and emplacement of the AMP-diorites from the lower lithosphere; emplacement of gabbros from the asthenosphere. c) Continental breakup; hybridization of melts from both the asthenosphere (DMM) and the lower continental lithosphere (EM1-EM2); emplacement of the dolerites and then of the basalts. d) Not seen on the Galicia margin; continental lithosphere breakup; the DMM melts are no longer contaminated by the enriched lithospheric mantle and outpour as N-MORB; to account for the Cebria et al. (2003) assumption (see Fig. 9), the hypothetical CAP slab is represented on this sketch.

Figura 8. *Evolución del margen de Galicia durante el "rifting". a) Comienzo del "rifting" y fusión parcial de la protuberancia astenosférica (DMM); emplazamiento de las websteritas GB en el interior del manto litosférico subcontinental. b) Cizalla de la litosfera y desarrollo de esquistosidad HT en las peridotitas; dispersión tectónica de las websteritas y formación de lherzolita; fusión parcial de la litosfera enriquecida (EM1-EM2); cristalización de AMP metasomático y emplazamiento de las dioritas AMP de la litosfera inferior; emplazamiento de gabros de la astenosfera. c) Ruptura continental; hibridación de fundidos, tanto de la astenosfera (DMM) como de la litosfera continental inferior (EM1-EM2); emplazamiento de las doleritas y después de los basaltos. d) No vista en el margen de Galicia; ruptura de la litosfera continental; los fundidos DMM ya no están contaminados por el manto litosférico enriquecido y rebosan como N-MORB; se representa en este esquema, para ilustrar la hipótesis de Cebria et al. (2003, ver Fig. 9), el supuesto bloque CAP.*

significant partial melting rates during their history within the mantle, and from which a significant melt-fraction was extracted. This is especially the case for the « abyssal peridotites » from the oceanic lithosphere. On the other hand, CPX from the IAP pyroxenites (no data is available for the CPX from the harzburgite) have relatively high $^{87}Sr/^{86}Sr$ ratios and very low $^{143}Nd/^{144}Nd$ ratios. This isotopic composition is close to that of the EM1-EM2 mantle sources of the OIB or E-MORB (e.g. Gale *et al.*, 2013).

Most CPX in ultramafic xenoliths from the continental alkali basalts also exhibit enriched isotopic ratios (e.g. Downes, 2001). This is one of the reasons why the sub-continental lithospheric mantle – from where the xenoliths originate - is believed to be enriched isotopically (e.g. Menzies, 1990). Considering only this point of view, the Iberian Abyssal Plain pyroxenites could be assigned to the continental lithosphere. However, in contrast to CPX from the IAP ultramafic rocks, CPX in mantle xenoliths is generally Na-rich and therefore fertile.

These contradictory data on the CPX from IAP are reconciled as follows. Before rifting, isotopically enriched IAP pyroxenites were, of course, parts of the sub-continental lithospheric mantle. During rifting, the lower lithospheric mantle did experience partial melting and melt extraction, which is consistent with the depleted compositions in incompatible elements of the IAP CPX, whereas the isotopic ratios were not modified. The partial melting conditions may have been reached by adiabatic decompression as well as rising temperature related to the asthenospheric bulge and emplacement of melts extracted from the asthenosphere. These mechanisms are those of the thermal erosion of the lithosphere (e.g. Davies, 1994; Lenoir *et al.*, 2001; Foley, 2008).

Igneous rocks in the Galicia Margin: direct injection from the asthenosphere and magma mixing

Partial melting of the asthenospheric bulge may have started at an early stage of rifting, with the emplacement of the Galicia Bank websterites in the peridotites, prior to the development of HT deformations. It worked after HT deformations, but before the continental break-up, during the emplacement of mylonitized (GB) and strongly deformed (IAP) gabbros. Both effectively exhibit typical geochemical features from the DMM reservoir (Seifert *et al.*, 1997; Schärer *et al.*, 2000).

Emplacement of the amphibole-diorites (Galicia Bank; 122.0 ± 0.6 Ma), related to modal metasomatism in the surrounding peridotites, shows the intervention of an isotopically enriched component by the end of HT deformation. This contribution continued with the later emplacement of the Galicia Bank gabbros, followed by dolerites and basalts throughout the study area. Indeed, REE concentrations in these rocks, as well as their Sr-Nd isotopic compositions, required the contribution of at least two mantle sources: on the one hand the DMM reservoir and, on the other hand, an enriched mantle source (Fig. 5). The latter would have probably contained enough water to account for amphibole in the diorites and some of the dolerites.

Where did the enriched components come from?

From the early work by Jean-Guy Schilling (e.g. Schilling, 1986; 1999; Fontignie and Schilling, 1996; etc), it is clear that basalts exhibit significant compositional variations all along the Atlantic ridge. These variations especially concern the REE patterns as well as several isotopic ratios, such as $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. These parameters change in between an end-member rather depleted in incompatible elements, or N-MORB, and an enriched end-member, or E-MORB. Such a variation is interpreted (Schilling, op. cit.) as the result of the contamination of the DMM reservoir by rising plumes feeding the oceanic island basalts (OIB; e.g. Iceland, Azores, Ascension, etc.). Actually, enriched basalts were sampled on the Atlantic Ridge, far from any plume (e.g. Gale *et al.*, 2013). In this case, their compositions would be linked to local heterogeneities of the asthenosphere. These would be related to the mixing by convection at depth, of two types (at least!) of mantle components: on the one hand, a DMM reservoir or N-MORB source and, on the other hand, slabs of the oceanic crust recycled in the mantle along with oceanic and terrigenous sediments in subduction zones (e.g. Workman *et al.*, 2004; Stracke *et al.*, 2005). Nevertheless, according to other authors (Gale *et al.*, 2013), subduction would not have played any part in the enrichment of the upper mantle. The latter process would be linked to the ascent of plumes, directly from a "primitive" lower mantle that was kept enriched with respect to DMM at the time of the mantle/crust segregation.

Therefore, it cannot be ruled out that the various enriched compositions of the igneous rocks from the Galicia Margin are the result of an hybridization of melts extracted from two different asthenospheric or deep mantle sources: the reservoir DMM on the one hand, and, on the other hand, an OIB or E-MORB enriched source. But actually, the parsimony principle encourages us to choose the simpler hypothesis, and to consider the sub-continental lithosphere as the enriched source. Enriched melts having been produced in the latter unit during the rifting may have been mixed with - or contaminated by - melts extracted

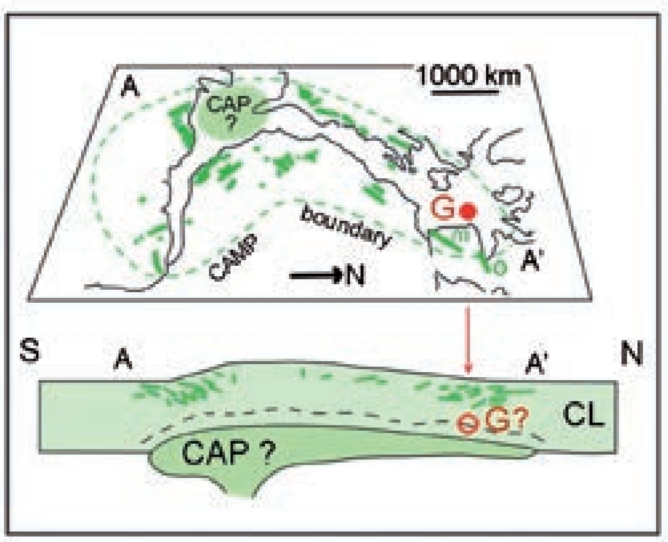

Figure 9. Situation of the Galicia margin (G) within Central Atlantic Magmatic Province (CAMP). The geological framework is from Cebria et al., 2003. The Central Atlantic Plume (CAP) is still a hypothetical feature, as a large thermal anomaly may also account for the production of the CAMP continental tholeiites (Coltice et al., 2007; Callegaro et al., 2014). CL = continental lithosphere; m = Messejana-Placensia dyke; o = Pyrenean "ophites".

Figura 9*. Situación del margen de Galicia (G) en la Provincia Magmática del Atlántico Central (CAMP). El marco geológico es de Cebria et al., 2003. El Penacho (domo mantélico) Atlántico Central (CAP) sigue siendo una característica hipotética, como una gran anomalía térmica también puede dar cuenta de la producción de las toleitas continentales CAMP (Coltice et al., 2007; Callegaro et al., 2014). CL = litosfera continental; m = dique Messejana-Plasencia; o = «ofitas» pirenaicas.*

from the asthenosphere en route towards the surface. This process could account for the compositions of the diorites, dolerites, basalts, as well as of some gabbros, which are presented in this paper. It could also account for the particular composition of CPX in the 5 100H harzburgite.

The above interpretation is supported by taking into account the magmatic history of the Iberian Peninsula and neighbouring areas. About 50 Ma before rifting, at the Triassic-Jurassic boundary (TJB), an important event resulted in the emplacement of the Messejana-Plasencia dyke along more than 600 km (e.g. Bertrand, 1987; Alibert, 1985; Cebria *et al.*, 2003), and of the Pyrenean « ophites » (e.g. Azambre *et al.*, 1981; Callegaro *et al.*, 2014). These intrusions (Fig. 9) were only a very small part of a large igneous province (LIP) which extended at that time, on the central part of the Pangea and included the west of Europe and Africa as well as the eastern part of North and South America (Marzoli *et al.*, 1999). The question of whether the CAMP (Central Atlantic Magmatic Province) is related or not to a mantle plume is still under discussion. According to some models (Coltice *et al.*, 2007), a global warming (or mantle warming; Callegaro, pers. com.) of about 100°C may be expected at the bottom of the lithosphere, as a result of the convection reorganization after the Pangea clustering. In contrast, another hypothesis (Cebria *et al.*, 2003) involves a mantle plume (CAP = Central Atlantic Plume), whose ascent may also have resulted in a significant temperature rise at the asthenosphere-lithosphere boundary. In both models however, the melts that fed the CAMP are supposed to have been produced by high-rate partial melting of the lithospheric mantle. A recent study (Callegaro *et al.*, 2014) confirms that the Messejana dyke and the ophites, neighbouring the Galicia Margin, have many geochemical characteristics in common with the CAMP occurrences, so that they integrally belong to the CAMP large igneous province (Callegaro *et al.*, 2014). The combined isotopic analysis of Sr, Nd, Pb and Os, leads us to the conclusion that these rocks were extracted from a mantle source that has been contaminated by lower and upper crustal components that have been introduced into the upper mantle during past subduction events in the area.

In the light of the above discussion on the geochemical characteristics of the Iberian sub-continental mantle, it is quite likely that the latter represents the enriched mantle source in the genesis of the Galicia Margin igneous rocks. Therefore, it is no longer necessary to consider an asthenospheric OIB-type component to account for their composition. Note, however, that the CAMP intrusion source is isotopically much more enriched than CPX in the IAP websterites. But, is there any good explanation for the lithospheric mantle being perfectly homogeneous?

Conclusions

Located at the foot of the Galicia Margin, the peridotites and associated igneous rocks of the ultramafic ridge raise the problem of their origin and evolution. Do they represent the Atlantic oceanic crust and lithosphere, or the sub-continental lithospheric mantle, or an intermediary zone between these two units?

1) Melts from the asthenosphere have been emplaced 122 Ma ago in the ridge, about 5 Ma before the continental break-up (Schärer *et al.*, 2000). Thus, the peridotites through which these melts have percolated, obviously belonged to the sub-continental lithospheric mantle. Therefore, an oceanic origin must be ruled out. Mylonitisation and flaserisation of the gabbros related to this igneous phase, have most probably resulted from shearing along the detachment fault between the continental crust and the lithospheric mantle (Boillot *et al.*, 1995b), rather than within the oceanic crust.

2) The peridotites of the Galicia Margin are very heterogeneous from the mineralogical as well as the isotopic point of view. Some may represent rocks that were fertilized by melts from the asthenosphere (Galicia Bank lherzolites), or by hydrous fluids isotopically enriched (amphibole peridotites). Other rocks, with depleted mineralogical compositions, exhibit relatively high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios. These have experienced significant partial melting and melt extraction. This suggests that the peridotites exemplify various parts of the sub-continental lithospheric mantle, having been more or less deeply transformed during the rifting, by melting and/or metasomatic contamination.

3) Some of the igneous rocks from the ultramafic ridge were (Galicia Bank websterites and most gabbros) extracted from the DMM reservoir. According to their REE concentrations and Sr-Nd isotope ratios, the other rocks (diorites, dolerites and basalts) have intermediate compositions in between the N-MORB and OIB. These compositions are the result of hybridization (whatever the mechanism) between melts extracted from the DMM reservoir, en route towards the surface, and melts having resulted from partial melting of the enriched sub-continental lithospheric mantle.

4) To consider the isotopically enriched peridotites from the ultramafic ridge (Iberian Abyssal Plain) as a piece of the sub-continental mantle of the Galicia Margin is also supported by a comparison with the lithosphere underneath the Iberian Peninsula. The

latter indeed, as well as being the probable source of the Messejana dyke continental tholeiites, has isotopic compositions close to those of the E-MORB mantle sources. In a more general fashion, such enriched isotopic compositions are likely to be those of the whole continental lithosphere of the central Pangea, from which the melts of the Central Atlantic Magmatic Province (CAMP) were extracted.

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