The rift-to-drift transition in the North Atlantic:  
A stuttering start of the MORB machine?

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ABSTRACT

We report U-Pb and 40Ar-39Ar measurements on plutonic rocks recovered from the Ocean Drilling Program (ODP) Legs 173 and 210. Drilling revealed continental crust (Sites 1067 and 1069) and exhumed mantle (Sites 1070 and 1068) along the Iberia margin and exhumed mantle (Site 1277) on the conjugate Newfoundland margin. Our data record a complex igneous and thermal history related to the transition from rifting to seafloor spreading. The results show that the rift-to-drift transition is marked by a stuttering start of MORB-type magmatic activity. Subsequent to initial alkaline magmatism, localized mid-oceanic ridge basalt (MORB) magmatism was again replaced by basin-wide alkaline events, caused by a low degree of decompression melting due to tectonic delocalization of deformation. Such “off-axis” magmatism might be a common process in (ultra-) slow oceanic spreading systems, where “magmatic” and “tectonic” spreading varies in both space and time.

Keywords: Ocean-Continent transition, MORB, rifting, magma-poor margins, age determinations.

INTRODUCTION

It is generally accepted that rupturing of continents is followed by localized seafloor spreading at mid-oceanic ridges (MOR), which are considered, on geological time scales, to be symmetric and steady state. The continuity of this process is documented by the correspondence of crustal accretion ages (dated by magnetic anomalies) and isotopic ages. While these processes are well studied at present-day MOR, little is known about how stable these systems are during their embryonic stage. Even though our understanding of the mechanisms associated with extension and rifting of continents has improved in the last decade (Whitmarsh et al., 2001), the processes that ultimately start the MOR basalt (MORB) machine and the switch from rifting (delocalized deformation) to spreading (localized deformation and accretion) are still poorly constrained. A striking discovery of ODP drilling along the Iberia-Newfoundland conjugate margins was the scarcity of effusive magmatism and only minor volumes of intrusive rocks in areas with weak magnetic anomalies (Sibuet et al., 2007). In this paper, we present new U-Pb and 40Ar-39Ar measurements across the conjugate Iberia-Newfoundland margins to document the magmatic and retrograde history of igneous rocks related to the final rifting and onset of seafloor spreading in the North Atlantic. The data show that the initiation of magmatic seafloor spreading is more complex than previously anticipated and is transitional in time and space.

THE IBERIA-NEWFOUNDLAND RIFTED MARGINS SYSTEM

The conjugate, magma-poor Iberia-Newfoundland rifted margins resulted from polyphase Late Triassic to Early Cretaceous rifting and separation of the North America and Iberia plates. Rifting migrated from proximal to distal parts of the future margin, leading to fault-bounded basins and local thinning of the crust to less than 10 km before final breakup (Whitmarsh et al., 2001). The Iberia-Newfoundland margins are the only example of rifted margins where scientific drilling has sampled basement rocks from the Ocean-Continent Transition (OCT). The 18 sites drilled during Deep Sea Drilling Project (DSDP) Leg 47B and ODP Legs 103, 149, 173, and 210, combined with a relatively dense geophysical data set, document the existence of a Zone of Exhumed Continental Mantle (ZECM) up to 200 km wide, which separates thinned continental crust from oceanic crust. Based on magnetic analyses and refraction studies (e.g., Russell and Whitmarsh, 2003; Lau et al., 2006), crust oceanward of the first unambiguous magnetic anomaly (M3, ca. 128 Ma; Gradstein et al., 2004) is generally referred to as oceanic. However, based on its proximity to the continental margins and its highly variable basement structure (Tucholke et al., 2004), we refer to it in this paper as embryonic oceanic crust, to emphasize the difference from “normal” slow-spreading oceanic crust.

Due to the polyphase evolution of rifting, subdued magmatic activity, and poorly constrained magnetic anomalies, the age of final breakup and the onset of seafloor spreading between Iberia and Newfoundland are debated. Based on the first undisputed oceanic magnetic anomaly, M3, Whitmarsh and Miles (1995) suggested a Barremian age (128 Ma), whereas Tucholke et al. (2007) and Péron-Pinvidic et al. (2007) proposed a late Aptian to earliest Albian age (ca. 112 Ma), based on drilling results and seismic stratigraphic arguments.

EMBRYONIC OCEANIC CRUST DRILLED AT ODP SITES 1070 AND 1277

Embryonic oceanic crust was drilled at a basement high near magnetic anomaly M1 at Site 1070 on the Iberia margin and at a basement high a few kilometers oceanward of magnetic anomaly M1 at Site 1277 on the Newfoundland margin. The locations of both sites, relative to seafloor spreading magnetic anomalies, suggest a similar crustal accretion age of ca. 127 Ma (Fig. 1).

At Site 1070, drilling penetrated tectonic breccias with gouge horizons grading downhole into massive serpentinitized peridotite intruded by an E(nriched)-MORB–derived pegmatitic hornblende gabbro (Hébert et al., 2001; Beard et al., 2002) (see Fig. DR1 in the GSA Data Repository1). A breccia overlying the pegmatite consists of serpentinite and rare gabbro and albite clasts. Sediments immediately on top are Late Aptian (Whitmarsh et al., 1998).

At Site 1277, drilling penetrated a 40-m-thick, volcanic-sedimentary unit composed of three basalt flows with a T-(transitional) to N(normal)-MORB composition (Tucholke et al. 2004) interlayered with debris flows and sandstones that are separated from the underlying basement by a tectonic contact (see Fig. DR1). Clasts in the sediments are composed of serpentinitized peridotites and gabros identical to rocks forming the underlying basement.

1GSA Data Repository item 2007270, analytical methods, tabulated and illustrated results, and a stratigraphic column indicating sample locations of Sites 1277 and 1070, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Although the breccias have not been dated, it has been suggested that they were deposited during or directly after accretion of the basement (Péron-Pinvidic et al., 2007). The Site 1277 basement consists of strongly altered serpentinitized harzburgite with a high-temperature mylonitic foliation and igneous veins. Based on the mineralogical composition of the magmatic products (clasts and veins) drilled at Site 1277, alkali rocks (characterized by phlogopite, albrite-rich feldspar, monazite, zircon, apatite, orthoamphibole, rutile, and ± xenotime) can be distinguished from MORB-derived rocks (characterized by plagioclase, clin-o-, orthopyroxene, ilmenite, and Ti-hornblende) (Müntener and Manatschal, 2006). However, small sample volumes (<1 cm³), coupled with the coarse-grained mineralogy (~0.5 cm), impede meaningful geochemical whole-rock characterizations.

Age Constraints for Magmatic and Post-Breakup Evolution

To shed light on the magmatic and thermal history of the embryonic-oceanic crust of the juvenile North Atlantic ocean basin, we dated several gabbroic clasts and veins from the embryonic oceanic crust (ODP Sites 1070 and 1277) and from the Iberia distal margin (ODP Sites 1067, 1068, and 1069) using U-Pb dating of zircons by sensitive high-resolution ion microprobe (SHRIMP) and ⁴⁰Ar-³⁹Ar techniques on hornblende, phlogopite, muscovite, and plagioclase mineral separates. ³⁹Ar-³⁹Ar measurements were conducted at the Institute of Geological Sciences at University of Bern, and at the Lamont-Doherty Earth Observatory. Details of the analytical techniques and results are presented as electronic supplement.

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RESULTS

Age Constraints from the Distal Margin (Sites 1067, 1068, and 1069)

A maximum age for the deformation leading to continental breakup is given by tilted Tithonian sediments (ca. 145 Ma) deposited over thinned continental crust drilled at Sites 901, 1065, and 1069 (Wilson et al., 2001). Devonian ³⁹Ar-³⁹Ar muscovite ages (361.5 ± 0.5 Ma; see Fig. DR1) separated from a conglomerate clast that was recovered at Site 1069 indicate no significant resetting of muscovite Ar ages during breakup. Jurassic ³⁹Ar-³⁹Ar ages (see Fig. DR1) of hornblende (167.3 ± 0.9 Ma, 164.6 ± 0.5 Ma, 160.5 ± 0.8 Ma, and 152.6 ± 0.9 Ma) and plagioclase (141.8 ± 0.4 Ma) were obtained from amphibolites drilled at Site 1067. Our results on plagioclase are slightly older than those from gabbro clasts drilled at Site 900 (136.4 ± 0.3 Ma; Féraud et al., 1996). Amphibolite clasts from Site 1068 yield hornblende ³⁹Ar-³⁹Ar ages of 140 ± 2 Ma and 131.7 ± 1.1 Ma and a plagioclase age of 133.1 ± 0.3 Ma.

Age Constraints from the Embryonic Oceanic Crust

Site 1070

Kaersutitic hornblende, separated from an E-MORB-derived gabbroic pegmatite analyzed at the University of Bern, yielded a ³⁹Ar-⁴⁰Ar age of 123.9 ± 1.2 Ma, statistically indistinguishable from the result from the Lamont laboratory (124.2 ± 0.7 Ma). Strongly altered plagioclase separates analyzed from the same sample in Bern yield a poorly constrained age of 101 ± 5 Ma, whereas samples analyzed by Lamont yield less-rejuvenated and better-constrained plagioclase ages (116.9 ± 0.8 Ma, 115.7 ± 0.3 Ma, and 111.0 ± 0.3 Ma). U/Pb dating on zircons from albite clasts overlying the pegmatite yields an age of 127 ± 4 Ma, interpreted as a crystallization age (Beard et al., 2002).

Site 1277

Igneous zircons from a hornblende gabbro dike yielded an intrusion age of 113.2 ± 2.1 Ma (95% confidence interval). A plagioclase separate from a different alkaline gabbroic dike yielded a ³⁹Ar-⁴⁰Ar age of 128 ± 3 Ma.

Plagioclase separates from four different brecciated, MORB-derived gabbroic clasts, present within mass flows found on top of the serpentinitized mantle and within the volcano sedimentary units, yielded well-constrained, albeit variable, ³⁹Ar-³⁹Ar ages (91.6 ± 0.3 Ma, 76.1 ± 0.4, 69.1 ± 1.1 Ma, and 69.3 ± 2.1 Ma).

DISCUSSION

Based on assumptions outlined in Figure DR1, we interpret our U-Pb zircon and ³⁹Ar-³⁹Ar hornblende and biotite ages to date several discrete phases of alkaline and MORB-type magmatism at Sites 1277 and 1070, and ³⁹Ar-³⁹Ar plagioclase ages date a prolonged retrograde history. The temporal and spatial distribution of the various magmatic and retrograde events is summarized in Figure 2.

Maggmatic Activity within an Embryonic Magma-Poor Oceanic Crust

The onset of embryonic oceanic crust formation is accompanied (or triggered?) by alkaline magmatism documented at Site 1277. A phlogopite ³⁹Ar-⁴⁰Ar age yields a minimum age for this alkaline episode of 128 ± 3 Ma, closely corresponding to the crustal accretion age of Site 1277. A contemporaneous magmatic event is documented on the Iberia margin at Site 1070 by the U-Pb age of a single zircon (127 ± 4 Ma) separated from a biotite-bearing albite clast.

Figure 2: Illustration of spatial and temporal relationship of various events along Newfoundland-Iberian margin. Symbol color code: orange and blue are alkaline and MORB-type igneous events, respectively. Black symbols are rejuvenated ages (see text for details). Post-Albian alkaline events and contemporaneous plagioclase rejuvenation ages are tentatively grouped in “basin-wide” events (transparent brown). Illustrating the possibility of repetitive, basin-wide alkaline events. Data from literature are the same as cited in Figure 1, and from Merle et al. (2006) and Schärer et al. (2000).
Retrograde History

Structural and sedimentary evidence constrains erosion and sedimentation of gabbro clasts at ODP Sites 1070 and 1277 to be older than 112 Ma (Aptian/Albian boundary) (Péron-Pinvidic et al., 2007). The plagioclase 39Ar-40Ar ages of these rocks are substantially younger, ranging from 116 Ma to ca. 101 Ma at Site 1070 and as young as ca. 69 Ma at Site 1277. The non-systematic age distribution with sample depth (see Fig. DR1) implies that the ages do not reflect regional cooling, nor are they related to the proximity of basaltic flows. Instead, the local difference in ages requires a sample-specific control on the meter scale on Ar exchange in plagioclase. Because fluid-induced recrystallization has a dominant effect on Ar exchange (Villa, 2006), we propose that the plagioclase 39Ar-40Ar ages record the termination of recrystallization, i.e., the end of hydrothermal activity. We emphasize that plagioclase 39Ar-40Ar ages within the oceanic realm cannot, a priori, be linked to regional exhumation and associated cooling.

Our measurements document rejuvenated 39Ar-40Ar plagioclase, which overlaps Upper Cretaceous alkaline magmatism, thus affecting the Newfoundland and Iberian margin (Schärer et al., 2000; Hart and Blusztajn, 2006; Merle et al., 2006) (Fig. 2).

A Plume Origin of Alkaline Magmatism in the North Atlantic?

One hypothesis to explain the prolonged and heterogeneous igneous history recorded at Sites 1277 and 1070 involves the passage of mantle plumes (Duncan, 1984; Hart and Blusztajn, 2006; Merle et al., 2006). An alternative hypothesis relates Cretaceous volcanism in Newfoundland to decompression melting along reactivated faults (Pe-Piper et al. 1994). Based on currently available data, none of these hypotheses can be excluded. However, several lines of evidence are not in accordance with the plume hypothesis. Alkaline sills at Site 1276 and from the Southern Grand Banks in Canada show an isotopic signature that is different from the known Atlantic hotspot system (Pe-Piper et al., 1994; Hart and Blusztajn, 2006). The age distribution observed at Madeira-Tore rise (Merle et al., 2006) does not favor a simple passing plume-head model. The similar magmatic histories at Sites 1070 and 1277 (Fig. 2) for at least 15 myr after onset of magmatic activity suggest a common process on either side of the proto–mid-Atlantic ridge. Assuming conservative average full spreading rates of ca. 10–20 mm/a (Sibuet et al., 2007), seafloor spreading would have separated these two localities by ~150–300 km. Although plume-head radii are considered to range between 200 and 1000 km, the small volume of igneous rocks in this part of the Atlantic does not favor plume activity prevailing for more than 15 myr. Finally, the alkaline magmatic event at 113.2 ± 2.1 Ma is contemporaneous with a basin-wide, delocalized, extensional morpho-tectonic event, recorded in the sedimentary architecture in the Iberia-Newfoundland margins (Péron-Pinvidic et al., 2007; Tucholke et al., 2007). Accordingly, we propose an alternative hypothesis to explain the revival of intra-plume alkaline magmatism.

A CONCEPTUAL MODEL FOR EMBRYONIC MAGMA-POOR SEAFLOOR SPREADING

The early alkaline magmatism (ca. 128 Ma), followed by younger (>124 Ma) E-MORB-type magmatism, can be explained by an low degree of melting of (fertile?) mantle. However, alkaline magmatism occurred ca. 15 m.y. later, at the same time as a regional-scale morpho-tectonic event that affected the two conjugate margins at the Apt-Albian boundary. We propose that during juvenile, ultra-slow spreading, melt supply along the Atlantic proto-ridge was subdued, and mantle exhumation was the dominant process. This magma-starved embryonic ocean crust accumulated in-plane stresses during further extension (Tucholke et al., 2007). Sudden
stress release triggers “tectonic spreading” episodes that are characterized by the distribution of extensional deformation away from the proto-ridge over previously accreted embryonic-oceanic crust, which resulted in the observed tilted blocks in Newfoundland and Iberia (Péron-Pinvidic et al., 2007; Tucholke et al., 2007). Associated low-degree decompression melting results in off-axis magmatism (Fig. 3). Our rejuvenated 39Ar-40Ar plagiozome ages are roughly contemporaneous with documented alkaline magmatism (Fig. 2). Although highly speculative, this basin-wide correlation between magmatic events and hydrothermal rejuvenation might imply that basin-wide, off-axis thermal pulses associated with alkaline magmatism are not uncommon in the northern Atlantic.

We speculate that “tectonic spreading” phases are rather short-lived, isolated events intervening between periods of “normal” igneous accretion on a timescale probably beyond the resolution of magnetic anomalies.

Several studies pointed out that the low magmatic flux along MOR is commonly associated with the formation of amagmatic segments at ultra-slow spreading rates (<20 mm/yr) (Dick et al., 2003). Our observations suggest that the delocalization of deformation is not restricted to the vicinity of MORs (tens of km), but might be distributed over much larger areas (>100 km), locally triggering off-axis volcanic phenomena as recorded from fast- (Zou et al., 2002) and slow-spreading systems (Meyer et al., 1996).

We conclude that off-axis, low-degree mantle melting is not necessarily related to plume activity, but might be coupled with low-melt productivity on axis associated with ultra-slow spreading rates, which by itself might be related to “tectonic” spreading. Alkaline magmatism observed at basement highs (Site 1277, this study; Madeira-Tore rise, Schärer et al., 2000; Geldmacher et al., 2006) might be reconciled with a non–steady-state mantle transition of the Iberia-Newfoundland rift and associated magnetic anomalies: Journal of Geophysical Research, v. 112, p. n/a-p.n/a.

CONCLUSIONS
U-Pb SHRIMP data and 39Ar/40Ar data demonstrate multiple episodes of magmatism along the Iberia-Newfoundland rift system variably being between alkaline and E-N MORB. Our results provide a mechanism to explain how substantially younger, off-axis alkaline magmatism might be reconciled with a non–steady-state MORB engine. Our new data suggest that the transition from rifting to magmatic seafloor spreading is not a well-defined event but, rather, is transitional, and occurred over a period of time lasting from Barremian to end-Aptian, i.e., over ~15 Myr.

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