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Geochemistry of a long in-situ section of intrusive slow-spread oceanic lithosphere: Results from IODP Site U1309 (Atlantis Massif, 30°N Mid-Atlantic-Ridge)

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ABSTRACT

IODP Site U1309 was drilled at Atlantis Massif, an oceanic core complex, at 30°N on the Mid-Atlantic Ridge (MAR). We present the results of a bulk rock geochemical study (major and trace elements) carried out on 228 samples representative of the different lithologies sampled at this location.

Over 96% of Hole U1309D is made up of gabbroic rocks. Diabases and basalts cross-cut the upper part of the section; they have depleted MORB compositions similar to basalts sampled at MAR 30°N. Relics of mantle were recovered at shallow depth. Mantle peridotites show petrographic and geochemical evidence of extensive melt–rock interactions. Gabbroic rocks comprise: olivine-rich troctolites (>70% modal olivine) and troctolites having high Mg# (82–89), high Ni (up to 2300 ppm) and depleted trace element compositions (Yb 0.06–0.8 ppm); olivine gabbros and gabbros (including gabbronorites) with Mg# of 60–86 and low trace element contents (Yb 0.125–2.5 ppm); and oxide gabbros and leucocratic dykes with low Mg# (<50), low Ni (~65 ppm) and high trace element contents (Yb up to 26 ppm). Troctolites and gabbros are amongst the most primitive and depleted oceanic gabbroic rocks. The main geochemical characteristics of Site U1309 gabbroic rocks are consistent with a formation as a cumulate sequence after a common parental MORB melt, although (lack of systematic) downhole variations indicate that the gabbroic series were built by multiple magma injections. In detail, textural and geochemical variations in olivine-rich troctolites and gabbronorites suggest chemical interaction (assimilation?) between the parental melt and the intruded lithosphere.

Site U1309 gabbroic rocks do not represent the complementary magmatic product of 30°N volcanics, although they sample the same mantle source. The bulk trace element composition of Site U1309 gabbroic rocks is similar to primitive MORB melt compositions; this implies that there was no large scale removal of melts from this gabbro section. The occurrence of such a large magmatic sequence implies that a high magmatic activity is associated with the formation of Atlantis Massif. Our results suggest that almost all melts feeding this magmatic system stays trapped into the intruded lithosphere.

1. Introduction

Slow and ultra-slow spreading ridges (<55 mm/yr full spreading rate) represent the most common modern ridge system (about half of the ~67,000 km long volcanic ridge system (Solomon, 1989; Bird, 2003)). Currently available data support hypotheses where magmatic dominated phases of rifting alternate with tectonically dominated extension (e.g., (Thatcher and Hill, 1995; Lagabrielle et al., 1998; Buck et al., 2005)), although the architecture of the oceanic crust produced

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in these environments, in particular in its deeper parts, is still poorly constrained. Seafloor sampling along axial zones and median valley walls show that slow spreading centres expose upper mantle rock and lesser gabbro in the axial zone. In some ultra-slow spreading areas, however, seafloor gabbro has not been sampled and basalt is found in proximity to altered peridotite (Dick et al., 2003; Standish et al., 2008). These seafloor exposures have been interpreted as evidence that part of the magmatism is intrusive and that the lithosphere is heterogeneous (Cannat, 1996). This model differs from the layered architecture suggested for intermediate to fast spread oceanic lithosphere i.e., an oceanic igneous crust comprising (from top to bottom) Mid-Ocean Ridge Basalts (MORB), sheeted dykes and gabbros, which overlies residual mantle peridotites. The mechanisms by which occurs the differentiation of primary MORB magmas (produced by mantle partial melting (Herzberg et al., 2007)) and how the magmatic intrusions are incorporated into the slow spread lithosphere remain largely unknown because of lack of data on the structure and composition of the deeper parts of oceanic lithosphere.

Deep drilling is technically challenging but it remains the only way of documenting long continuous sections of present-day oceanic lithosphere. Long-lived oceanic detachment faults, which are interpreted as characterizing tectonically-dominated rifting (Tucholke et al., 1998; Lavier et al., 1999), are inferred to expose the deepest parts of the oceanic crust (Cann et al., 1997; Escartin et al., 2003; Blackman et al., 2004). Detachment faulting close to fracture zones can proceed to a stage where a large and shallow domal structure forms an inside corner high, sometimes called megamullion or oceanic core complex (OCC). Because of these unique features, OCCs have been favored as targets for deep drilling of slow spread lithosphere. Currently, four OCCs have been drilled in the frame of Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP): the deepest hole was drilled at Atlantis Bank, on the South West Indian Ridge (ODP Hole 735B – 1500 m deep – (Dick et al., 2000)), and the three others are located on the Mid-Atlantic Ridge (MAR). The MARK (23°32′N — Sites 921–924) and MAR 15°44′N (Site 1275) areas were drilled down to ~82 and 209 m below seafloor (mbsf) respectively, during ODP Legs 153 and 209 (Cannat et al., 1995; Kelemen et al., 2004). The last location, Atlantis Massif (Fig. 1), was drilled during IODP Expeditions 304/305 (Blackman et al., 2006) at Site U1309, which is the object of this communication.

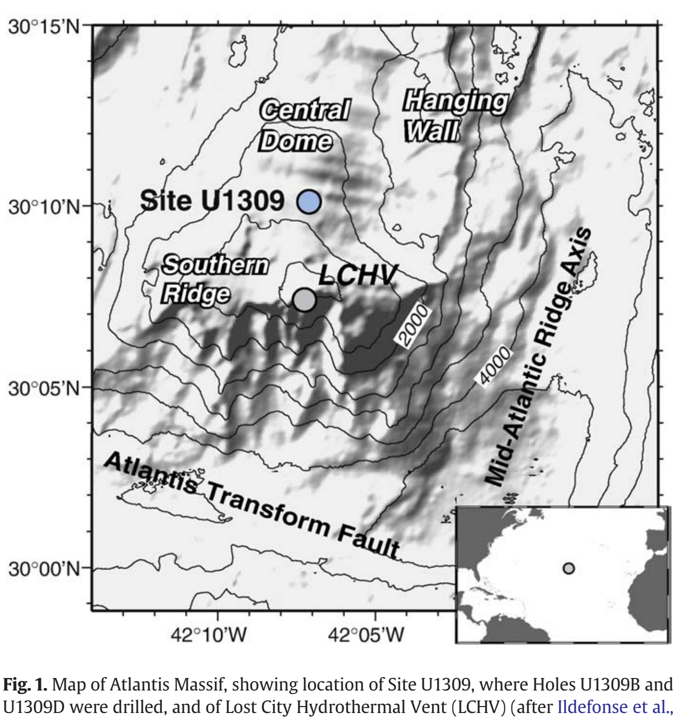

Fig. 1. Map of Atlantis Massif, showing location of Site U1309, where Holes U1309B and U1309D were drilled, and of Lost City Hydrothermal Vent (LCHV) (after Ildefonse et al., 2007).

We carried out a geochemical study (major and trace elements) of 228 samples representative of the different lithologies sampled at Site U1309. Our results allow documenting the bulk composition and downhole variations at Hole U1309D and provide new insights into the nature of the slow spread lithosphere, magmatic differentiation and melt/rock interactions within gabbroic intrusions and the intruded mantle lithosphere.

2. Geological setting

Atlantis Massif is located at 30°N on the west side of the MAR axial valley at the intersection with the Atlantis fracture zone; it extends ~15 km N–S, parallel to the ridge, and 8–10 km parallel to spreading direction, and was formed during the past 1.5–2 m.y (Blackman et al., 2006). The massif is dominated by variably serpentinized peridotite at the surface (Blackman et al., 2004). On the northeastern part of the massif, the hanging wall, a basaltic block, is in contact with the footwall (core) of the detachment fault. The southern ridge shallows up to 700 m below sea level (mbsl); it hosts the H_2-generating low temperature Lost City hydrothermal field (Kelley et al., 2001; Früh-Green et al., 2003).

Site U1309 is located on the central part of the massif where the seafloor coincides with what is interpreted to be a gently sloping, corrugated detachment fault surface (Fig. 1). During IODP Expeditions 304/305 (Blackman et al., 2006), two deep holes located at ~20 m from each other were drilled at this site: Hole U1309B (30°10.11′N, 42°07.11′W; 1642 mbsl), a single-bit pilot hole, and Hole U1309D (30°10.12′N, 42°07.11′W; 1645 mbsl) were drilled down to 101.8 mbsf and 1415.5 mbsf respectively (Fig. 2). The upper 20.5 m of Hole U1309D was not cored; it was cased to provide stable reentry for a deep hole. A total of 46.8 m of core was recovered at Hole U1309B and 1043.3 m at Hole U1309D, with an overall average recovery of, respectively, 46% and 75% (the upper 20.5 m of Hole U1309D excluded). Hole U1309D is the second deepest hole drilled into slow spread lithosphere.

3. Methods

The primary mineralogy (igneous modes, grain size and textures), alteration and structure of the core were described on-board (Fig. 2), on both hand samples (Visual Core Description —VCD-) and thin sections (74 thin sections were made from Hole U1309B samples and 632 at Hole U1309D). Detailed VCD and thin section descriptions are provided in Expeditions 304/305 Proceedings (Blackman et al., 2006). A total of 62 and 770 igneous units were defined at Hole U1309B and Hole U1309D respectively. Each unit is distinguished on the basis of igneous contacts and variations in primary modes and grain size.

243 samples, representative of the drilled material, were chosen for geochemical analysis onboard of the drillship Joides Resolution by Expeditions 304/305 scientific party. Thin sections were made wherever a geochemistry sample was taken. Due to the high petrographic variability of the core, even at the scale of a single igneous unit, the rock-names of the geochemistry samples were determined on the basis of the detailed descriptions of these thin sections and not only using the VCD. Loss on Ignition (LOI) was determined on each sample. Inductive coupled plasma atomic emission spectroscopy (ICP-AES) was used for determining major and some trace element (Sr, V, Cr, Co, Ni, Cu, Sc, Y, Zr, Ba and Nb) concentrations and gas chromatography for H_2O and CO_2. The sample preparation procedure (which involved grinding in a shatterbox with a tungsten carbide —WC- barrel), ICP-AES and gas chromatography analytical techniques (including accuracy and precision) and results are reported in Blackman et al. (2006).