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Basalts, underplated gabbros and pyroxenites record the rifting process of the West Iberian margin

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With 11 Figures

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Summary

New petrological data on magmatic rocks obtained from the Iberia Abyssal Plain and from the Gorringe Bank, combined with those already known on the Galicia Bank, allow to better constrain the formation of the West Iberian Margin. These three zones were sampled along East-West transects of the ocean-continent transition, immediately West or at the foot of the last tilted continental block of the margin.

These sections expose similar lithological successions including scarce basalts, locally pillowed, resting directly on peridotites (predominant) which themselves include layers of pyroxenites and rare lenses of gabbros and gabbroic differentiates. The latter are locally strongly sheared and metamorphosed e.g. to chlorite schists.

At the Galicia Bank the exposed undepleted lherzolites are considered to be typical of a sub-continental lithospheric mantle environment. The mantle sections exposed at both the Iberia Abyssal Plain and the Gorringe Bank are clearly different. The presence of plagioclase-bearing websterite lenses and of small alkaline pyroxenites within the predominant harzburgites, is unknown in pure oceanic environments and supports their lithospheric sub-continental origin.

Along each transect, the mineralogy of the gabbroic series documents various depths of emplacement and deformation. The highest pressures near 0.8 GPa ($\sim$ 24 km depth) at Galicia Bank and Iberia Abyssal Plain are estimated from Al-rich pyroxenes and from the occurrence of metamorphic spinels in the sheared gabbros (Iberia Abyssal Plain). These gabbros are interpreted as deriving from underplated magmas at the base of a slightly thinned continental crust. The lower pressures ($\leq$ 0.6 GPa) registered in the Gorringe Bank gabbroic rocks and in some reexamined gabbros from the Galicia Bank, suggest the existence of successive intrusions during the stretching process.

The few basalts sampled on top of the exposed peridotites of the sea floor are inferred to be among the first post-rift extrusive magmas. They differ slightly from the

North to the South of the margin: enriched and transitional tholeiites occur at Galicia Bank and in the Iberia Abyssal Plain, transitional and depleted tholeiites at the Gorringe Bank. The trace elements and the isotope data available show that the basalts and the gabbros derived from similar heterogeneous mantle sources ($10.3 \geq \varepsilon Nd_T \geq 3.6$). The behavior of some incompatible elements (Nb in particular) documents locally either a possible fractionation of rutile in shallow lithospheric mantle or some contamination by the continental crust. A very slow lithospheric stretching, assisted by the intrusion, underplating, and the shearing of a few gabbroic sills, followed by the unroofing of heterogeneous subcontinental mantle can account for the formation of the entire West Iberian margin.

Résumé

De nouveaux résultats obtenus à partir de l'étude des roches magmatiques dans la plaine Abyssale Ibérique et sur le Banc de Gorringe permettent avec ceux obtenus sur le Banc de Galice de mieux contraindre la formation de la marge Ouest Ibérique. Ces trois zones ont été échantillonnées selon des coupes Est-Ouest de la transition océan-continent, à partir du pied ou immédiatement à l'Ouest des derniers blocs continentaux basculés.

La croûte de chacun de ces secteurs est composée de rares basaltes, localement en coussin, reposant directement sur des péridotites (prédominantes) qui elles-mêmes contiennent des niveaux de pyroxénites et de rares lentilles de gabbros localement différenciés. Ces derniers sont souvent fortement cisaillés et métamorphisés et parfois transformés en schistes chloriteux.

Les péridotites fertiles (lherzolites) du Banc de Galice sont considérées comme représentatives d'un manteau lithosphérique sous-continental. Cette origine est étendue aux sections mantelliques à dominante harzburgitique de la plaine Abyssale Ibérique et du Banc de Gorringe. En effet elles exposent de rares pyroxénites alcalines et d'abondantes lentilles de webstérite à plagioclase, inconnues en domaine purement océanique.

La minéralogie des séries gabbroïques indique des conditions variées de mise en place des magmas. Les pyroxènes riches en aluminium du Banc de Galice et de la Plaine Abyssale Ibérique et la présence locale de spinelle dans les gabbros cisaillés (Plaine Abyssale Ibérique) supposent une cristallisation sous des pressions proches de 0.8 GPa ($\sim$ profondeur de 24 km). Ces gabbros ne peuvent donc pas avoir cristallisé sous une croûte océanique normale et sont interprétés comme provenant de magmas sous-plaqués à la base d'une croûte continentale faiblement amincie. Quelques gabbros du Banc de Galice et ceux du Banc de Gorringe ont enregistré des conditions de cristallisation plus superficielles (à moins de 18 km), donc au sein de péridotites situées sous une croûte continentale plus mince ou inexistante. Dans un processus d'étirement crustal la mise en place de ces gabbros apparaît ainsi échelonnée avec des venues précoces dans le cas de la Plaine Abyssale Ibérique et plus tardives dans le cas du Banc de Gorringe.

Les basaltes reposant directement sur les péridotites du fond océanique correspondent aux premiers magmas extrusifs post-rift. Ils diffèrent sensiblement du Nord au Sud de la marge: depuis des tholeiites enrichies et transitionnelles exposées sur le Banc de Galice et dans la Plaine Abyssale Ibérique, jusqu'à des tholeiites transitionnelles et appauvries sur le Banc de Gorringe. Les éléments traces et les données isotopiques disponibles montrent que les basaltes et les gabbros dérivent de sources mantelliques similaires et hétérogènes ($10.3 \geq \varepsilon Nd_T \geq 3.6$). Le comportement de quelques éléments incompatibles (Nb en particulier) témoigne localement d'un possible fractionnement de rutile à faible profondeur dans le manteau lithosphérique ou d'une contamination par de la croûte continentale. Un amincissement lithosphérique très lent, partiellement aidé par l'injection, le sous-plaquage et le cisaillement de quelques sills de gabbro et suivi de la dénudation d'un manteau sous-continental hétérogène, rend compte de la formation de l'ensemble de la marge Ouest Ibérique.

Introduction

The occurrence of serpentinized peridotites at the Ocean-Continent Transition (OCT) has been reported from a few passive margins where basement is accessible and not hidden by great piles of volcanics or sediments (*Bonatti* and *Michael*, 1989). These peridotites separate the magmatic oceanic crust with its characteristic magnetic and seismic signature, from the thinned continental crust. Such peridotite occurences on the West Iberian OCT are documented in three areas: the Galicia bank (*Boillot* et al., 1980), the southern Iberia Abyssal Plain (IAP; *Whitmarsh* et al., 1993, 1998) and the Gorringe Bank (*Honnorez* and *Fox*, 1973; Fig. 1). Petro-structural data obtained on the Galicia lherzolites have shown that their history is compatible with a mantle uplift related to continental rifting (*Boillot* et al., 1988; *Evans* and *Girardeau*, 1988; *Girardeau* et al., 1988; *Kornprobst* and *Tabit*, 1988). The evolution of the peridotites sampled southward at the IAP and at the Gorringe Bank is not so clear, and the rare amount of associated extrusive and intrusive rocks may provide useful information. The available radiometric dates (Galicia Bank, IAP and Gorringe Bank) agree with the emplacement and metamorphism of the intrusive rocks during the early phases of the North Atlantic Ocean opening (*Féraud* et al., 1986, 1996) according to the kinematic frame of *Olivet* (1996).

This paper deals with new petrological and geochemical data that we have acquired on the mafic and ultramafic magmatic rocks from the IAP and the Gorringe Bank. These data are used to constrain the formation and the evolution of the deep West Iberian margin. They document also a few characteristics of the magmatic rocks emplaced in both mature mid oceanic ridge and passive continental margin environments.

Characteristics of the West Iberian oceanic-continental transition

The OCT at Galicia Bank is marked by the presence of a peridotite ridge identified and widely sampled during dredging (*Boillot* et al., 1980), drilling (ODP Leg 103; *Boillot* et al., 1988) and diving cruises (*Boillot* et al., 1995). The ultramafic basement is covered on its northernmost part (on the Biscaye Bay side) by a basaltic apron estimated to be 100Ma old (*Kornprobst* et al., 1988; *Charpentier* et al., 1998). To the south, it is veined by rare massive gabbros (up to 700 m thick), chlorite schists (up to 200 m thick) and diorites. It may be locally overlain by a breccia with peridotite and granite blocks in a serpentine matrix. This breccia is interpreted as a melange marking the shear zone interface of the continental tilted blocks upon the exposed mantle (*Boillot* et al., 1995). The undepleted compositions of the peridotites support a subcontinental lithospheric mantle origin (*Kornprobst* and *Tabit*, 1988). Magmatism, produced 122 Ma ago (U/Pb data; *Schärer* et al.,

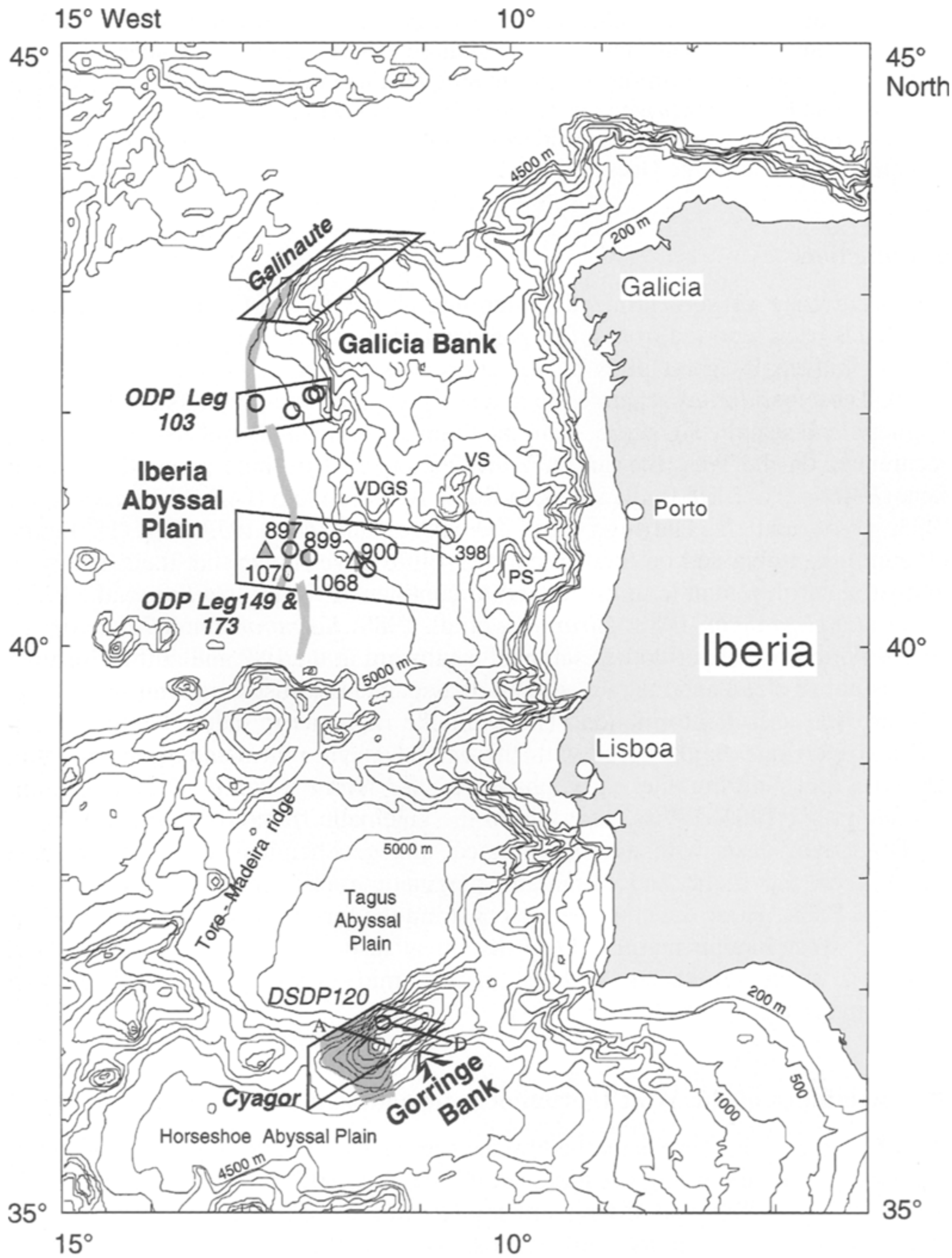

Fig. 1. Bathymetric map of Western Iberia showing the location of the studied areas. Shaded areas correspond to the peridotite occurrences.VDGS, VS and PS correspond to heights named respectively Vasco de Gama, Vigo and Porto Seamounts. Isobaths interval: 500 m. Cyagor and Galinaute areas correspond to the 1977, 1981, 1986 and 1995 diving campaigns

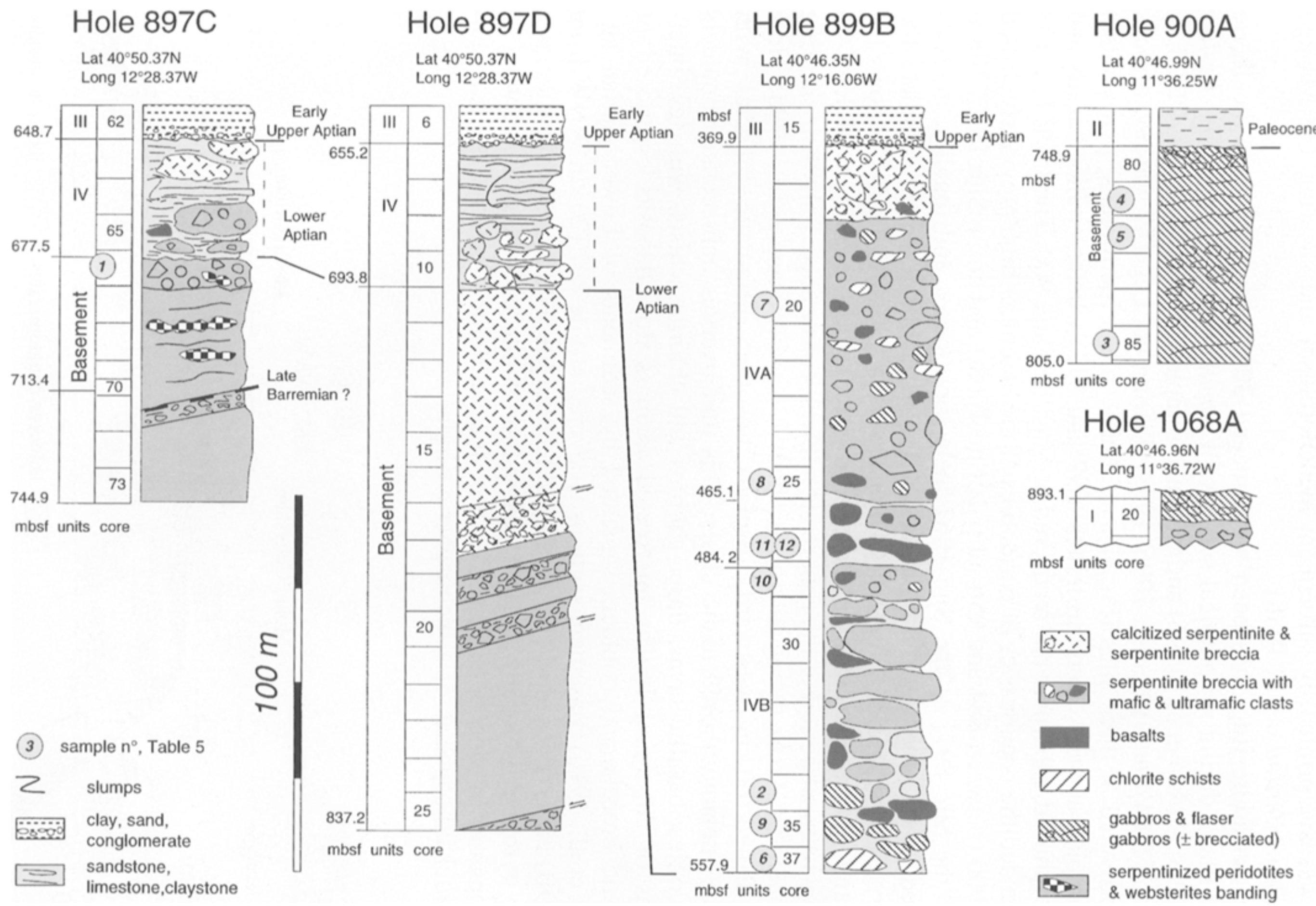

Fig. 2. Lithologic log of basement recovered at Sites 897, 899 and 900, after *Comas* et al. (1996); Hole 1068 adapted from *Whitmarsh* et al. (1998). *mbsf* meters below sea floor. The numbers in italic correspond to the analyses reported in Table 5

1995), was overprinted by subsequent metamorphism and shearing 118 Ma ago (Ar/Ar data; *Féraud* et al., 1988).

This peridotite ridge has been well imaged 300 km southward in the Iberia Abyssal Plain, during geophysical surveys (*Whitmarsh* et al., 1990, 1993; *Beslier* et al., 1993; *Pickup* et al., 1996) and has been sampled by drilling during ODP Leg 149 and 173 (*Whitmarsh* et al., 1996, 1998). During the Leg 149, basement rocks were recovered at three sites (Fig. 1): ultramafic rocks (peridotites, pyroxenites) were sampled at the westernmost sites (897 and 899) whereas minor basalts and metamorphosed gabbros were recovered at Sites 899 and 900. The ODP Leg 173 has extended the occurrences of peridotites at the basement high previously drilled at Site 900 (between 884 and 956 mbsf at Site 1068,) and at the Site 1070, 20 km west of the Site 897. At the Site 1067 meta-anorthosites and tonalitic gneisses estimated to be probably differentiates of former gabbroic series complete the lithology of the close by Site 900 (*Whitmarsh* et al., 1998). Figure 2 shows the spatial and vertical distribution of the basement rocks drilled during ODP leg 149. The emplacement period of the gabbros is not well constrained, only their shearing is estimated by Ar/Ar dating to stop at about 136 Ma (*Féraud* et al., 1996). Hole 899B, drilled 60 km westward, displays unsorted ultramafic breccias with accessory metamorphosed mafic clasts. This unit overlies unbrecciated boulders of peridotites, basaltic lavas, flaser gabbros and chlorite schists, with few intercalations of siltstones. It was interpreted as mass flow deposits composed of cataclastic breccia and boulders separated by sediments of Lower Aptian age (*Comas* et al., 1996). Basement sections recovered at Site 897 (20 km WNW from Site 899B) are composed of coarse-grained harzburgite with lenses of plagioclase-bearing pyroxenites locally sheared, and minor dunite and lherzolite. Owing to their apparent depleted dominant features, the peridotites have not a clear subcontinental lithospheric or asthenospheric origin.

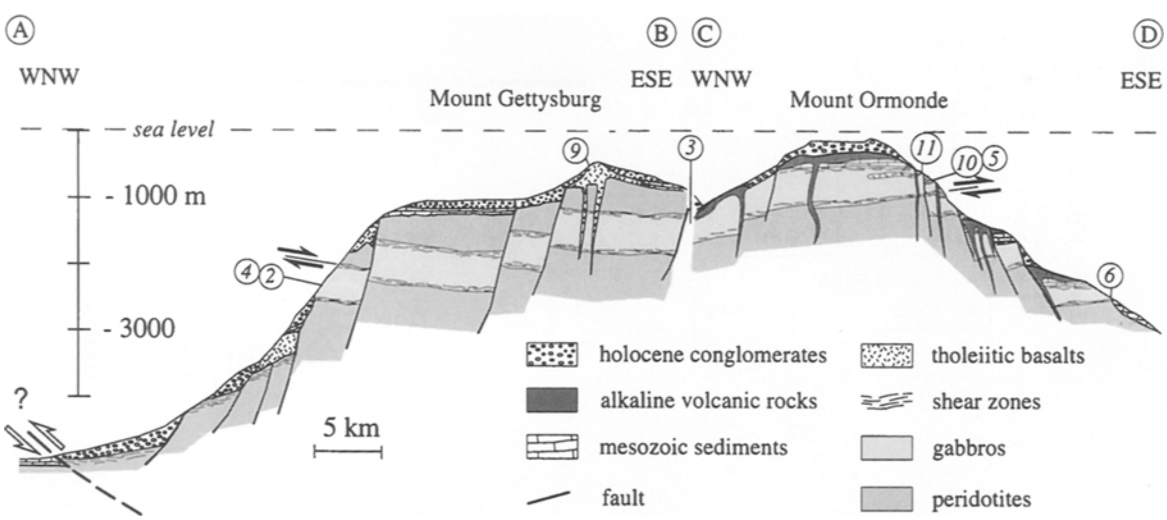

Fig. 3. Synthetic section of the Gorringe Bank, from *Girardeau* et al. (1998). The location of the section is drawn on Fig. 1 (lines A and D). The numbers in italics correspond to the analysed samples reported in Table 6

At the southernmost edge of Iberia, a similar succession including harzburgite, lherzolite, websterite, gabbros and basalts has been described on the Gorringe Bank (*Honnorez* and *Fox*, 1973; *Gavasci* et al., 1973; *Auzende* et al., 1978, 1979; *Prichard* and *Cann*, 1982; *CYAGOR II Group,* 1984a, b; *Mével*, 1988). The gabbros were emplaced as a laccolith (500 m thick and 50 km extent) around 143 Ma (Ar/Ar dating on igneous brown amphiboles) and sheared until 110 Ma ago (*Féraud* et al., 1982, 1986; *Prichard* and *Mitchell*, 1979; *Girardeau* et al., 1998; Fig. 3). The basement section defined in the Gorringe area was considered as representative of oceanic crust formed at a slow spreading ridge (*CYAGOR II Group*, 1984b). However the origin of the ultramafics and intrusives as well as extrusives rocks remained poorly constrained.

Petrological features

We present hereafter new data on magmatic rocks sampled at the Iberia Abyssal Plain during Leg ODP 149 (1993) and at Gorringe Bank between 1973 and 1981 during several dredging and diving cruises (*Gibraco* 1972, *Cyagor* I and II, 1977 and 1981). The sites sampled are illustrated in Figs. 1 and 2 for the Leg ODP 149 and detailed in the cruise reports for Gorringe Bank (*Cyagor I Group*, 1979; *Cyagor II Group*, 1984a). At this latter location most of the basement rocks remained partly or poorly studied. These new data, dealing with the pyroxenites, gabbros and basalts sampled on or within peridotites, are compared to those already obtained and published on similar rocks from the Galicia Bank (*Evans* and *Girardeau*, 1988; *Kornprobst* and *Tabit*, 1988; *Boillot* et al., 1995; *Schärer* et al., 1995; *Charpentier* et al., 1998).

Pyroxenites

Galicia Bank. At Galicia Bank, very few (0.5 mm to 10 cm thick) plagioclase bearing pyroxenite were sampled within the plagioclase-bearing peridotites (*Girardeau* et al., 1988; *Charpentier* et al., 1998). Only their broad mineralogical composition has been reported (clinopyroxene dominant, orthopyroxene and less than 5% plagioclase). Based on the composition of their spinel (Al-rich) and of their clinopyroxene (high Ti, Na contents and Al^{VI}/Al^{IV} ratios) it has been shown that the surrounding peridotites underwent very little partial melting and bear all the features of the known undepleted sub-continental peridotites (*Evans* and *Girardeau*, 1988; *Kornprobst* and *Tabit*, 1988; *Seyler* and *Bonatti*, 1994).

Iberia Abyssal Plain. The peridotites sampled in the IAP are different as they are mainly composed of harzburgite, i.e. depleted peridotites. However, about 8 m height of the cores recovered at the site 897, are constituted (>50%) of a dense centimetric to decimetric layers or patches of pyroxenites. These pyroxenites are plagioclase- and olivine-bearing websterite, with coarse-grained, porphyroclastic and locally mylonitic textures. They contain about 37% modal diopside ($92 > Mg\# = Mg_{*}100/[Mg+Fe] > 86$), 30% enstatite, 16% olivine (Fo_{85-87}) 14% plagioclase (An_{90-96}) and 3% spinel. The diopside is Al-rich (6–8% Al_2O_3; Table 1, n°1–2) and commonly displays large bent exsolution lamellae of plagioclase and

Table 1. *Selected analyses of pyroxenes.* P *porphyroclast core;* N *neoblast.* Mg# *Mg* 100/(Mg+Fe) and the molecular proportion of wollastonite, enstatite and ferrosilite (Wo, En, Fs) are deduced from a formula unit calculated on a basis of 6 oxygens and 4 cations. Phase compositions have been obtained through a CAMEBAX (SX50) microprobe (Microsonde Ouest, Brest), using silicates and vanadate standards (albite, wollastonite, orthoclase, vanadinite) for calibration of Na, Si, Ca, K, Cl, and oxides standards for calibration of Fe, Mn, Ti, Cr, Al and Ni. The accelerating voltage was 15 kV, the beam current 15 nA and the counting times 25 s for Cl and Ni and 6 s for other elements. All phases have been analysed in several spots, on their cores and margins*

Lithology	websterite				alkaline pyroxenite		gabbro and ferro-gabbro					basalt	
Location	IAP		Gorringe		IAP		IAP		Gorringe			IAP	Gorringe
Ref.	897C 64R-5 77–81		77CY 12-01		897D 14R-4 95–100		900A 80/84/85R (mean)		77CY 14-1	071-1	81CY 17-2	899B 28R-2 8–10	77CY D6
N°	1	2	3	4	5	6	7	8	9	10	11	12	13
	P	N	P	N	P	N	P	N	P	P	P	C	C
SiO_2	49.48	49.69	51.02	52.58	52.28	51.97	51.02	50.87	52.47	52.61	51.89	47.60	52.75
TiO_2	0.64	0.63	0.27	0.26	0.16	1.06	0.71	0.75	0.45	0.55	0.51	2.67	0.62
Al_2O_3	6.01	6.48	5.41	3.27	3.44	2.61	5.38	5.50	3.02	2.48	2.31	6.48	2.47
Cr_2O_3	0.77	0.59	1.14	1.07	1.47	1.05	0.18	0.18	0.57	0.02	0.03	0.14	0.23
FeO	3.63	3.82	3.16	2.86	2.16	2.39	6.55	6.69	4.99	6.05	10.61	6.30	6.36
MnO	0.29	0.13	0.13	0.12	0.03	0.09	0.16	0.18	0.15	0.27	0.28	0.15	0.20
MgO	15.47	15.85	17.23	17.44	16.88	16.73	14.07	14.36	16.17	15.59	12.95	14.23	17.02
CaO	23.00	22.21	21.24	22.04	22.50	23.33	21.30	21.22	22.36	22.51	20.98	21.90	19.70
Na_2O	0.44	0.39	0.27	0.26	0.64	0.53	0.72	0.67	0.44	0.42	0.37	0.32	0.30
Total	99.72	99.79	99.87	99.90	99.549	99.752	100.08	100.43	100.80	100.69	99.93	99.78	99.64
Mg#	88.35	88.08	90.67	91.58	92.70	93.24	79.27	79.24	85.21	82.15	68.51	80.08	82.38
Wo	48.57	47.02	44.55	45.41	47.02	48.31	46.98	46.80	47.00	47.16	44.43	48.75	40.67
En	45.44	46.67	50.28	49.99	49.11	48.20	43.13	44.03	47.28	45.44	38.14	44.07	48.88
Fs	5.99	6.31	5.17	4.60	3.87	3.49	9.89	9.17	5.73	7.40	17.43	7.18	10.46

Table 2. *Selected analyses of oxides: ilmenite (n° 6) and spinels (others).* C *porphyroclast core;* M *porphyroclast margin;* N *neoblasts. Analyses 10 and 11 from* Serri *et al. (1988).* Cr# *Cr*100/(Cr+Al) in atomic proportion*

Lithology	websterite				alk. pyroxenite		websterite		flaser gabbro		
Location	IAP						Gorringe Bank		IAP		
Ref.	897C	897C		897C	897D		77CY12-01		899B	900A	
Core, Section	66R-4	66R-4		67R-3	14R4				34R-1	85R-1	
Interval (cm)	57–61	67–70		102–107	95–100				10–15	21–24	
N°	1	2	3	4	5	6	7	8	9	10	11
	C	C	M	C	C	N	C	M	N	N	N
SiO_2	0.00	0.00	0.01	0.03	0.00	0.00	0.00	0.05	0.01	0.03	0.01
TiO_2	0.28	0.04	0.00	0.14	0.29	56.75	0.49	0.44	0.01	0.22	0.13
Al_2O_3	48.48	61.11	62.61	56.06	43.94	0.03	28.28	25.10	62.39	54.20	59.92
Cr_2O_3	13.41	3.26	0.95	8.63	24.26	0.09	38.72	42.21	0.15	5.21	0.96
FeO	19.44	14.62	16.14	13.94	16.26	33.58	17.68	20.79	24.10	29.30	26.58
MnO	0.36	0.19	0.19	0.20	0.10	0.75	0.40	0.26	0.28	0.39	0.37
NiO	0.15	0.23	0.17		0.05	0.02		0.05	0.20		
MgO	16.61	19.88	19.10	20.03	15.12	7.92	13.89	11.04	11.87	8.54	11.39
CaO					0.07	0.17					
Total	98.73	99.33	99.17	99.03	100.08	99.32	99.46	99.93	99.14	97.90	99.37
Mg#	68.31	76.71	73.69	78.18	62.40		61.98	50.59	47.62	36.19	46.10
Cr#	15.66	3.45	0.99	9.34	27.04		47.88	53.01	0.18	6.05	1.07

orthopyroxene. Green or light-brown coloured mm-size spinels, have a holly-leaf shape and are rimmed by plagioclase. They are aluminous ($Cr\# = Cr^{*}100/[Cr+Al] \approx 34$ to 1) (Table 2 n° 1–3, Fig. 4) with frequent hexagonal ilmenite platelets exsolutions. Based on the diopside composition and owing to the presence of syntectonic plagioclase, the high temperature deformation of the websterites stops at a temperature near 970 °C and at pressure between 0.8 and 1 GPa. These rocks subsequently underwent a subsolidus reequilibration phase which ended at about 730° (*Cornen* et al., 1996).

An unusual kind of pyroxenite occurs in millimetric fine-grained ribbons scattered within the calcitized peridotite of the upper part of Hole 897D. Because of this texture its parentage can only be deduced from its mineralogical assemblage, no bulk analyses can be done. It contains 40% clinopyroxene ($Wo_{49}En_{44}Fs_7$), 30% phlogopite and 20% kaersutite, probably former orthopyroxene transformed into bastite, and nearly 3% of rutile and Mg-ilmenite, Al-rich spinel and Cl-apatite (Fig. 5). The kaersutite and phlogopite are unusually Cr- and Mg-rich (Table 3 and Table 4, n° 1). The rutile is chrome-bearing (up to 0.4% Cr_2O_3) and ilmenite is magnesian-rich (up to 8% MgO) (Table 2, n° 6). Such mineralogy is known to occur in the 'MARID' (Mica-Amphibole-Rutile-Ilmenite-Diopside) xenoliths from kimberlite. The presence of kaersutite, instead of the 'MARID' K-richteritic amphibole, infers shallower conditions of crystallization. (*Sweeney* et al., 1993; *Dautria* et al., 1987; *Bodinier* et al., 1987). According to these authors, such veins

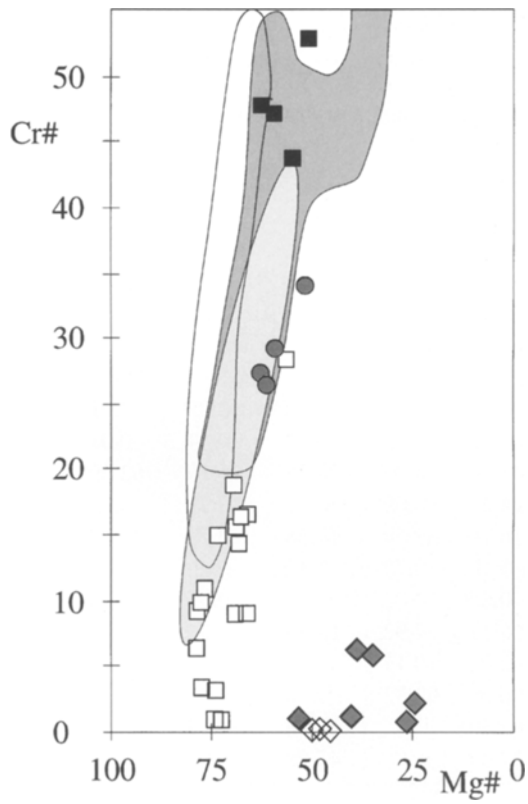

Fig. 4. Cr# (Cr*100/(Cr+Al)) versus Mg# (Mg*100/(Mg+Fe) in atomic proportions) diagram for spinels from pyroxenites and flaser gabbros. Square: websterite (open symbol: IAP; filled symbol: Gorringe Bank), circle: IAP alkaline pyroxenite, diamonds: IAP gabbros (open symbol: site 899B, filled symbol: site 900A). Heavy shaded area: IAP peridotites (Sites 897 and 899; *Cornen* et al., 1996); light shaded zone: ultramafics of Galicia Bank (*Kornprobst* and *Tabit*, 1988); 'abyssal' peridotites from *Dick* and *Bullen* (1984)

correspond to local intrusion of alkaline melts under high fO_2 inside peridotites with sub-continental mantle affinities. This pyroxenite exhibits dynamically recrystallized neoblasts which indicates that the melts infiltrated peridotites before, or during, their shearing.

Similar interactions of pervasive alkali and Ti-rich magmas with the surrounding peridotite were noticed at Galicia (*Agrinier* et al., 1988; *Girardeau* et al., 1998) and Gorringe Banks. They produce either scattered high temperature Ti- and Cr-rich pargasites (between 1000 and 850 °C) after mylonitization of the peridotites or phlogopites in dykelets (Gorringe Bank). Similar magnesian kaersutitic amphibole and phlogopite in sheared dykelet within the peridotites at Zabargad Island (Red Sea), were considered to have crystallized between 1.5 and 0.6 GPa. (50–20 km depth) and 900–1000 °C (*Piccardo* et al., 1988a; *Agrinier* et al., 1993).

Gorringe Bank. Pyroxenites from the Gorringe Bank were recovered in decimetric to centimetric lenses within the harzburgite of the North flank of Mt. Gettysburg. They are plagioclase-bearing websterite (*CYAGOR I group*, 1979) with coarse porphyroclastic texture and a modal composition of 54% diopside, 26% enstatite (Mg# 89–91), 11% olivine (Fo_{89}), 8% plagioclase (An_{88}), 1% spinel (Cr# = 50), with scarce crystals of pentlandite. Brown coloured spinels, exhibit intense resorption features. Compared to the spinels of the IAP websterites, their higher Cr# would be indicative of a slightly more depleted environment (Table 2,

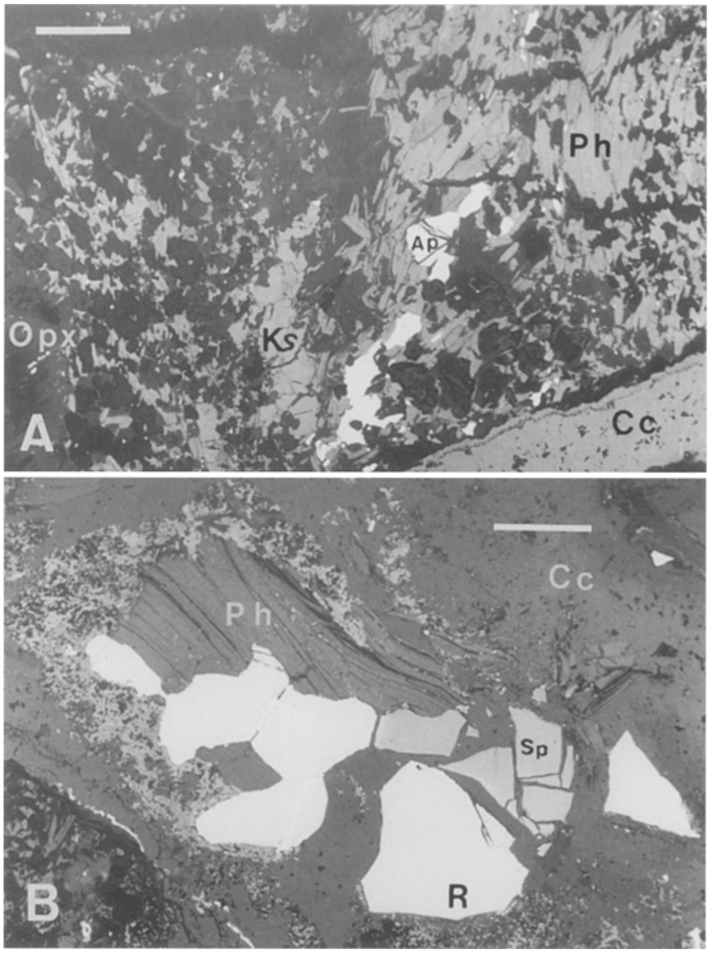

Fig. 5. Back scattered electron photomicrograph of sheared alkaline pyroxenite ribbon in calcitized (Cc) peridotite of Site 897. **A** association of orthopyroxene (Opx), kaersutite (Ks), phlogopite (Ph), and apatite (Ap). **B** association of rutile (R), spinel (Sp) and phlogopite (Ph). Scale bars are 100 µm

n° 7–8, Fig. 4). Using spinel analyses, *Serri* et al. (1988) estimated that the websterite crystallization ended at about 0.8 GPa pressure.

Gabbros, diorites and chlorite schists

Galicia Bank. Gabbros recovered on the Galicia Bank are coarse-grained (*Schärer* et al., 1995; *Boillot* et al., 1995) and are mainly composed of clinopyroxene and interstitial plagioclase (An_{59-57}) with rare orthopyroxene and altered olivine. A few of them bear Al-rich diopside (6 to 9 wt% Al_2O_3) which points to equilibrium under pressures of about 0.8 GPa (*Schärer* et al., 1995). The preliminary results obtained on a thick (500–700m) and close by gabbro body (site 34, *Boillot* et al., 1995) are however indicative of crystallisation under lower pressures (Fig. 6). Diorites occur in sheared dykes in the upper part of the ultramafic section (*Beslier*

Table 3. *Selected analyses of amphiboles from pyroxenite and mafic rocks. Analysis n° 6 is from* Prichard *and* Cann *(1982). H_2O, Fe oxidation and Mg# calculated assuming stoichiometry and formula units based on 23 oxygens and 2 (OH, Cl). Barometric estimations after* Schmidt *(1992); thermometric ones are related to an edenite-tremolite substitution* (Holland *and* Blundy, *1994)*

Location	IAP	Galicia Bk.	IAP		Gorringe Bank (NW)			Gorringe Bank (SE)				IAP	
Lithology	alk. pyroxe-nite	flaser diorite	flaser gabbro		gabbro		flaser ferro-gabbro	gabbro	flaser gabbro	flaser diorite	dolerite	micro-gabbro	basalt
Ref.	897D 14R 4, 95–100	GAL 86 10-4	899B 34R 1, 10–15	900A 81R 1 44–49	81CY 20-9	071-1	069-18	81CY D5.9(1)	77CY 14-1	81CY 17-2	81CY D5.2(4)	899B 34R-1 37–42	899B 28R-2 8–10
Color	brown	brown	brown	green	brown	brown	brown	brown (patch)	green	brown	brown-green	light brown	brown
N°	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	41.51	40.18	42.41	51.84	42.27	43.06	42.79	44.02	49.66	48.27	45.52	51.02	39.13
TiO_2	6.50	4.33	2.97	0.35	4.10	2.79	4.19	3.10	0.42	1.16	2.15	2.72	4.92
Al_2O_3	12.37	11.54	12.50	4.02	10.19	11.63	10.46	10.55	5.34	6.64	8.05	1.67	10.76
Cr_2O_3	1.74	0.00	0.21	0.03	0.00	0.00	0.00	0.09	0.17	0.01	0.04	0.00	0.00
Fe_2O_3	0.00	5.55	1.10	8.24	1.28	2.78	2.55	0.76	7.93	7.18	3.06	7.17	0.00
FeO	3.57	13.12	10.22	4.20	12.13	7.52	11.36	8.63	8.87	9.92	11.81	13.56	22.04
MnO	0.07	0.36	0.17	0.27	0.19	0.22	0.23	0.13	0.24	0.17	0.15	0.41	0.43
MgO	15.52	9.78	12.93	16.73	12.35	14.54	12.19	15.03	13.68	12.79	12.77	10.92	5.90
NiO		0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00		
CaO	12.32	10.53	11.60	11.78	10.98	11.84	10.87	12.12	11.07	11.23	11.74	5.27	11.01
Na_2O	2.71	3.16	2.71	0.30	3.02	2.39	2.79	2.65	1.36	1.01	1.75	5.47	2.50
K_2O	1.29	0.49	0.60	0.12	0.68	0.77	0.50	0.22	0.29	0.58	0.60	0.61	1.19
Cl		0.01	0.83	0.12	0.02	0.02	0.00	0.01	0.29	0.34		0.00	0.02
H_2O^*	2.08	2.01	1.83	2.08	2.00	2.05	2.03	2.05	2.01	1.99	2.03	2.04	1.91
total		101.07	100.08	100.09	99.19	99.61	99.95	99.37	101.34	101.27	99.66	100.84	99.80
(-O=Cl)		0.00	0.19	0.03	0.01	0.01	0.00	0.00	0.06	0.08		0.00	0.01
Total	99.67	101.07	99.89	100.07	99.18	99.61	99.95	99.37	101.28	101.19	99.66	100.84	99.79
Mg#	88.58	57.07	69.27	87.65	64.47	77.50	65.67	75.65	73.33	69.68	65.83	57.80	31.88
P (GPa)		0.67	0.73		0.55	0.65	0.57	0.56		(0.24)			
T °C		950	794		914	846	888	879		(693)			

Table 4. *Selected analyses of micas and chlorites. Analysis n° 8 from* Prichard *and* Cann *(1982).* Fe# = *100* Fe/(Mg+Fe) in atomic proportion*

Lithology	pyroxenite	flaser diorite		basalt	flaser diorite	chlorite schist		ferro-gabbro
Mineral	phlogopite	biotite			chlorite			
Location	IAP	Galicia Bk.	Gorringe	IAP	Galicia Bk.		IAP	Gorringe
Ref.	897D 14R-4 95–100	GAL86 10-4	81CY 17-2	899B 28R-2 8–10	GAL86 10-4	GAL86 10-9	899B 37R-1 28–33	
N°	1	2	3	4	5	6	7	8
SiO_2	36.64	33.53	35.41	36.65	23.44	24.75	25.11	26.07
TiO_2	9.33	3.88	4.18	7.11	0.06	0.10	0.03	
Al_2O_3	14.76	15.50	13.83	12.50	19.45	21.34	20.88	21.03
Cr_2O_3	1.39	0.00	0.11	0.00	0.18	0.06	0.06	
FeO	4.62	22.41	24.60	19.24	39.43	27.03	29.57	20.44
MnO	0.03	0.14	0.29	0.21	0.32	0.07	0.20	0.30
MgO	18.33	10.62	8.41	11.52	6.33	15.30	12.36	18.59
CaO	0.03	0.24	0.07	0.03	0.02	0.01	0.02	
Na_2O	0.37	0.52	0.17	0.78	0.06	0.01	0.00	
K_2O	10.07	7.97	8.53	8.17	0.01	0.00	0.00	
Cl		0.01		0.02	0.02	0.00	0.00	
Total	95.57	94.82	95.60	96.23	89.32	88.67	88.17	86.43
Fe#	12.40	54.21	62.13	51.34	77.75	49.77	57.30	38.15

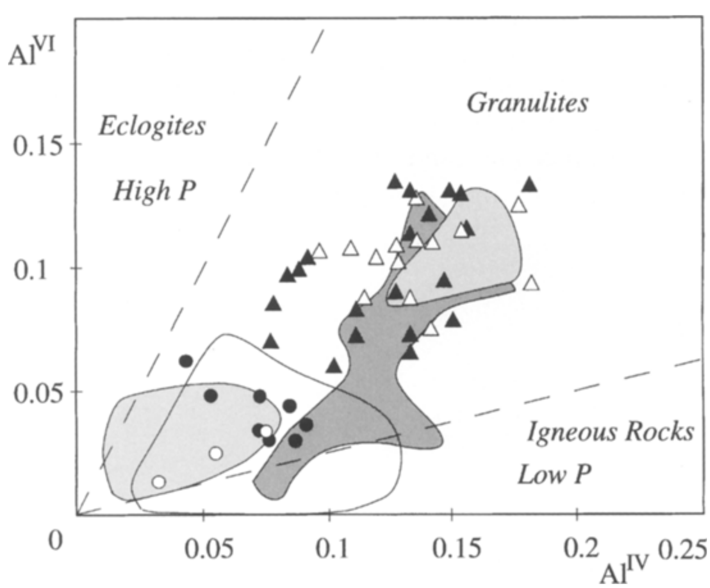

Fig. 6. Al^{VI} versus Al^{IV} diagram for clinopyroxenes (structural formula calculated on a base of 6 oxygens and 4 cations) of gabbros and ferro-gabbros from IAP (triangle), Gorringe Bank (circle) and Galicia Bank (heavy shaded area). Filled symbol: porphyroclast core; open symbol: porphyroclast margin and neoblast). Pressure domains from *Aoki* and *Shiba* (1973); open area: clinopyroxenes of South West Indian Ridge gabbros (SWIR) from *Hébert* et al. (1991), light shaded area: clinopyroxene from Zabargad Island (notice the two areas corresponding respectively to HP porphyroclasts and LP neoblasts; *Bonatti* and *Seyler*, 1987 and *Boudier* et al., 1988)

et al., 1990). They are composed of centimeter-sized kaersutite porphyroclasts inside a matrix composed of neoblasts of brown hornblende and plagioclase, with rare biotite (0.5 mm-sized; Table 4, n° 2), ilmenite, altered Ti-magnetite, and abundant apatite. Amphiboles crystallized under high temperature (near 950°) and pressure up to 0.67 GPa (*Schmidt*, 1992; *Holland* and *Blundy*, 1994) (Table 3 n° 2).

The chlorite schists, recovered at a distance less than 1 km from this diorite outcrop, are composed of Fe-rich chlorite (ripidolite) and apatite (>90% modal), with ilmenite and zircon as accessory minerals (*Beslier* et al., 1990). *Schärer* et al. (1995) interpreted them as derived from ferrogabbros. It is most likely the chlorite schist derived from the sheared diorites as they have similar relictual textures and large amounts of apatite.

Iberia Abyssal Plain. Shearing and metamorphism strongly imprint the gabbros from Site 899 and 900; rare coarse-grained and porphyroclastic sections are interspersed within the predominant fine-grained and granuloblastic textures. A 'primary' mineralogy, generally preserved, is composed of clinopyroxene, plagioclase and rare ilmenite.

A green spinel, locally euhedral, occurs inside the plagioclase neoblasts (Fig. 7). With Mg#35–54 and very low Cr# (0.2–6) (Table 2, ne° 9–11, Fig. 4) this spinel (pleonaste) is typically of metamorphic origin (*Frost*, 1991) and indicative of pressures close to 0.8 GPa as it is at equilibrium with plagioclase (*Whitney*, 1972; *Frost*, 1991).

Porphyroclastic pyroxenes show undulose extinctions and very rarely few exsolution lamellae. Porphyroclasts and neoblasts are all diopside and display a short evolution toward augite (Table 1, n° 7–8). Their specific high contents in Al_2O_3 and Na_2O (respectively up to 7.3% and 0.9%) have no counterpart in gabbros recovered at mature slow-spreading ridges which crystallized and locally

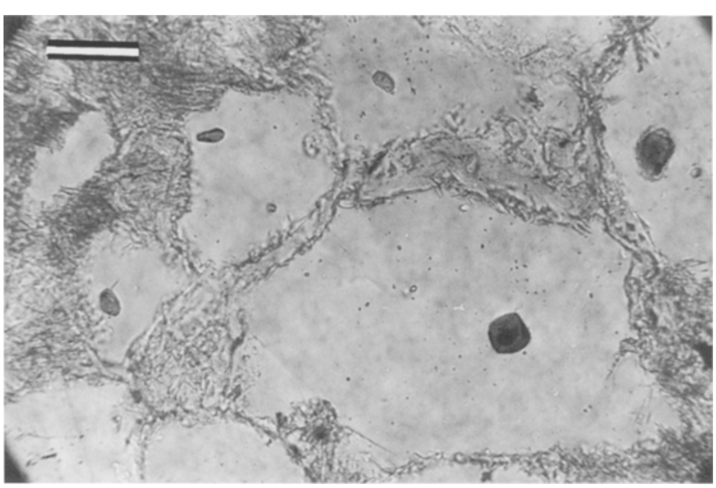

Fig. 7. Photomicrograph of spinel inclusions in plagioclase neoblasts from the flaser gabbros of site 900. The spinel (dark grains) is green and locally euhedral. Notice the polygonal shape of the plagioclase neoblasts and the chlorite and tremolite in the interstices. Scale bar is 100 μm

were sheared under low pressures. This is true for the Mid Atlantic Ridge (*Helmstaedt* and *Allen*, 1977; *Honnorez* et al., 1984; *Tiezzi* and *Scott*, 1980), the Mid-Cayman Rise (*Ito* and *Anderson*, 1983), and for the well documented gabbroic section of the South West Indian Ridge (SWIR; *Bloomer* et al., 1989; *Hébert* et al., 1991). This is obvious in the diagram Al^{IV}/Al^{VI} (Fig. 6), where the clinopyroxenes (porphyroclasts and neoblasts) from IAP-flaser gabbros overlap the high grade field of the porphyroclastic clinopyroxenes from the metagabbros of Zabargad Island (*Bonatti* and *Seyler*, 1987; *Boudier* et al., 1988) well apart from the low P field of the SWIR gabbros.

Porphyroclasts and neoblasts of plagioclase are usually unzoned with similar compositions (An_{72} to An_{54}). Only few sections of coarse-grained entirely amphibolitized rocks display Ca-rich relics (up to An_{85}) coexisting with albite and/or analcime. This discrepancy would be indicative of the initial coexistence of different types of gabbros or induced by metamorphic reactions. Amphiboles replacing pyroxenes are little deformed and typical of greenschist grade (actinolitic-hornblende and actinolite). It is slightly different at Site 899 where the green spinel bearing amphibolitized gabbros (Fig. 4) exhibit brown amphiboles remnants. These brown titanian pargasites with low Cr-, high Cl- (up to 1.24%), and high Ti and Al^{IV} contents and the presence of spinel are compatible with a crystallization under high amphibolite grade and PT conditions close to 0.73 GPa and 790 °C (Table 3, n° 3).

At the same site (899) chlorite schists recovered at the bottom of the Hole are mainly composed of ripidolite (up to 90%) (Table 4, n° 7) with titanite, rutile, hydrogarnet, apatite and zircon as accessory minerals. This peculiar mineralogy and the recovery of few rocks with an intermediate composition between amphibolitized gabbros and chlorite-schists led us to infer that these chlorite schists derived from a differentiated gabbroic protolith. At this site, the gabbroic series is indicative of differentiation and shearing under high amphibolite grade followed by low temperatures conditions while eastward and close by the continent similar greenschist grade minerals overprint the initial dry granulite grade conditions of the shearing.

Gorringe Bank. The exposed laccolith is mainly composed of gabbros, ferro-gabbros and diorites with subordinate troctolites and gabbronorites. These rocks show undeformed coarse-grained magmatic textures to typical flaser ones in flat shear zones (*Prichard* and *Cann*, 1982; *CYAGOR II group*, 1984a; *Mével*, 1988; *Girardeau* et al., 1998). Their plagioclase (An_{52-57}) is unzoned. Moderate to low pressure of crystallization of these gabbros are inferred from the low Na and Al contents of their clinopyroxenes (0.4% Na_2O and 2% Al_2O_3, Mg# = 85) (Table 1, n° 9–11, Fig. 6). However locally these pyroxenes include patches of primary brown amphiboles, similar to the primary brown titanian-magnesian-pargasite which mainly compose the differentiated ferro-gabbros and diorites. These primary amphiboles would have crystallized at pressures close to 0.55 GPa and $T° \approx 900$ °C (Table 3, n° 5–8). Compared to the gabbros, the differentiated rocks are characterized by a slight increase in Fe content in clinopyroxenes ($82 \leq Mg\# \leq 68$), of Na in plagioclase (An_{57} to An_{19}) and by the occurrence of accessory apatite, ilmenite, rutile, titanite, rare flakes of biotite and zircon. A subsequent low grade metamorphism overprint all these rocks with the crystallization of green fibrous hornblende and oligoclase (An_{8-10}) (*Prichard* and *Cann*, 1982; *Mével*, 1988). The replacement of brown amphiboles by ripidolite is common in the differentiates (Table 4, n° 8; *Prichard* and *Cann*, 1982), but no true chlorite schist occurrence has been reported on the Gorringe Bank.

Basalts

Galicia Bank. Basalts from the Galicia Bank display variolitic to intersertal textures, locally porphyritic. According to *Kornprobst* et al. (1988) and *Charpentier* et al. (1998), the primary mineralogy is olivine, plagioclase, clinopyroxene and titanomagnetite with frequent accessory brown amphibole and biotite, which is unusual in oceanic tholeiitic basalts.

Iberia Abyssal Plain. Mainly recovered at Site 899, the basalts display porphyritic, variolitic to intergranular (doleritic) textures. Although deeply altered and in some cases metamorphosed in the chlorite-prehnite facies, there are sufficient remnants of the primary mineralogy to identify two basaltic populations. The first are alkaline basalts with Ti-rich diopside (with up to 3.66% TiO2; Table 1, n° 12), plagioclase ($Or_1Ab_{32}An_{67}$), kaersutite (up to 200 µm) or titanian-richterite in coarser grained types (Table 3, n° 12, 13) and minor biotite (Table 4, n° 4). The second are tholeiitic basalts with phenocrysts of Ca-rich plagioclase (An_{84-65}) and quenched augite ($Wo_{48-46}En_{40-31}Fs_{22-12}$). In both types olivine is rare and always replaced by serpentine and smectites.

Gorringe Bank. On the Gorringe Bank, besides the late alkaline lavas (65–67 Ma) restricted to Mount Ormonde (*Cornen*, 1982; *Féraud* et al., 1986), a few basaltic rocks occur as pillow lavas upon the peridotitic sea floor and as intrusive dikes and sills (*CYAGOR I group*, 1979). Dolerites from Mt Gettysburg (westward) contain remnants of Ti-poor ($TiO_2 \leq 1\%$) augite ($Wo_{42}En_{49}Fs_9$) (Table 1, n° 13) and pheno- and microcrysts of plagioclase (An_{82-66} and An_{60-47}); olivine is entirely replaced by epidote. The dolerites of Mt Ormonde, intrusive within gabbros, have their pyroxenes completely replaced by chlorite and green-, fibrous amphibole or rarely by brown Ti-bearing magnesio-hornblende (Table 3, n° 11).

Geochemistry

The analyses of major elements, main trace elements and rare earth elements (REE) of the most representative lithological types are reported respectively in Tables 5 and 6 for the IAP and Gorringe Bank occurrences. Among these new data, six major elements analyses from Gorringe Bank are issued from litterature (references are reported in the table caption), all the trace elements analyses are new excepted the n° 3 (DSDP120).

Pyroxenites

Websterites from the Iberia Abyssal Plain and from the Gorringe Bank are very similar (Table 5, 6; n° 1). They are characterized by Mg# = 87–89 and high

Table 5. *Bulk-rock analyses from Iberia Abyssal Plain. Their label precise the sampling location illustrated in Fig. 1 and 2.* Mg# *Mg* 100/(Mg+Fe^{total}), atomic proportion. All the rock powders were obtained through the grinding in agate jar, down to size particles < 1 µm,* of clean gravels (Ø ~ 2mm) devoid of filled vesicles. Major and trace elements, except for Rb, have been measured by Inductively Coupled Atomic Emission Spectrometry (ICP-AES), and Rb by flame atomic emission using a Perkin-Elmer® 5000 spectrometer as described by Cotten *et al. (1995). Analyst:* J. Cotten, *UMR 6538, UBO, Brest. Trace elements analyzed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) have been obtained by* C. Monnier *in Toulouse (UMR 5563, P. Sabatier University, Toulouse). For most of the samples, acid dissolution and further evaporation have been performed in a CEM microwave oven following the procedure described by* Benoit *et al. (1996). The final solution is HNO_3 0.37N diluted 300 times (peridotites) and 1000 times (basalts) for acid-digested samples. ICP-MS is a Perkin Elmer® ELAN 5000 equipped with a classical cross flow nebulizer and a Scott spray chamber.* D.L. *detection limits in ppm*

Hole			897C	899B	900A	900A	900A	899B	899B	899B	899B	899B	899B	899B
Core, Section			66R-4	34R-1	85R-1	81R-1	82R-1	37R-1	20R-2	25R-2	35R-1	28R-1	27R-1	27R-1
Interval (cm)			57–61	10–15	2–7	44–49	25–31	28–33	134–136	33–37	29–33	42–45	15–18	27–30
Lithology			websterite	amphibolitized flaser gabbro	flaser gabbro	amphibolitized flaser gabbro	amphibolitized flaser gabbro	chlorite schist	metabasalt	metabasalt (porphyritic)	microgabbro	metabasalt (porphyritic)	variolitic basalt	porphyritic basalt
N°			1	2	3	4	5	6	7	8	9	10	11	12
SiO_2			39.00	41.20	46.50	49.70	49.20	24.80	38.50	35.70	43.60	34.40	46.00	47.10
TiO_2			0.15	0.30	0.30	0.95	0.41	1.56	1.29	0.60	0.85	0.93	1.34	0.69
Al_2O_3			14.00	17.10	14.90	15.48	18.40	21.65	17.90	19.34	18.50	19.39	15.60	20.60
Fe_2O_3			5.92	8.96	7.41	8.85	5.96	28.00	8.30	7.65	7.55	6.70	6.95	6.20
MnO			0.11	0.12	0.12	0.13	0.09	0.20	0.14	0.14	0.12	0.13	0.15	0.16
MgO			20.50	16.05	11.60	9.28	7.76	9.25	11.65	13.20	9.92	16.50	11.65	7.54
CaO			9.90	4.70	13.65	7.65	10.65	5.05	15.00	12.90	3.80	10.10	6.25	10.25
Na_2O			0.31	1.41	1.52	3.02	2.80	0.01	0.18	0.12	1.95	0.13	2.40	2.80
K_2O			0.10	1.44	0.15	0.71	0.77	0.00	0.02	0.01	2.50	0.01	1.79	0.22
P_2O_5			0.03	0.05	0.03	0.04	0.04	0.37	0.16	0.08	0.10	0.12	0.25	0.09
LOI			9.54	8.00	4.18	3.68	4.68	8.90	7.08	10.16	10.67	11.01	7.20	4.37
Total			99.56	99.33	100.26	99.49	100.76	99.85	100.22	99.90	99.56	99.42	99.58	100.02
Mg#			87.28	87.75	86.23	80.75	83.89	56.92	84.88	87.34	84.01	90.78	87.02	82.95
Method (ppm)	ICP-MS D.L.	ICP-AES D.L.	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-AES	ICP-AES	IPC-MS	ICP-AES	ICP-MS	ICP-AES
Sc		0.5	28	32	46	45	48	41	35	25	32	27	26	25
V		3	140	115	171	223	165	237	205	106	150	160	183	119
Cr		3	1320	360	865	164	367	263	195	188	250	228	220	202
Co		3	58	56	51	49	36	116	33	35	65	29	38	37
Ni		3	770	190	225	122	91	105	54	145	180	80	217	162
Rb	0.007	0.5	0.44	11.94	1.54	6.20	7.55	0.12	0.5	0.2	21.88	0.20	31.87	3.50
Sr	0.038	1	168	143	197	224	364	11	38	43	127	52	249	225
Y	0.003	0.5	3.37	6.16	5.64	9.48	7.20	34.22	22.5	15.4	19.02	16.00	18.87	15.00
Zr	0.033	2	2.25	35.71	6.37	16.80	44.03	128.19	88	33	47.61	57.00	110.96	46.00
Nb	0.003	1	0.01	0.36	0.12	0.05	0.12	12.68	7.1	2.1	3.18	5.50	25.71	3.20
Cs	0.002		0.03	0.19	0.09	0.05	1.09	0.02			0.68		0.10	
Ba	0.019	3		591.76	24.56	103.07	79.07	1.85	2.0	3.0	259.54	1.00	321.49	44.00
La	0.001	1	0.05	0.72	0.58	0.47	0.76	6.00	6.4	2.2	3.77	4.70	13.63	3.00
Ce	0.005	2	0.33	2.26	1.64	1.40	2.04	14.98	17.0	6.0	9.70	12.00	30.77	7.60
Pr	0.001		0.09	0.38	0.29	0.27	0.36	2.21			1.44		3.96	
Nd	0.010	2	0.70	2.00	1.75	1.87	2.11	10.12	12.0	3.9	6.97	9.00	16.57	5.20
Sm	0.003		0.36	0.69	0.66	0.88	0.88	3.81			2.04		3.63	
Eu	0.003	0.2	0.16	0.57	0.37	0.43	0.45	0.45	1.1	0.6	1.11	0.63	1.25	0.74
Gd	0.003		0.53	0.85	0.94	1.43	1.27	5.00			2.70		3.84	
Tb	0.002		0.10	0.16	0.17	0.26	0.22	1.12			0.50		0.58	
Dy	0.004	0.4	0.65	1.12	1.14	1.82	1.37	7.15	4.1	2.6	3.41	3.00	3.45	2.60
Ho	0.001		0.13	0.23	0.23	0.39	0.28	1.53			0.76		0.71	
Er	0.002	1	0.38	0.64	0.64	1.08	0.78	4.15	2.2	1.5	2.22	1.60	1.95	1.50
Tm	0.001		0.05	0.09	0.09	0.15	0.10	0.56			0.33		0.27	
Yb	0.003	0.2	0.33	0.61	0.56	1.00	0.67	3.35	2.2	1.7	2.10	1.57	1.69	1.51
Lu	0.001		0.05		0.08			0.49			0.32		0.26	
Hf	0.006		0.12	0.31	0.28	1.25	1.65	3.10			1.28		2.61	
Ta	0.038			0.40	0.04	0.30	0.40	1.25			0.17		3.46	
Th	0.001		0.002	0.02	0.02	0.01	0.05	1.62			0.39		1.48	

contents of Cr (1000–6870 ppm) and Ni (700–1700 ppm). The REE patterns (Fig. 8) are devoid of Eu anomaly and show a strong depletion in LREE: 0.2–0.5 time the chondrite for La and $Ce_N/Yb_N = 0.2–0.4$. A lower ratio (0.1) and 7 times the HREE content of the chondrites is noticed in one decimeter thick websterite lense of IAP

Table 6. *Bulk-rock analyses from Gorringe Bank (Gettysburg and Ormonde Mounts respectively situated in SW and NE of the Bank). Detailed sampling sites are reported in* Cyagor I Group *(1979) and* Cyagor II Group *(1984a). Major elements and transitional elements obtained by XRF (Analyses 7 to 9: analyst* F. Vidal, *UPR4661 Rennes); Analyses n° 1 after* Serri *et al. (1988); n° 2, 10, 11, from* Mével *(1984); 3, from* Gavasci *et al. (1973). Major elements and transitional elements obtained by ICP-AES (n° 4, 5, 6) Analyst:* J. Cotten, *(Brest). Trace elements analyses by ICP-MS (Analysts:* C. Monnier *and* M. Polvé, *UMR 5563, P. Sabatier University, Toulouse); by INAA: Analyst:* J. L. Joron *(Lab. 'Pierre Süe' CEN Saclay); n° 3 from* Montigny *(1975)*

Location	Gettysburg				Ormonde		Gettysburg			Ormonde	
Lithology	websterite	gabbro	gabbro	ferro-gabbro	gabbro	diorite	dolerite	dolerite	pillowed-basalt	dolerite	dolerite
Ref.	77CY 12.01	81CY 20.05	DSDP 120-8-7	81CY 20.7	81CY 18.3	81CY 17.2	77CY 12.6	77CY 12.2B	77CYD6	81CY 15.2	81CY 15.3
Lat N	36°36.60	36°41.99	36°42.17	36°42.00	36°41.20	36°34.42	36°36.17	36°35.57	36°43.20	36°41.26	36°41.37
Long W	11°40.56	11°34.31	11°22.67	11°34.30	11°04.45	11°06.89	11°39.57	11°40.58	11°21.50	11°03.91	11°04.07
depth (m)	−1720	−2340	−1957	−2340	−750	−2500	−1300	−1800	−500	−757	−637
No	1	2	3	4	5	6	7	8	9	10	11
SiO_2	46.49	50.66	48.61	48.00	51.80	53.50	49.58	48.85	50.00	52.47	52.32
TiO_2	0.22	0.18	0.51	4.28	0.21	0.90	1.09	0.84	1.53	1.22	1.43
Al_2O_3	6.84	15.95	17.18	14.20	17.80	14.83	15.66	20.98	17.42	17.03	16.44
Fe_2O_3	5.45	3.54	7.42	10.60	3.15	11.14	8.66	5.56	8.40	6.56	8.31
MnO	0.20	0.08	0.14	0.20	0.06	0.20	0.09	0.10	0.11	0.08	0.12
MgO	24.14	11.16	9.94	8.05	8.75	5.77	6.96	7.48	6.12	8.06	7.45
CaO	10.45	13.15	8.65	9.85	14.20	8.10	7.30	8.34	4.29	10.72	10.15
Na_2O	0.33	2.27	3.05	3.00	1.89	3.95	4.78	3.95	3.52	2.76	2.95
K_2O	0.01	0.63	0.20	0.17	0.34	0.50	0.34	0.38	3.66	0.16	0.11
P_2O_5	0.02	0.02	0.03	0.03	0.01	0.06	0.13	0.11	0.21	0.10	0.15
LOI	5.72	2.36	4.59	1.86	2.66	1.18	6.14	2.79	3.99	1.80	1.88
Total	99.77	100.00	100.32	100.24	100.87	100.13	100.73	99.38	99.25	100.96	101.31
Mg#	89.77	86.20	72.63	60.07	84.62	50.64	61.42	72.71	59.07	70.88	63.97
Method	ICP-MS *INAA	INAA	D.I.	ICP-MS	ICP-MS	ICP-MS	ICP-Ms	INAA	INAA	INAA	ICP-MS
Sc (ppm)	42.53	39.70		54.53	35.04	39.38	41.62	27.80	33.30	33.10	37.08
V				560	126	220	225.53				264
Cr	*6828	610		30	660	5	179.21	352	69	417	310
Co	51.87	25.7		42	21	39	35.79	26	21.8	44.6	41
Ni	*1528	190		68	154	40	119.38	269	37	182	124
Rb	0.24	3	1.39	0.77	3.88	16.27	3.31	2.5	80.4	1.7	3.35
Sr	26	403	17	250	92	111	387	464	245	224	148
Y	6.98			18.63	5.87	41.16	20.96				31.02
Zr	3.07	20		30.20	14.73	64.75	53.51	86	145	91	60.98
Nb	0.02			10.03	0.39	3.68	4.67				2.46
Cs	0.02	0.03		0.03	0.11	0.62	0.08	0.03	3	0.08	0.20
Ba	0.60	70	8.9	99.14	11.72	84.60	126.60	49	269	15	44.79
La	0.09	0.41		2.11	0.32	3.54	5.71	3.6	6.8	2	3.39
Ce	0.64	1.4	2.29	6.84	1.15	13.15	15.56	8.4	19.7	8.6	11.32
Pr	0.14			1.26	0.18	2.11	2.28				2.00
Nd	1.04		2.18	7.25	1.17	12.75	11.22				11.53
Sm	0.52		0.68	2.43	0.54	4.77	3.03				4.00
Eu	0.21	0.35	0.3	1.08	0.29	1.88	1.14	0.88	1.27	1.11	1.30
Gd	0.89		1	3.25	0.87	6.63	3.67				5.16
Tb	0.18	0.14		0.57	0.17	1.24	0.63	0.41	0.57	0.6	0.92
Dy	1.30		1.48	3.80	1.17	8.42	4.07				5.89
Ho	0.30			0.80	0.25	1.78	0.86				1.25
Er	0.91		1	2.31	0.75	5.18	2.34				3.51
Tm	0.14			0.33	0.11	0.76	0.33				0.52
Yb	0.85		0.92	2.10	0.66	4.93	2.06				3.16
Lu	0.13			0.32	0.10	0.75	0.29				0.47
Hf	0.21	0.22		1.21	0.39	0.81	1.56	1.68	3	2.25	2.10
Ta	0.08	0.01		0.77	0.07	0.25	0.36	0.21	0.52	0.098	0.21
Th	0.001	0.019		0.09	0.02	0.06	0.32	0.24	0.54	0.076	0.17

ultramafics (Site 897). Comparable websterites occur as layers in the ultramafics of the Ronda and Lanzo massifs (*Bodinier*, 1989; *Remaïdi*, 1993), corresponding respectively to continental and passive-margin occurrences (*Froitzheim* and *Manatschal*, 1996). All these websterites display near identical trace element

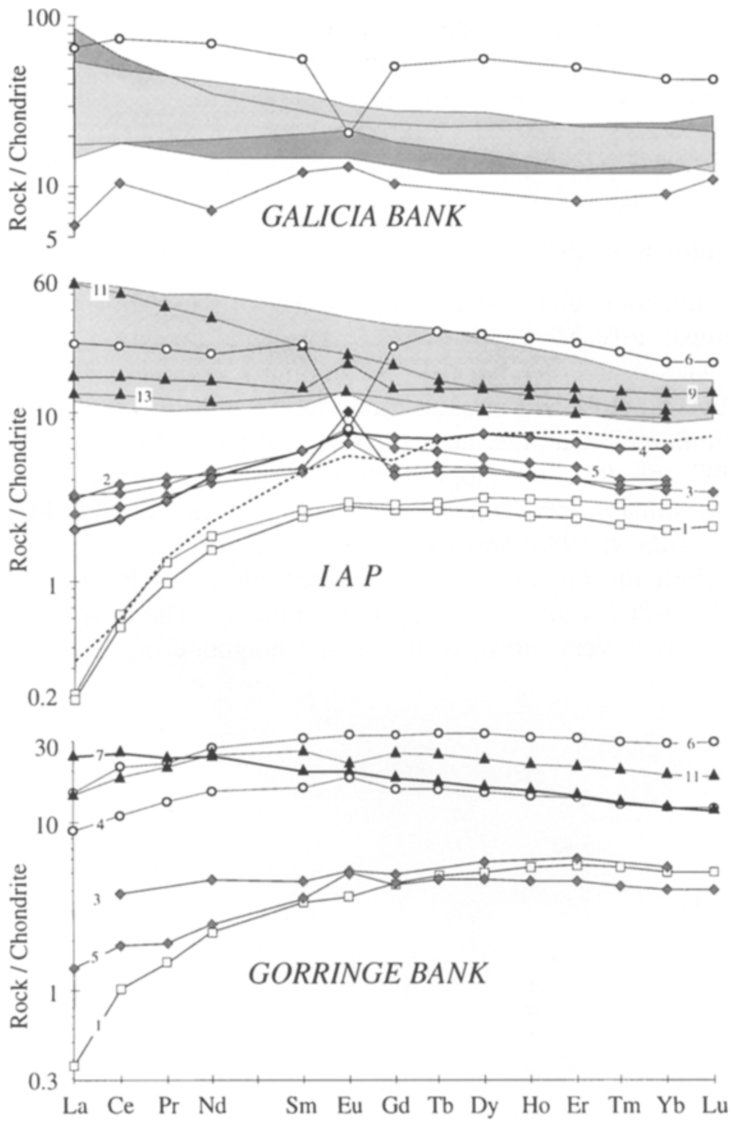

Fig. 8. Chondrite normalized rare-earth element patterns for the magmatic rocks from Galicia Bank *(Kornprobst* et al., 1988; *Schärer* et al., 1995), IAP and Gorringe Bank (this work). Pyroxenites: empty square, gabbros: filled diamond, ferro-gabbros and chlorite-schists: open circles, basalts: shaded areas and filled triangle. The Galicia Bank basalts: light shaded area, superimpose a heavy one which refers to the basalts from Zabargad Island (*Petrini* et al., 1988). The dashed pattern and the shaded area in IAP zone correspond respectively to the pyroxenite (149-897C-67R-1-33-36cm) and to the IAP basalts analyzed by *Seifert* and *Brunotte* (1996) and *Seifert* et al. (1996). Numbers on IAP and Gorringe Bank patterns correspond respectively to analyses of Table 5 and 6; Normalization values of *Sun* and *McDonough* (1989)

patterns. Their strong depletion in high field strength elements (HFSE) precludes a crystallization from an unmodified primitive melt. According to *Serri* et al. (1988), *Bodinier* (1989) and *Remaïdi* (1993), these pyroxenites would be segregates of liquid with T to E-MORB affinity, produced in the spinel zone of the mantle and reequilibrated during their subsequent uplift.

Gabbros, diorites and chlorite schists

Galicia Bank. Only one bulk rock analysis of gabbro is available (*Schärer* et al., 1995). Its cumulate features: 19% MgO, Mg# = 79.2, a relative depletion in Zr (23ppm) and Ti (0.5% TiO_2), and the positive Eu anomaly contrast with its relatively high REE contents at about 10 times the chondrites (Fig. 8). Isotopic data obtained respectively on bulk rock and on separated clinopyroxenes ($\varepsilon Nd_{[122\,Ma]} = +4.7$; *Schärer* et al., 1995) are close to isotopic features of continental tholeiitic dykes related to the preliminary break up of the Atlantic ocean at 200 Ma (Messejana and Pyrénées: *Alibert*, 1985; *Sebai* et al., 1991) (Fig. 9).

The chlorite schists from the Galicia Bank are differentiated rocks with a Mg# = 50 and high P_2O_5 (1.86%) and Zr (113 ppm) contents. Their isotopic signature ($\varepsilon Nd_{[122Ma]} = +5.6$) is very close to that of the neighbouring gabbros

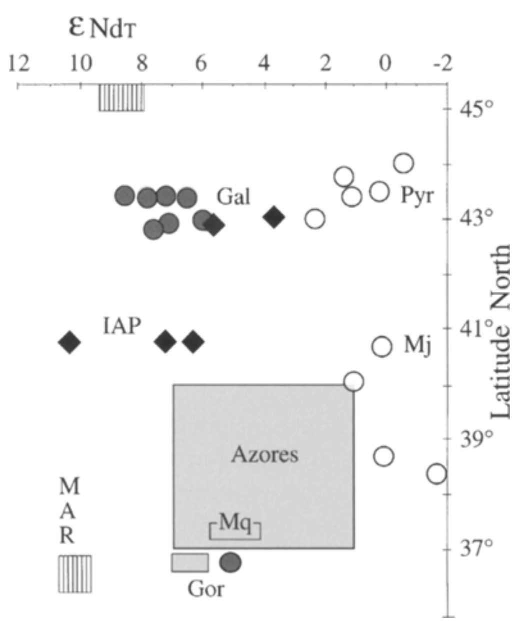

Fig. 9. $\varepsilon Nd_{[T]}$ versus Latitude diagram of the main intrusive and extrusive rocks related to the early rifting and opening of the Atlantic ocean between 200 Ma and present. Diamond: gabbro series, filled circles: dolerites and basalts of the West Iberian margin, open circles: CFTs; hatched areas: Mid Atlantic ridge basalts, shaded areas: OIB. Gal: Galicia Bank (*Schärer* et al., 1995; *Charpentier* et al., 1998), IAP (*Seifert* et al., 1996), Gor: Gorringe Bank and Mq: Monchique, (*Bernard-Griffith* et al., 1997 and this work, see Table 7); Pyr: Pyrénées and Mj: Messejana (*Alibert*, 1985), Azores basalts from *White* and *Hofmann* (1982)

(*Schärer* et al., 1995) and shows that they are not remnants of continental crust. Despite the drastic leaching suffered by the protolith (strong Cs, Rb and Sr depletion), these rocks have kept their original REE signature (*Tribuzio* et al., 1996). Their flat REE pattern ($Ce_N/Yb_N = 1.77$) with 70 times the REE chondritic content, and a pronounced negative Eu anomaly are compatible with that of plagiogranites or diorites (Fig. 8) (*Pedersen* and *Malpas*, 1984).

Iberia Abyssal Plain. Flaser gabbros from Sites 899 and 900 have a bulk rock Mg# of 80 to 88 (Table 5, n° 2–5). The most differentiated rocks correspond to the rare weakly Fe-enriched samples ($Fe_2O_3 \sim 9\%$) with Zr up to 48 ppm. All of these gabbros display relatively flat REE-patterns, situated between 2 and 7 times the chondritic values and a positive Eu anomaly related to the accumulation of plagioclase crystals (Fig. 8). This Eu anomaly is however less pronounced in a 'shallow' amphibolitized and Ti-rich section (core 81, $\approx$3 m length; Table 5, n° 4) which exhibits higher HREE-contents and a lower Ce_N/Yb_N ratio (0.39 against 0.8 to 1.0). This distinction is also apparent in the isotopic data obtained by *Seifert* et al. (1996). This upper Ti-rich section appears depleted ($\varepsilon Nd_{[136Ma]} = +10.32$) with N-MORB signature (*Dosso* et al., 1993). With $\varepsilon Nd_{[136Ma]} = +6.29$ to $+7$, the other gabbroic sections (cores 82 and 85) have signatures comparable to those of the Galicia Bank gabbros and of the Gorringe Bank dolerite. They fit the range of the Paleocene alkaline basalts of the Gorringe Bank ($\varepsilon Nd_{[65Ma]} = +6.6$; *Bernard-Griffiths* et al., 1997), or the alkaline basalts from Azores Islands (*White* and *Hoffmann*, 1982) (Fig. 9). The contrasted εNd of gabbros sampled about 10 meters apart in the same Hole (900A) indicates different sources for the melts. Owing to sea water interactions and alteration of the rocks, Sr and Pb isotopic data do not provide any useful information.

Chlorite schists from IAP and from Galicia Bank have comparable compositions (Table 5, n° 6). They display low Mg# = 39.6 value, high LILE content (Zr = 128 ppm) and flat REE patterns ($Ce_N/Yb_N = 1.24$) at about 25 times the chondrites (against 70 in chlorite schist of Galicia Bank), relatively high Tb contents consistent with the amount of titanite and an obvious negative Eu anomaly (Fig. 8). The chemistry suggests a dioritic or plagiogranite protolith (*Lécuyer* et al., 1991; *Pedersen* and *Malpas*, 1984).

Gorringe Bank. The gabbroic series from the Gorringe Bank (Table 6, n° 2, 3, 5) have a wide range of composition with: $TiO_2 = 0.2$–4%, MgO = 11–5%, Mg# = 86–49. They have a flat to slightly LREE depleted pattern situated between 2 to 30 times the chondritic values owing to their differentiation level (decreasing Mg# value) (Fig. 8). Eu anomaly is not apparent or weakly positive. A fractional crystallization process in a closed system may account for the regular increase of the most hygromagmaphile elements with the decreasing Mg#.

Basalts

Galicia Bank. Basalts from the Galicia Bank are moderately to highly altered (LOI contents between 2 and 10%). They display high TiO_2 contents (between 1.4 and 2.3%), and MgO between 7.7 and 2% (*Kornprobst* et al., 1988). Most of them are

LREE-undepleted (Fig. 8). Their La enrichment factor between 16 and 55 and their Ce_N/Yb_N ratio between 1 and 3 are features of T to E-MORB. According to *Kornprobst* et al. (1988) and *Charpentier* et al. (1998) they would derive from melt produced through the interaction between a sub-continental lithospheric source and a depleted asthenospheric one.

Iberia Abyssal Plain. Basalts recovered are highly altered. Nonetheless, those identified as alkaline by their mineralogy have low SiO_2 (less than 46%), high MgO contents (10–12%) and Mg# between 83 and 87 (Table 5, n° 7–11) but moderate TiO_2 contents between 1 and 1.5%. They display significative enrichments of the light REE elements (Fig. 8) with La-enriched by 50 to 15 times chondritic and $Ce_N/Yb_N = 5.05$. The other ('tholeiitic') end member has significantly less TiO_2 ($\sim 0.6\%$) and a rather flat REE pattern, at about 10 times chondritic without significant LREE depletion (Table 5, n° 10, 12). Few microgabbroic basalts display additional positive Eu anomaly, showing some plagioclase accumulation. All these patterns correspond typically to E-MORB signatures.

The IAP basalts, as those from Galicia bank, are very similar to lavas and dolerites from Zabargad Island in the Red Sea Rift (*Petrini* et al., 1988). Basalts

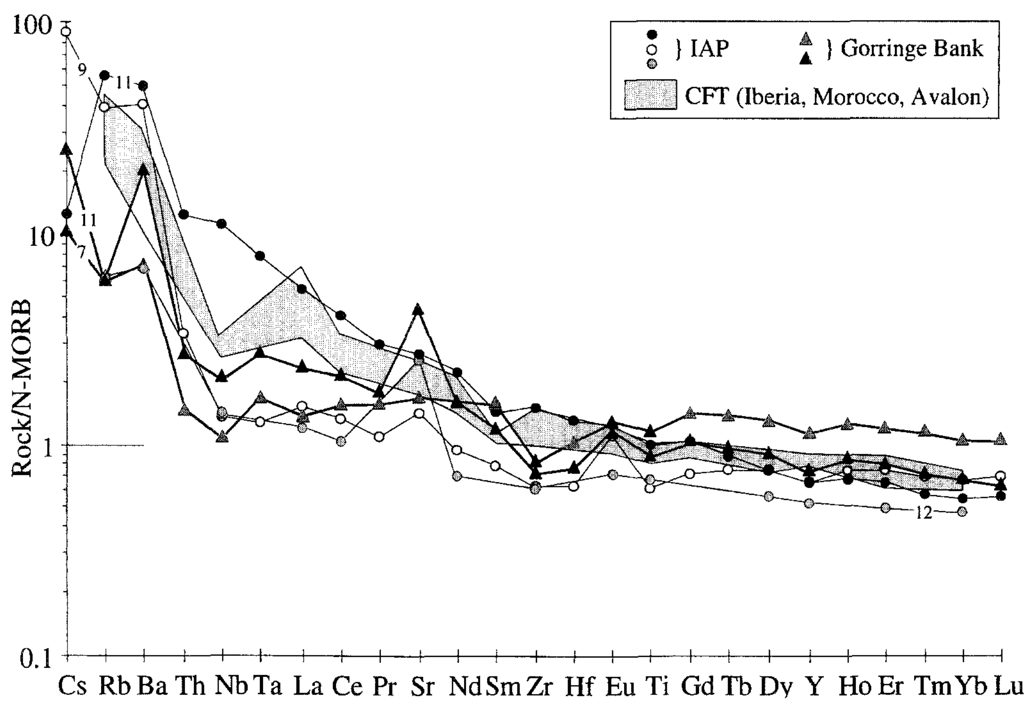

Fig. 10. N-MORB normalized trace elements diagram for selected representative basalts recovered in the IAP (numbers refer to analyses of Table 5) and Gorringe Bank (heavy lines, numbers refer to analyses of Table 6). The continental flood tholeiites (CFT) from Iberia, Avalon and Morocco (*Alibert*, 1985; *Papezik* and *Hodych*, 1980; *Bertrand* et al., 1982; *Sebai* et al., 1991) are plotted in the light shaded area. Normalization values of *Sun* and *McDonough* (1989)

from the IAP appear however HREE poorer (10 times less, Fig. 8). This combined with the ratios $(La/Sm)_N$ up to 2.4 and Lu/Hf up to 0.25, supports that some of the basalts derive from garnet-bearing mantle sources (*Fram* et al., 1998).

Gorringe Bank. High K_2O contents (up to 3.66%) related to moderate to high LOI (between 2 and 6%) underline the alteration of the basalts recovered at Gorringe Bank (Table 6, n° 7–11). They have primitive features owing to their Mg# between 60 and 72 and Ni content between 119 and 660 ppm. Their SiO_2 and TiO_2 content remains moderate (respectively 49–52% and 0.8–1.5%). Dolerites within the gabbros of Mt. Ormonde (eastward, Fig. 3) appear LREE depleted ($0.6 \leq La_N/Ce_N \leq 0.8$), while those of Mt. Gettysburg (westward) correspond to T-MORB ($0.9 \leq La_N/Ce_N \leq 1.1$) (Fig. 8). This T-MORB signature is confirmed by isotopic data and $\varepsilon Nd_{[120Ma]} = +5.06$ (Table 7). All of them exhibit a weak negative Nb anomaly (La/Nb = 1.22–1.38) which differentiates these basalts from those of the Galicia Bank and Iberia Abyssal Plain (Fig. 10). Negative Nb anomalies are documented in the 200 Ma continental tholeiites (Messejana dyke system in Iberia, Morocco and Avalon) (*Sebai* et al., 1991; *Alibert*, 1985; *Bertrand* et al., 1982; *Papezik* and *Hodych*, 1980) which, however, remain slightly more LREE enriched (Fig. 8).

Discussion

The alkaline veins (Galicia and Gorringe Bank) and the sheared 'MARID'-like pyroxenites (IAP) present in the peridotites document local metasomatic events of the mantle by melts enriched in incompatible elements. These high fO_2 examples of metasomatism are a common feature of subcontinental mantle and of mantle enriched by OIB melt.

The plagioclase-bearing websterites (Gorringe Bank and IAP) form layers that underwent the same evolution (shearing at about 1000 °C and ≤ 1 GPa, and reequilibration at about 700 °C in sub-solidus conditions) as their surrounding ultramafic rocks. They likely correspond to cumulates crystallized in the spinel zone from T-MORB melt en route, as already proposed for the Gorringe Bank websterite (*Serri* et al., 1988). Up to now, only one very small occurrence of similar pyroxenite, restricted to infra millimetric lenses in a unique sample of sheared lherzolite, has been reported to occur in deep transform faults of the Mid-Atlantic ridge (*Cannat* and *Seyler*, 1995). Another scale of development of plagioclase after Al-rich pyroxenes and spinel is clearly exposed by the IAP and Gorringe outcrops. These layers reach an extension comparable to those of Ronda, Pyrénées and Voltri known to be included in sub-continental peridotites (*Piccardo* et al., 1988b). Consequently, as well as the fertile lherzolites for the Galicia Bank, the pyroxenites of the IAP and the Gorringe Bank support the subcontinental mantle origin of their host peridotites.

All the gabbroic series examined are located near the top of the ultramafic units and, for Galicia Bank and IAP Site 900, probably at the contact with or close by the continental crust (*Boillot* et al., 1995; *Louden* et al., 1997). A part of these gabbros (the main part at IAP Site 900) was emplaced and subsequently sheared at a depth of about 24 km (or under 0.8 GPa) according to their phase compositions. The dating available (*Féraud* et al., 1988, 1996; *Schärer* et al., 1995) are compatible with an early emplacement, during continental rifting. Consequently, these gabbros were underplated. Following the same paths, new pulses of gabbroic magmas continue to be emplaced and to be sheared at lower pressures, presumably at the end of the thinning of the crust or immediately after its break-up. This is probably the case at the Galicia Bank and at the Gorringe Bank where pressures ≤ 0.6 GPa are documented. The shearing ended under greenschist facies conditions as widely documented in oceanic crust (*Mével*, 1988).

The chlorite-schists recovered in the IAP have flat REE patterns (Fig. 8) that perfectly fit those of leucogabbros or plagiogranites. At Galicia Bank their $\varepsilon Nd_{[122\,Ma]} = +5.6$ show their unlikely continental origin (*Schärer* et al., 1995). Their high LILE and REE concentrations (20–25 times chondritic) strongly suggest that they correspond to differentiated products of E-MORB magma. Similar progressive transformation during differentiation and shearing of gabbroic magmas has been clearly documented on continent in Morocco (*Essaifi* et al., 1995). In IAP, as in Galicia Bank, the chlorite-schists are considered to derive from gabbroic differentiates sheared, probably up to the end of the break-up episode, under low pressure. The cumulate origin and the very high content of HFSE of these chlorite schists ($Nb \approx 12.7$ ppm) underline the possibility of HFSE sinking within a shallow mantle environment.

All the lavas recovered on the Galicia Bank, in the Iberia Abyssal Plain and on the Gorringe Bank, are relatively 'primitive' basalts which correspond to transitional and enriched tholeiites; differentiated lavas have not been found. The basalts from Gorringe Bank, which are a little more LREE-depleted, bear a distinct negative Nb anomaly (Fig. 10). By comparison, the volcanic margin of East Greenland sampled during ODP Legs 152 and 163 at about 875 m depth, is composed of formerly sub-aerial basalts interspersed with differentiated lavas. In Fig. 11, the most recent basalts (upper series) of the East Greenland margin mimic exactly the N-MORB recovered at 35° N close to the MAR during Leg 82 (*Weaver* et al., 1985). The tholeiites from the lower series of East Greenland margin are considered as strongly contaminated by the continental crust (*ODP Leg 152 Shipboard Scientific Party*, 1994; *ODP Leg 163 Shipboard Scientific Party*, 1996). The two kinds of lavas (uncontaminated and contaminated) are clearly distinguished by their Zr/Nb and Ce/Y ratios, unaffected by fractionation but sensitive to both the crustal contamination and the melting depth and process (*Ellam* 1992). The contaminated lower series is shifted toward higher values of their La/Nb and Zr/Nb ratios (respectively up to 2.5 and to 115; Fig. 11) compared to the N-MORB of the upper series (*Fram* et al., 1998).

In the same figure, most of the basalts from the Iberian margin fit the mixing line of melts derived from both N-MORB and OIB mantle sources. However few of them, in particular those from Gorringe Bank which exhibit a negative Nb anomaly, plot above this mixing line. Although negative Nb anomalies (high La/Nb ratio) are well known in basalts from arc environments and common in continental flood tholeiites (CFT; *Arndt* et al., 1993; *Dupuy* and *Dostal*, 1984), such a depletion remains difficult to explain. Recent N-MORB are known to bear this anomaly on the MAR south of 33° N and north of 50° N, off the influence of main hotspots (*Bougault* et al., 1985). The basalts sampled in the West part of the Gorringe Bank

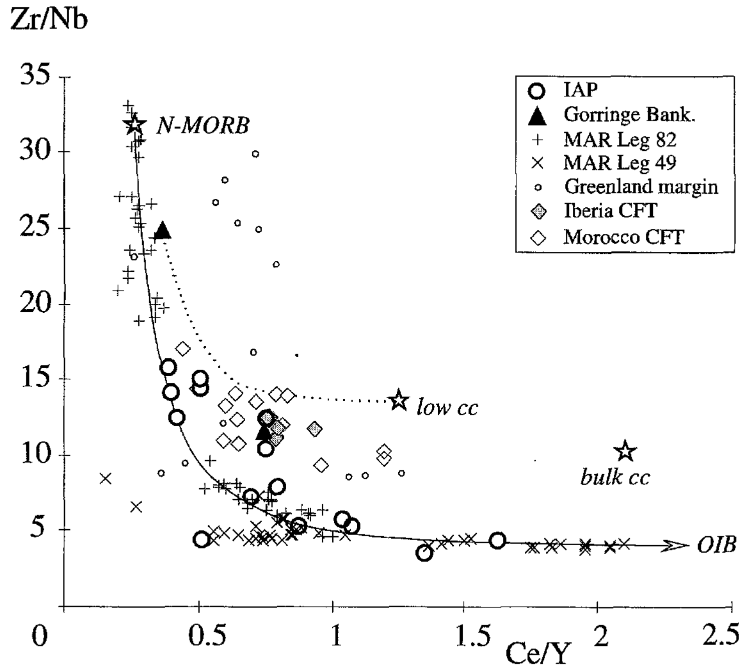

Fig. 11. Zr/Nb versus Ce/Y diagram for selected representative basalts from IAP (circles) and Gorringe Bank (triangle). MAR basalts data from *Tarney* et al. (1978) and *Weaver* et al. (1985); CFT: Messejana from *Alibert* (1985) and Morocco from *Bertrand* et al. (1982). N-MORB and OIB (Zr/Nb = 5.83 and Ce/Y = 2.76) end member from *Sun* and *McDonough* (1989). Lower and bulk continental crust (cc) from *Rudnick* and *Fountain* (1995). From the Greenland East margin only the basalts with Mg# > 60 of Site 917 and Site 988 are reported (*ODP Leg 152 & 163 Shipboard Scientific Parties*, 1994, 1996)

have La_N/Sm_N~1.2 and $\varepsilon Nd_{[120Ma]} = +5.06$ which clearly distinguish them from N-MORB (Table 7; Fig. 9). This εNd_T is exactly comparable to that of the onland Serra de Monchique alkaline complex, 70 Ma old. The shift of ~2 εNd units between this onland complex compared to the offshore Mt Ormonde alkaline complex, 67 Ma old, is related by *Bernard-Griffith* et al. (1997) to a lithospheric subcontinental mantle contaminant. It might be deduced also, from their position in figure 11, that the Gorringe Bank tholeiites and a few basalts of the IAP are comparable to the CFTs, the Nb anomalies and the low εNd_T of which are related to a contamination by continental crust (Fig. 9; *Arndt* et al., 1993). In the case of IAP and of Gorringe Bank, such a contamination would imply a delamination of lower continental crust inside the mantle section during the stretching process. At the present time, such continental crust remnants have not been identified in the IAP while at the Gorringe Bank the xenolithic occurrence described in the eastern part of Mount Ormonde by *Al'mukhamedov* et al. (1991) needs obviously further investigations. On the other hand, the basalts recovered in the three transects frequently bear low to moderate amounts of primary hydrated minerals which is unusual in true MORB. As already envisaged by *Arai* et al. (1997), basaltic melt circulating through thin conduits in an oxidized mantle are able to cristallize Ti-rich minerals such as phlogopite, kaersutite and rutile by an effect of melt/wall

Table 7. *Isotope data obtained on the dolerite (77CY12-6; bulk rock) sampled on the West tip of the Gorringe Bank at 1300 m depth, by 36°36′14 Lat N and 11°39′57 Long W. Initial* $^{87}Sr/^{86}Sr$ *and* $^{143}Nd/^{144}Nd$ *are based on a 120 Ma age* (Féraud *et al. 1982). Analyst* J. Bernard-Griffiths *(Géosciences Rennes, UPR4661 CNRS). Analytical procedures are detailed in* Bernard-Griffiths *et al. (1997)*

dolerite	Rb ppm	Sr ppm	$^{87}Sr/^{86}Sr$	Sm ppm	Nd ppm	$^{143}Nd/^{144}Nd$	εNd_0	εNd_{120Ma}
77CY12-06	3.4	282.1	0.70484	2.9	10.5	0.512875	4.6	5.06

interaction. These minerals, known to drastically sink Nb, Ta, and, if joined with apatite, to decrease $(La/Sm)_N$ and Ce/Y ratios in residual melts (*Irving* and *Frey*, 1984; *Ionov* and *Hofmann*, 1995) offer another explanation for such Nb-anomalies. Ti-rich cumulates within shallow peridotites like rutile-bearing pyroxenite sampled in the IAP could be representative of such Nb-repositories.

Conclusions

1. The ultramafics occurring on NS ridges along the West Iberian margin display compositions changing from fertile lherzolite in the North on the Galicia Bank, to harzburgite southward, in the IAP and on the Gorringe Bank. All these peridotites are veined locally by plagioclase- and spinel-rich pyroxenites and by few alkaline cumulates. They correspond to subcontinental mantle stripped at a very low rate which may explain the limited amount of magmatic rocks emplaced.
2. In the IAP and on the Galicia Bank, some of the gabbros emplaced near the top of the ultramafics were underplated and sheared at about 24 km depth, i.e. during continental rifting. At shallower depths and probably later in the rifting process, few subsequent magma pulses underwent differentiation and hydration. According to their trace elements and isotope signatures, the gabbros originate from heterogeneous mantle sources.
3. The basalts which intrude and cover the serpentinized ultramafics are post-rift extrusives. Their features change slightly from one transect to another. Basalts are dominantly enriched and transitional tholeiites at the Galicia Bank and the IAP, and transitional to depleted ones at the Gorringe Bank. They show compositions compatible with the gabbros (and likely the pyroxenites) previously emplaced and share with them a few common Nd isotope signatures. At the scale of the transects studied (200 km maximum) only the northern one (Galicia Bank) presents an evolution of the magmatic sources in relation with time. This evolution is related by *Charpentier* et al. (1998) to a decreasing melt-contribution of an enriched sub-continental lithospheric mantle. As a whole, the magmatic rocks examined may only be considered as the result of the mixing of melts from depleted (N-MORB) and enriched (OIB) mantle sources. These melt would occasionally be contaminated through delaminated subcontinental lithospheric mantle possibly including lower continental crust remnants.
4. The formation of the entire West Iberian margin is well accounted for by a schematic process of lithospheric stretching compatible with the northward

opening of the Atlantic ocean. It involves three successive steps which comprise: **A** – the production and the underplating of small amounts of magmas while an heterogeneous subcontinental mantle is passively thinned and very slowly uplifted. This stage is sealed 143 Ma ago at the Gorringe Bank (crystallization of euhedral high T amphibole in ferrogabbros), it remains poorly constrained in the IAP, and it takes place 122 Ma ago at the Galicia Bank (crystallization of high T amphibole in diorites and of magmatic zircon included in chlorite schists; *Féraud* et al., 1986, 1988; *Schärer* et al., 1995). This interval documents a northward propagation of the ocean opening at a mean rate of about 3.5 cm/year; **B** – the shearing and the unroofing of both the mantle and the underplated rocks and their increasing hydration while the ocean window enlarged. This stage is registered up to 110 Ma at the Gorringe Bank (recrystallized plagioclases and low PT amphiboles of the sheared gabbros), at 136 Ma at the IAP (recrystallized plagioclases of the flaser gabbros), and up to 118 Ma at the Galicia Bank (recrystallized plagioclases of the diorites; *Féraud* et al., 1982, 1996); **C** – the outpouring of low amounts of basalts on the serpentinized peridotites 120 Ma and 100 Ma ago, respectively at the Gorringe Bank and at the Galicia Bank (the age remains indefinite in the IAP; *Féraud* et al., 1982; *Charpentier* et al., 1998). These dates and the estimation of the (half) width of the oceanic window created, allow a broad estimation of 5 mm/year half rate spreading in the IAP (*Pickup* et al., 1996) and of 8 mm/year at the latitude of Gorringe Bank. The true oceanic accretion is presumed to begin westward with the Tore-Madeira ridge and the M0-J anomaly.

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