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

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In press, Boletin Geol.Minero, spec.issue Michel Durand-Delga - 2016, 127, 2

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

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ABSTRACT

An ultramafic/mafic complex is exposed at sea, 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 this DMM melts together with the enriched melts extracted from the lithosphere, provided the intermediate isotopic melt-compositions - in between DMM and Oceanic Islands Basalts reservoir - observed for the dolerites and basalts, none of which being 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 (Spain) 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 rocas ígneas máficas del margen de Galicia : litosfera oceánica o lithosphera continental ? Discusión.

RESUMEN

Un complexe ultramafique/mafique affleure en mer, au pied de la Marge de Galice (Espagne et Portugal). Il comporte divers types de péridotites et pyroxénites, ainsi que des diorites à amphibole, des gabbros, des dolérites et des basaltes. Pour des raisons structurales et chronologiques (les gabbros ont été mis en place dans les péridotites avant la déchirure continentale), ce complexe ne peut être attribué à la croûte océanique atlantique. La compilation de toutes les données pétrologiques et géochimiques disponibles suggère que les péridotites proviennent du manteau lithosphérique sous-continental, profondément transformé au cours du rifting crétacé. La mise en place précoce, dans les harzburgites lithosphériques, de filons de webstérites en provenance du manteau appauvri source des MORB (DMM), a conduit à la formation de lherzolites, fertiles mais isotopiquement appauvries, par boudinage et dispersion tectonique de ces webstérites dans les péridotites au cours des déformations contemporaines du rifting. Des websterites de la lithosphère sous-continentale, maintenant stériles mais enrichies isotopiquement, auraient subi fusion partielle et extraction de liquide au cours d'une érosion thermique de la lithosphère. Ces liquides sont probablement à l'origine de la cristallisation métasomatique d'amphibole brune dans certaines péridotites et de la mise en place des filons de diorite à amphibole. Des gabbros provenant de l'asthénosphère, ont été injectés entre manteau sous-continental et croûte continentale. L'hybridation de ces liquides DMM et des liquides enrichis extraits de la lithosphère rend compte des compositions isotopiques intermédiaires - entre celles des réservoirs DMM et celles des "basaltes des îles océaniques" (OIB) - des dolérites et des basaltes, aucune de ces roches ne présentant une authentique signature N-MORB. L'existence dans cette région, avant le rifting, d'un manteau lithosphérique enrichi isotopiquement, est en accord avec les compositions du dyke triasico-liasique de Messejana-Placensia (Espagne) et, d'une façon plus générale, avec celles de toutes les tholéiites continentales de la Province Magmatique de l'Atlantique Central (CAMP).

Palabras clave : Margen de Galicia, transición océano-continente, rifting, manto litosférico, contaminación del manto

VERSIÓN ABREVIADA EN CASTELLANO

Introduction

Les relations entre manteau lithosphérique sous-continental et asthénosphère ne sont généralement pas sérieusement prises en considération dans les modèles de rifting et d'ouverture océanique. L'existence de péridotites et de roches ignées au pied de la marge de Galice (Espagne et Portugal), donne l'opportunité d'étudier une zone de transition entre continent européen et océan atlantique : s'agit-il de la lithosphère océanique, de la lithosphère continentale, ou bien d'un domaine intermédiaire ? L'examen de l'ensemble des données pétrologiques et géochimiques permet de proposer un modèle cohérent, même s'il repose encore sur plusieurs hypothèses.

Rappel des données

La localisation et les principaux stades de l'évolution structurale de la marge de Galice sont présentés par les figures 1 et 3. Les roches échantillonnées sont des péridotites serpentinisées, des pyroxénites (webstérites et clinopyroxénite), des diorites à amphibole, des gabbros, des dolérites et des basaltes (Fig. 2).

1) Les péridotites serpentinisées

Ce sont des lherzolites et des harzburgites, à spinelle et à spinelle + plagioclase. Le clinopyroxène (CPX) est parfois remplacé métasomatiquement par de l'amphibole brune (AMP). Les péridotites ont subi plusieurs phases de déformation à haute (900°C) et basse température (mylonitisation). Elles sont hétérogènes sur les plans minéralogiques et géochimiques. Dans les lherzolites du Banc de Galice (GB), le CPX est riche en Na ; il est très pauvre en Na dans les harzburgites de la plaine abyssale ibérique (IAP) ; entre les deux (colline 5100 = 5100H), les concentrations en Na sont intermédiaires (Fig. 4). Les profils de Terres Rares des CPX sont tous appauvris en LREE, mais aucun ne l'est autant que ceux des CPX des péridotites abyssales. Les rapports isotopiques Sr-Nd montrent que les CPX des lherzolites sont fortement déprimés isotopiquement tandis que ceux du CPX de 5100H, et ceux des AMP métasomatiques, sont au contraire relativement enrichis (Fig. 5).

2) *Webstérites et clinopyroxenite*

Ces roches constituent de rares intercalations dans les lherzolites (GB) et dans les harzburgites (IAP). Leurs CPX ont des compositions identiques (mais moins chromifères) à celles des CPX des péridotites encaissantes (Fig. 4). Tous les profils de REE sont déprimés en LREE par rapport aux chondrites. Alors que les CPX GB sont appauvris isotopiquement, ceux des webstérites IAP sont au contraire très enrichis, avec des rapports Sr-Nd proches de ceux des sources mantelliques EM1-EM2 (Fig. 5).

3) *Les diorites à amphibole*

Elles constituent des veines injectées dans les péridotites à AMP, tardivement par rapport à la déformation HT. L'AMP des diorites a été datée à 122 ± 0,6 Ma (^{39}Ar-^{40}Ar) ce qui est donc aussi l'âge de la fin de la déformation HT. Les spectres de Terres Rares des AMP sont plats, très enrichis par rapport aux chondrites et par rapport à ceux des AMP des péridotites encaissantes. Les rapports isotopiques Sr-Nb sont intermédiaires (entre DMM et EM1-EM2), analogues à ceux des AMP des péridotites (Fig. 5).

4) *Les Gabbros*

Des gabbros déformés à températures modérées ont été observés au nord (GB) comme au Sud (IAP). Des gabbros mylonitisés riches en zircon ont fourni des âges U-Pb à 122,3 ± 0,3 et 121,7 ± 0,4 Ma, antérieurs à la déchirure continentale. Le CPX de certains gabbros GB est caractérisé des rapports isotopiques Sr-Nd intermédiaires. Des données sur les gabbros IAP indiquent en revanche des rapports isotopiques ^{143}Nd/^{144}Nd élevés, suggérant qu'ils ont été extraits directement de l'asthénosphère. De la même façon, le système ^{167}Lu-^{177}Hf indique une origine asthénosphérique pour les zircons des gabbros mylonitisés.

5) *Dolérites et basaltes*

Des dolérites et des basaltes ont été échantillonnés en filons et en coulées (GB), ainsi que dans des avalanches de débris (IAP). Les dolérites sont légèrement déformées alors que les basaltes ne le sont pas. La forme des spectres de terres rares est variable, évoluant depuis des termes enrichis en LREE, jusqu'à des termes déprimés, mais jamais aussi déprimés que ceux des N-MORB. Tous les rapports isotopiques du Sr et du Nd sont reportés dans le domaine intermédiaire du « mantle array » (Fig. 5).

Interprétation des données

1) Les lherzolites du Banc de Galice (GB) : manteau lithosphérique sous continental contaminé par des liquides issus de l'asthénosphère

Les CPX des lherzolites GB et des webstérites associées ont des caractéristiques contradictoires : ils sont à la fois riches en Na, donc fertiles (ce qui les éloigne des péridotites abyssales stériles de la lithosphère océanique) et isotopiquement appauvris (ce qui les rapproche pourtant du manteau appauvri source des MORB (DMM). L'évolution temporelle du rapport isotopique du Nd d'une webstérite recoupe le domaine du DMM, définissant un « âge modèle » compris entre 80 et 350 Ma. Il est fait l'hypothèse que les liquides à l'origine des webstérites GB ont été extraits du réservoir DMM au moment du rifting, vers 130-135 Ma (Fig. 8). Après leur mise en place, les webstérites ont été étirées par les déformations HT. La dispersion tectonique du CPX dans les péridotites a conduit à la formation des lherzolites GB dont le CPX, très semblable chimiquement à celui des webstérites, est cependant ré-équilibré avec la paragenèse à spinelle chromifère.

2) Les harzburgites et les webstérites de la Plaine abyssale Ibérique (IAP) : un manteau lithosphérique sous continental ayant subi fusion partielle et extraction de liquide

Les CPX des harzburgites IAP et des pyroxénites associées sont très pauvres en Na et fortement appauvris en LREE. Les CPX des webstérites et d'une clinopyroxénites sont au contraire enrichis isotopiquement. Cette caractéristique est généralement celle des CPX des xénolithes des basaltes alcalins continentaux, représentant le manteau lithosphérique sous-continental, mais qui sont en général riches en Na. Les pyroxénites IAP auraient donc appartenu, avant le rifting, au manteau lithosphérique sous continental enrichi ; la fusion partielle de celui-ci au cours de l'érosion thermique de la lithosphère, aurait provoqué son appauvrissement en éléments incompatibles tandis que ses rapports isotopiques restaient inchangés.

3) Les roches ignées de la marge de Galice : injection directe depuis l'asthénosphère et mélange de magmas

L'âge modèle Nd indique que les webstérites ont pu se mettre en place dans les péridotites GB, à partir du réservoir DMM, dès le début du rifting. Des gabbros issus de l'asthénosphère ont été injectés, après la déformation HT mais avant la déchirure continentale. Les diorites à amphiboles, accompagnées d'une métasomatose modale dans les péridotites voisines, montrent l'intervention d'un composant magmatique enrichi en isotopes radiogénique à la fin de la déformation HT ; la contribution de ce composant se poursuit avec la mise en place de certains gabbros GB, des dolérites et des basaltes. La composition des roches ignées de la marge de Galice implique donc la participation de deux sources distinctes (au moins !) : une source appauvrie de type DMM et une source enrichie.

4) D'où provient le composant enrichi ?

Plutôt que de faire appel à une source de type OIB, il est plus simple d'admettre que la source enrichie est tout simplement la lithosphère sous-continentale telle qu'elle est représentée par les péridotites et webstérites de la Plaine abyssale ibérique (IAP). L'hybridation des liquides extraits des webstérites IAP au cours du rifting, avec des liquides issus du réservoir DMM, peut rendre compte des compositions isotopiques des diverses roches ignées observées sur la marge de Galice. Cette interprétation est en accord avec les *caractéristiques des roches ignées mises en place dans la péninsule ibérique bien avant le rifting (dyke de Messejana et ophites des Pyrénées, à la fin du Trias ou au début du Jurassique), et d'une façon plus générale de toutes celles qui appartiennent à la province magmatique de l'Atlantique central (CAMP). Toutes sont en effet considérées comme résultant de la fusion partielle du manteau supérieur lithosphérique enrichi de la Pangée.*

Conclusions

Les péridotites de la marge de Galice ont été recoupées par des gabbros AVANT la déchirure continentale. Il est donc exclu, pour des raisons structurales, qu'elles puissent appartenir à la lithosphère océanique. Certaines ont été fertilisées par des liquides issus de l'asthénosphère ; d'autres ont partiellement fondu. Ces roches paraissent donc représenter différentes zones du manteau supérieur lithosphérique sous-continental, ayant subi des transformations importantes, mais diversifiées, au cours du rifting. Les roches ignées associées aux péridotites sont, pour certaines d'entre elles, directement issues du réservoir DMM ; les autres, et en particulier les dolérites et les basaltes, résulteraient de l'hybridation de liquides DMM et de liquides enrichis résultant de la fusion partielle du manteau sous-continental. Les caractéristiques isotopiques de ce dernier sont compatibles avec celles de la lithosphère continentale de la Pangée dont la fusion partielle a fourni, au Trias-Lias, les tholéiites continentales de la Province magmatique de l'Atlantique central (CAMP).

Introduction

Since the early 1950s, the multiplication of oceanographic vessels led to detailed studies of continental passive margins - especially in the Atlantic Ocean - for economic as well as scientific purposes. Oil companies and academic researchers have conducted a number of surveys at sea (bathymetry, seismic reflection, gravimetry, magnetism, etc), while the DSDP and ODP programs, involving the *Glomar Challenger* and then the *Joides Resolution*, recovered miles of cores and loggings. This large amount of new data allowed 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 exceed a few km depth while seismic data recognize all 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, analog and digital modeling 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 were 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 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 available data about these rocks, the present paper tries to build a consistent model of the lithospheric mantle evolution during rifting and continental break-up.

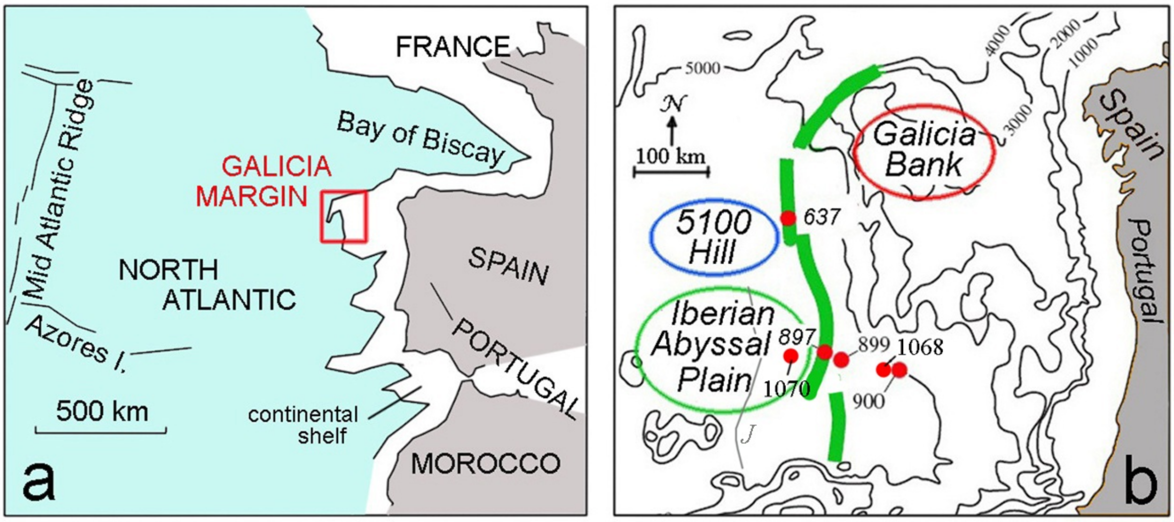

Fig. 1 - *Situation of the Galicia margin: a) In the North Atlantic Ocean; b) Off the Iberian Peninsula. Areas described in this paper are surrounded by circles whose the colors (red: Galicia Bank = GB; blue: 5100 Hill; green: Iberian Abyssal Plain = IAP) characterize each sampling sites in the next diagrams. The wide green band is the ultramafic ridge, which, in the Iberian Abyssal Plain (IAP) at least, actually extends eastwards for several tenth of km. Red dots: ODP sites. J = J magnetic anomaly.*

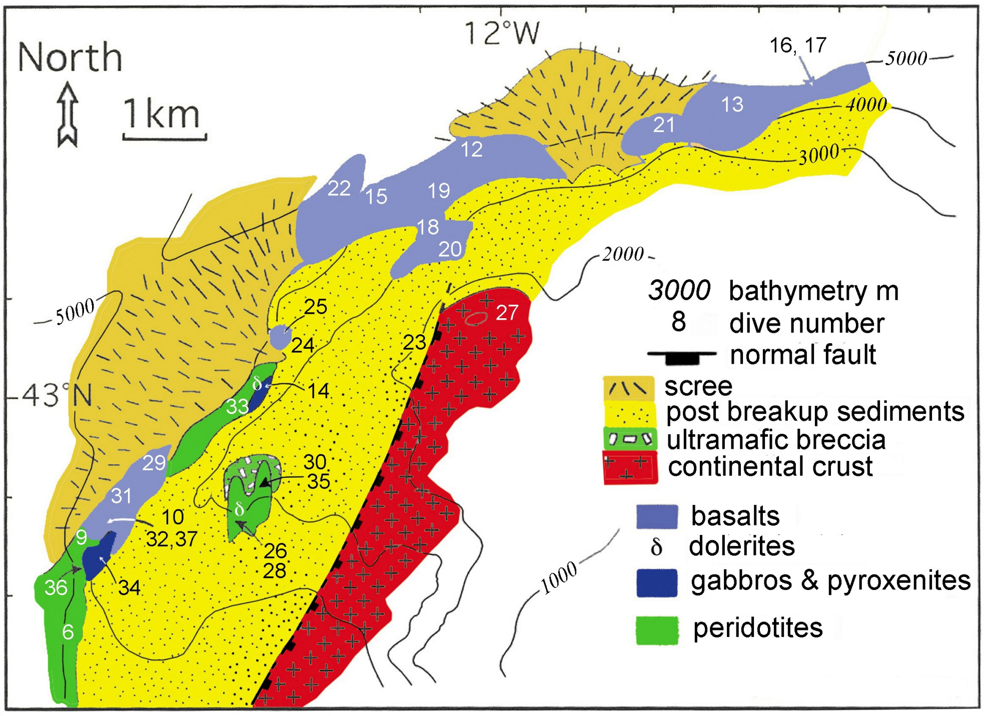

Fig. 2 - *Geological sketch of the Galicia Bank (IFREMER Galinaute cruises I and II).*

A - 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 to sample websterites, amphibole-diorites, gabbros, dolerites and basalts (Fig. 3). Descriptions of these rocks were already presented in several papers acknowledged all along the present article; the main features only, useful for a general interpretation, are emphasized in this section. From north to south, the sampling sites are referenced as follows (Fig. 1): Galicia Bank = GB; 5100 Hill = 5100H; Iberian abyssal plain = IAP.

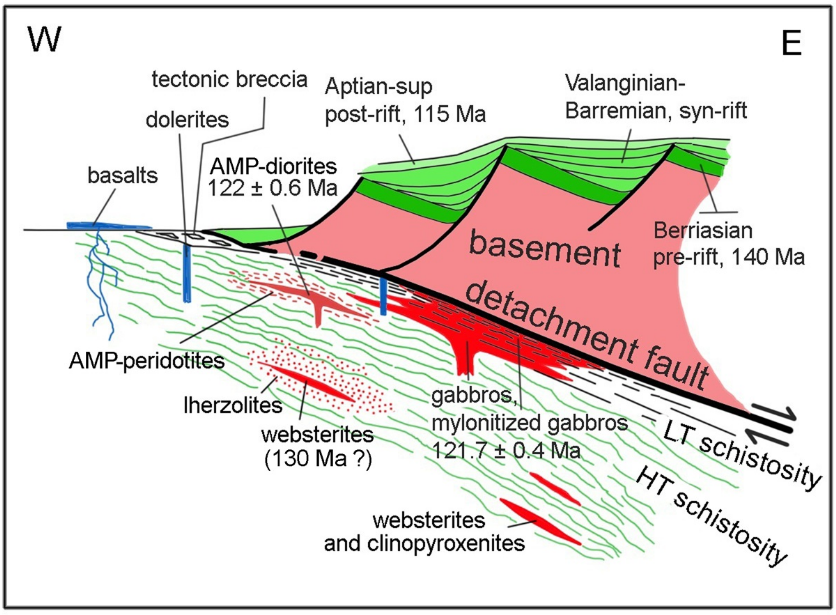

Fig. 3 - *Structural evolution of the Galicia Margin (modified from Boillot et al., 1995b). The rifting occurred between 140 and 115 Ma. AMP = amphibole; HT and LT: high and low temperature, respectively. Gabbro U-Pb age: Schärer et al, 2000. AMP-diorite K-Ar age: Féraud et al., 1988). Websterite model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

1) Serpentinized peridotites

These rocks are strongly foliated and have experienced one or more deformation stages at high temperature (ca 900°C). They have locally been mylonitized later, at lower temperatures (Evans and 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 at lower pressure, of the primary assemblage orthopyroxene (OPX) + clinopyroxene (CPX) + spinel (SP). Brown amphibole (AMP) occurs in several samples (GB) in which it has metasomatically replaced the CPX.

CPX composition (remember that all data are available in the publications referenced below) varies widely, depending on the sampling site (Fig. 4). Especially Na-rich in the lherzolites to the north of the ultramafic ridge (GB), this mineral is on the contrary very poor in Na southwards (IAP); it has intermediate Na-concentrations at 5100 Hill, 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 subcontinental mantle (i.e. rich enough in incompatible elements to provide a significant amount of melt by partial melting). On the contrary, the IAP harzburgites are sterile or nearly sterile. Therefore, they have been inferred to come from the oceanic lithosphere partially molten during its history (Cornen et al., 1996a; 1999). The intermediate composition of harzburgite CPX (5100H) could 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 will show that the reality is more complex.

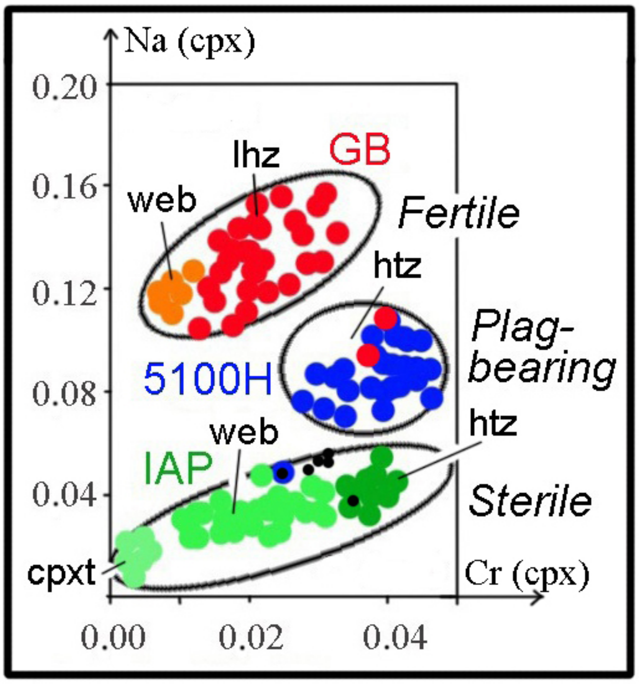

Fig. 4 - *Na vs Cr in CPX from peridotites (cations per formula unit on 6 oxygens). See text for explanation. lhz: lherzolites; web: websterites; htz: harzburgites; cpxt: clinopyroxenite; plag: plagioclase. Black dots: data from holes 1068A and 1070A (Abe, 2001). Modified from Kornprobst et al., 1981.*

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 brings quite surprising results (Fig. 5). The fertile CPX (GB) is depleted in ^{87}Sr and strongly radiogenic in ^{143}Nd, even more than the N-MORB 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).

2) 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). As the « ariégites » in the french Pyrénées or in other ultramafic massifs, these rocks are considered as cumulates extracted from melts having been injected within the peridotites before the 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, similar in shape to the profiles observed from the CPX in the peridotites. However, the isotopic ratios Sr-Nd are radically different from one occurrence to the other. The GB websterite, as the lherzolite in 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, are related to the generation of the oceanic islands basalts (OIB; e.g. Workman et al, 2004; Willbold & Stracke, 2010).

3) 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) provide all together the age of the injection as well as that 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).

4) 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 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 may 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 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 enable 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).

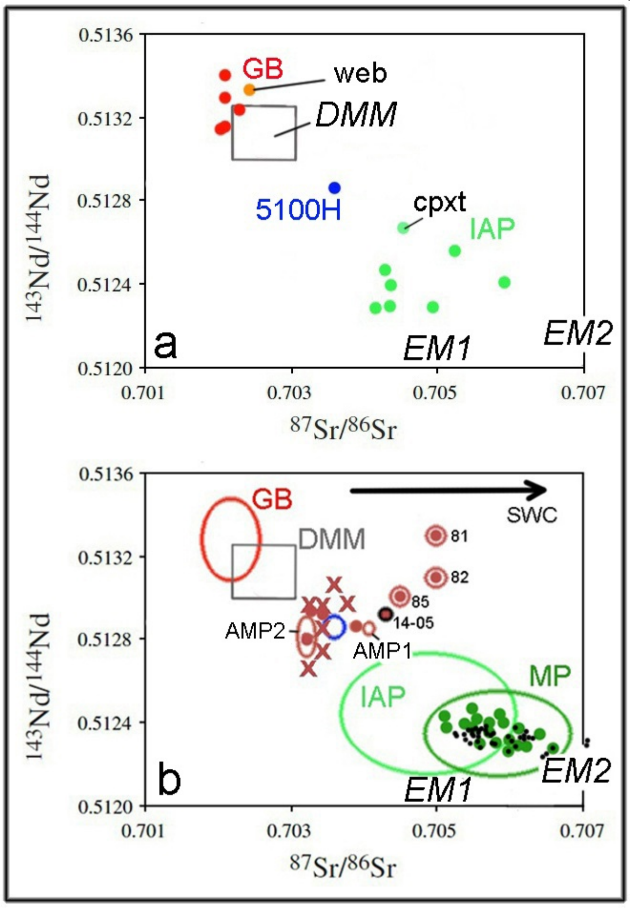

Fig. 5 - *Sr-Nd isotopic compositions of ultramafic and igneous rocks from the Galicia margin (modified from Chazot et al., 2005). See text for explanation. a) CPX from the ultramafic rocks; b) Igneous rocks. DMM = depleted MORB mantle average; EM1 and EM2 = enriched mantle sources; web = GB websterite; 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 Fig. 5a, is also reported in Fig. 5b (blue circle) for comparison.*

5) Dolerites and basalts

On the Galicia Bank side, several outcrops of dolerites and basalts were identified and sampled. For example, dive 14 leads 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 were 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 slighly deformed (crystals in thin section show ondulose extinction) while the basalts are not. This means that the doleritic dyke emplacement took place before the outpouring of lava-flows. All these rocks have experienced hydrothermal recrystallisations.

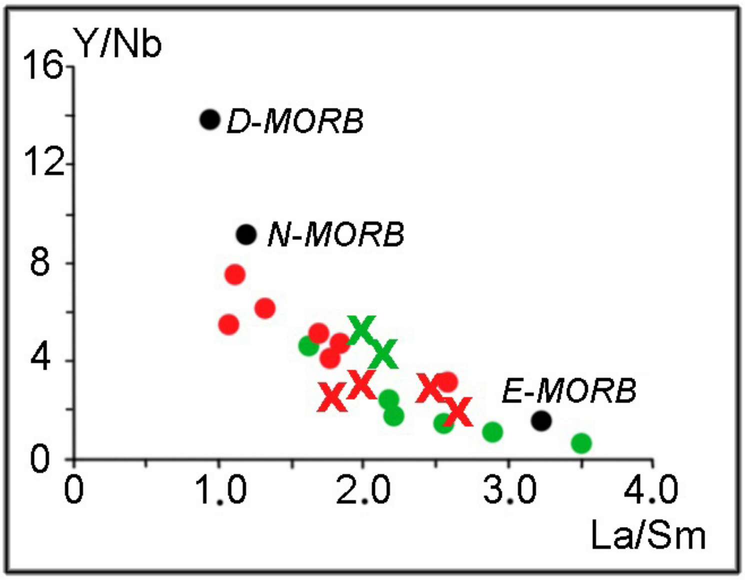

Fig. 6 - *Y/Nb vs La/Sm for the igneous rocks of the Galicia Margin. Red symbols: GB; green symbols: IAP (Cornen et al., 1996b; Seifert et al., 1997); crosses: dolerites; dots: basalts. Black dots: average compositions for D-MORB (depleted MORB), N-MORB (normal MORB) and E-MORB (enriched MORB), according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

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 by considering 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 while all 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 compositions are plotted on the mantle array, in the field located in between DMM and EM1-EM2 (Fig. 5b).

B - 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 to characterize the Pb isotopic ratios. However, we try to give below a consistent interpretation of all data.

1) 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 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 in the surrounding peridotites within the same time interval. Taking into account the dynamics of this area during the lower Cretaceous, it is suggested 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).

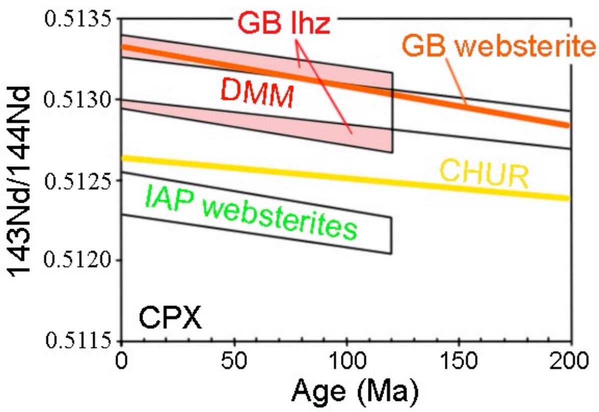

Fig. 7 - *Temporal evolution of the $^{143}Nd/^{144}Nd$ ratio for the CPX from the GB websterite (orange line). The line intersects the DMM field (Sue and Langmuir, 2003; Workmann et Hart, 2005) between 80 and 350 Ma. The CHUR line (Chondritic Uniform Reservoir) and boxes for the GB and IAP CPX have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

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 re-equilibration of the latter with the chromite-rich spinel from peridotite. Such a stirring mechanism is rather 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 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 supported so far by observations in this particular locality.

2) The Iberian Abyssal Plain peridotites and websterites: partially molten subcontinental lithospheric mantle

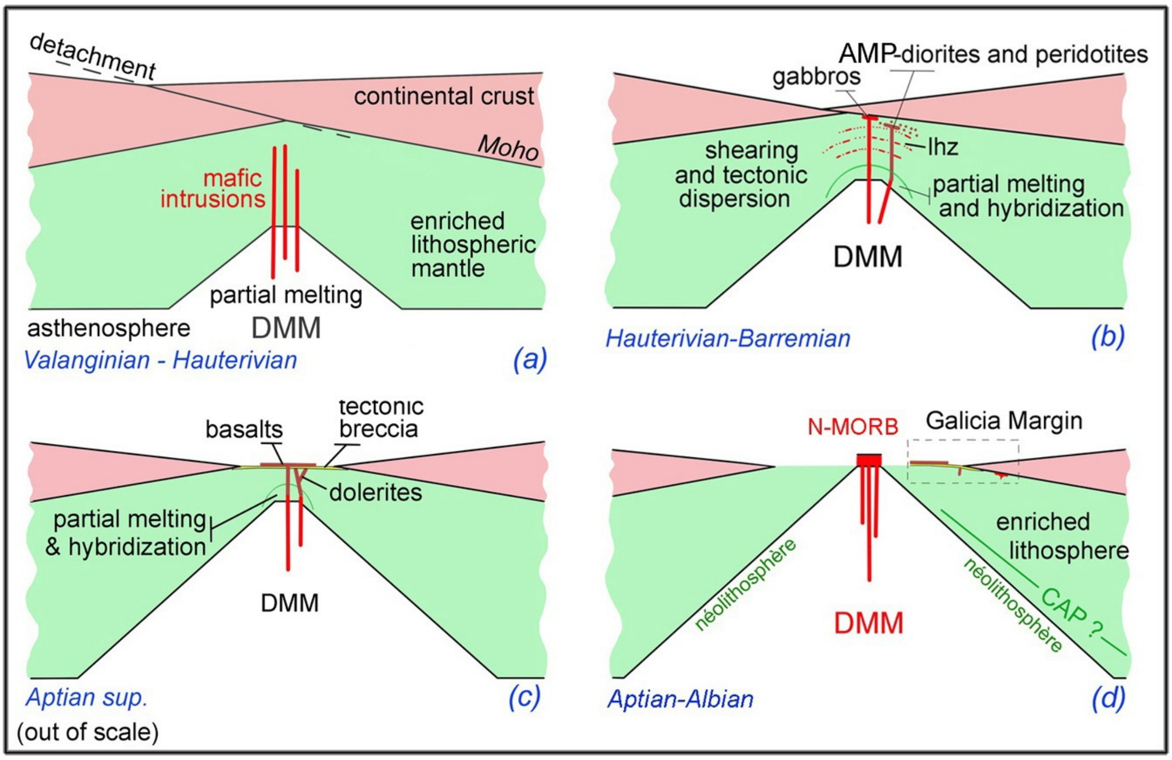

Fig. 8 - *Evolution of the Galicia margin during rifting. a) Beginning of rifting and partial melting of the asthenospheric bulge (DMM); emplacement of the GB websterites within the lithospheric subcontinental mantle. b) Shearing of the lithosphere and development of HT schistosity in the peridotites; 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 break-up; 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 break-up; the DMM melts are not anymore 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.*

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 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 subcontinental lithospheric mantle – from where the xenoliths originate - is believed to be enriched isotopically (e.g. Menzies, 1990). From this only point of view, the Iberian Abyssal Plain pyroxenites could be assigned to the continental lithosphere. However, by contrast with CPX from the IAP ultramafic rocks, CPX in mantle xenoliths is generally Na-rich and therefore is 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).

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

Partial melting of the asthenospheric bulge could 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 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.

4) Where did the enriched component 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 concern especially 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 subductions zones (e.g. Workman et al., 2004; Stracke et al., 2005). Nevertheless, according to other authors (Gale et al., 2013), subduction would not play 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.

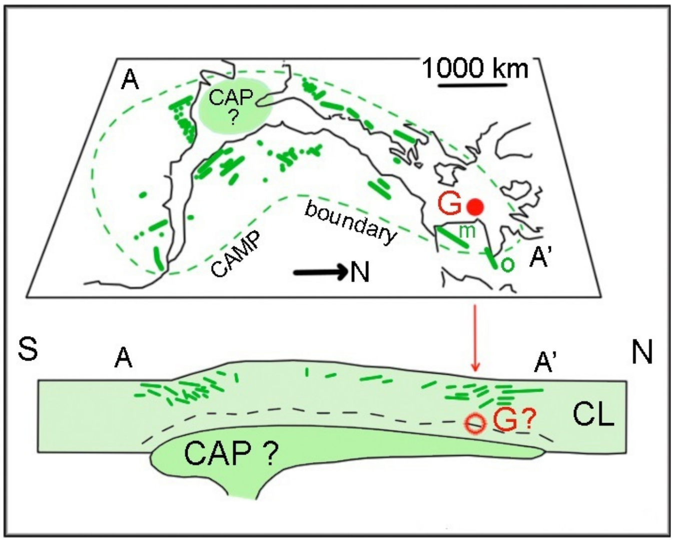

Fig. 9 - *Situation of the Galicia margin (G) within Central Atlantic Magmatic Province (CAMP). The geological framework is from Cebria et al., 2003. The Central Atlantic Plume (CAP) is still a hypothetical feature, as a large thermal anomaly may also account for the production of the CAMP continental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

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 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 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 present paper. It could also account for the particular composition of CPX in the 5100H harzburgite.

The interpretation above is supported by taking into account the magmatic history of the Iberian Peninsula and neighboring areas. About 50 Ma before rifting, at 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. By contrast, another hypothesis (Cebria et al., 2003) involves a mantle plume (CAP = Central Atlantic Plume), whose ascent could 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, neighbor to 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 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 not anymore necessary to consider an asthenospheric OIB-type component to account for their composition. Note, however, that the CAMP intrusions source is isotopically much more enriched than CPX in the IAP websterites. But, is there any good reason for the lithospheric mantle, to be 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 subcontinental lithospheric mantle, or an intermediary zone in 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 subcontinental lithospheric mantle. Therefore an oceanic origin must be dropped out. Mylonitisation and flaserisation of the gabbros related to this igneous phase, have most probably resulted of 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 mineralogical as well as isotopic point of view. Some may represent rocks having been 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 subcontinental lithospheric mantle having been more or less deeply transformed during the rifting, by melting and/or metasomatic contamination.

3) The igneous rocks from the ultramafic ridge were, for some of them (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 would be 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 subcontinental mantle of the Galicia Margin, is also supported by a comparison with the lithosphere underneath the Iberian Peninsula. The latter indeed, as being the probable source of the Messejana dyke continental tholeiites, have isotopic compositions close to those of the E-MORB mantle sources. In a more general fashion, such enriched isotopic compositions would be those of the whole continental lithosphere of the central Pangea, from which the melts of the Central Atlantic Magmatic Province (CAMP) were extracted.

Acknowledgements

One of us (J.K.) is heavily indebted to Prof. Michel Durand-Delga who instilled in him the scientific rigor. Most isotopic data were obtained thanks to the patience of Sophie Charpentier. Riccardo Vanucci and Béatrice Luais have also played their part. For writing this article, assistance was provided by Gilbert Boillot, Hervé Bertrand, Sara Callegaro and José María Cebriá Gómez. The manuscript was carefully reviewed by Urs Schärer and Sara Callegaro; thanks very much to both of them. Thank you also to two very benevolent anonymous reviewers. This work was carried out with the support of CNRS and IFREMER. Thank you very much to *Nautile* and *Nadir* crews.

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