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The temporal and spatial distribution of magmatism during lower crustal accretion at an ultraslow-spreading ridge: High-precision U–Pb zircon dating of ODP Holes 735B and 1105A, Atlantis Bank, Southwest Indian Ridge

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ABSTRACT

Ocean Drilling Program Hole 735B at Atlantis Bank on the Southwest Indian Ridge sampled 1508 m of plutonic oceanic crust, hosted in the footwall of an oceanic detachment fault. We present new high-precision isotope dilution-thermal ionization mass spectrometry (ID-TIMS) U–Pb zircon dates from samples spanning the length of Hole 735B, and from the shallower adjacent Hole 1105A (158 m). The new dates provide the most complete and precise record of both the spatial and temporal distribution of magmatism during accretion of the lower oceanic crust to date. Whole rock and mineral geochemistry from Hole 735B define three main igneous series. Weighted mean $^{206}Pb/^{238}U$ dates suggest each igneous series intruded beneath the preceding series. Weighted mean $^{206}Pb/^{238}U$ dates range from 12.175 to 11.986 Ma in Series 1; 11.974 to 11.926 Ma in Series 2; and 11.936 to 11.902 Ma in Series 3 (±0.015 to 0.069 Ma). Weighted mean $^{206}Pb/^{238}U$ dates from Hole 1105A range from 11.9745 to 11.9573 Ma (±0.0082 to 0.0086 Ma). The Hole 1105A dates are coeval with Series 2 in Hole 735B, consistent with previous correlations of Fe-Ti oxide-rich layers between the two holes, suggesting individual magmatic series formed sheet-like bodies that were ≥250 m thick and extended ≥1.1 km parallel to the ridge axis (E–W) and ≥0.48 km in the spreading direction (N–S). The data suggest a total duration of magmatism in Hole 735B of ≥0.214 ± 0.032 Ma, corresponding to accretion over a horizontal distance of ≥2.6 ± 0.4 km. The crust at Atlantis Bank was formed during active detachment faulting, and the successive underplating of each magmatic unit may have been favored in this environment. The combined U–Pb dates, and reported Ti-in-zircon temperatures, are consistent with magmatic cooling rates of 10^3–10^4 °C/Ma over the temperature interval of 900–700 °C.

1. Introduction

Early models of crustal accretion at slow- and ultraslow-spreading ridges focused on crust generated during symmetric or near-symmetric plate spreading. Nisbet and Fowler (1978) suggested that slow-spread crust is generated by repeated intrusion of small magma batches along the ridge axis from melts ponding at the base of the crust (the 'infinite leek'). In another widely cited model, Sinton and Detrick (1992) combined geophysical, geochemical and petrologic constraints to argue that slow-spreading ridges are underlain by vertical mush zones, and that the lower crust is formed by the repeated intrusion of interconnected sills.

An increasing body of evidence now indicates that there may be two distinct forms of crustal accretion at slow- and ultraslow-spreading ridges: symmetric and asymmetric accretion (Escartin et al., 2008; John and Cheadle, 2010; Smith et al., 2006). During asymmetric accretion, the majority of plate motion is taken up by oceanic detachment faulting, where convex upward normal or detachment faults cut from the sea floor to below the ridge axis. The surficial expression of detachment faulting is the formation of oceanic core complexes; domal exposures of lower crust and upper mantle exposed on the sea floor, and interpreted to represent the footwalls of large detachment systems. Numerous oceanic core complexes have been identified along the Mid-Atlantic Ridge (MAR) (e.g., Cann et al., 1997; Escartin et al., 2008;

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MacLeod et al., 2002; Smith et al., 2006; Tucholke et al., 1998) and Southwest Indian Ridge (SWIR) (Cannat et al., 2006, 2009; Dick et al., 1991; Searle et al., 2003), and detachment faulting may occur along ∼50% of the MAR from 12°40′N to 35°15′N (Escartin et al., 2008).

Given the prevalence of oceanic core complexes and detachment faulting, it is necessary to study the processes of detachment-related crustal accretion, to ultimately understand the formation of slow- and ultraslow-spread crust. Several studies have developed models outlining the conditions necessary for the formation of oceanic detachment faults and their large-scale temporal evolution (e.g., Ildefonse et al., 2007; MacLeod et al., 2009; Tucholke et al., 2008); however, there are currently few detailed models of the spatial and temporal distribution of magmatism during detachment-related lower crustal accretion.

We present new high-precision isotope dilution-thermal ionization mass spectrometry (ID-TIMS) U–Pb zircon dates from the lengths of Ocean Drilling Program (ODP) Holes 735B and 1105A, on the Atlantis Bank core complex, SWIR. The high-precision dates are an order of magnitude more precise than existing sensitive high-resolution ion microprobe (SHRIMP) data, and provide detailed constraints on the duration, spatial distribution, and length scale of magmatism during asymmetric, detachment-related, lower crustal accretion. We combine our new U–Pb dates, with previous geochemical and paleomagnetic data, to develop a comprehensive model for crustal accretion during detachment faulting at this location.

2. Prior studies of the distribution of magmatism during asymmetric lower crustal accretion

Three prior studies have looked in detail at the temporal evolution of magmatism during asymmetric crustal accretion. These studies have focused on (Integrated) Ocean Drilling Program (ODP/IODP) holes drilled into large oceanic core complexes: ODP Holes 923A and 921E on the Kane core complex (MAR), IODP Hole 1309D on Atlantis Massif (MAR), and ODP Holes 735B and 1105A on Atlantis Bank (SWIR). Meurer and Gee (2002) used paleomagnetic data from the Kane drill holes to argue that the crust was constructed over ∼210 ka, by repeated sill intrusions. Grimes et al. (2008) used SHRIMP U–Pb zircon geochronology to date the timing of magmatism in Hole 1309D at Atlantis Massif. The data suggested that the recovered crust was constructed by at least two intrusive pulses, spaced ∼70 ka apart. At Atlantis Bank, Natland and Dick (2002) suggested that observed geochemical variations in ODP Hole 735B are consistent with formation of the uppermost igneous series in interconnected mush zones, followed by underplating of more differentiated magmas. Baines et al. (2009) used SHRIMP U–Pb dates to determine the relative timing of the igneous series; but measured $^{206}Pb/^{238}U$ dates overlap within uncertainty, and therefore do not constrain the spatial distribution of magmatism during crustal accretion. Here we present new high-precision dates from Holes 735B and Hole 1105A at Atlantis Bank, which provide a detailed record of the spatial and temporal distribution of magmatism during lower crustal accretion.

3. Geologic setting

ODP Holes 735B and 1105A were drilled into the top of Atlantis Bank, a bathymetric high (700 mbsl) interpreted as the footwall of a large oceanic detachment fault (Fig. 1) (Dick et al., 1991). The bank is located 95 km south of the present-day SWIR, in ∼10–14 Ma crust (Baines et al., 2008; Schwartz et al., 2005). The surface of Atlantis Bank is predominantly composed of gabbroic crust denuded by detachment faulting, and Holes 735B and

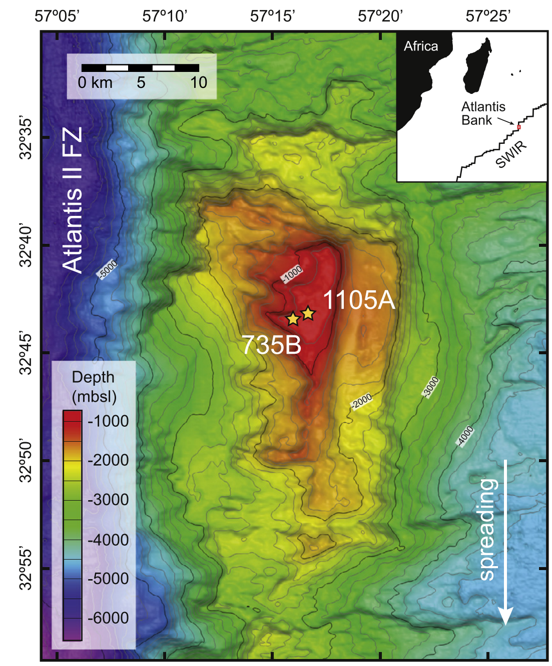

Fig. 1. Bathymetric map of Atlantis Bank, showing the locations of Ocean Drilling Program Holes 735B and 1105A (200 m contour interval). SWIR, Southwest Indian Ridge; Atlantis II FZ, Atlantis II fracture zone. Bathymetry from Arai et al. (2000) and Matsumoto et al. (2002).

1105A were drilled into the exposed gabbro. Hole 735B penetrated 1508 mbsf and is currently the deepest drill hole into lower ocean crust (Natland and Dick, 2002; Robinson et al., 1988). Hole 1105A is offset by a total of 1.2 km NE, and 0.48 km in the north-south spreading direction, and penetrated 158 mbsf (Casey et al., 2007). The two ODP holes, a series of surface drill cores (Coogan et al., 2001a), numerous dredge hauls, and detailed ROV and submersible mapping and sampling (Arai et al., 2000; Matsumoto et al., 2002), make Atlantis Bank an outstanding location to study the processes of lower crustal accretion at an ultraslow-spreading ridge.

The recovered core is predominantly an olivine gabbro suite, including olivine gabbro, troctolitic gabbro and troctolite. The remainder of the core is made up of more evolved, zircon-bearing, oxide gabbro, and minor quartz diorite, diorite, tonalite, trondhjemite and granite veins and dikes. In Hole 735B, the proportions of olivine gabbro and related rocks, oxide gabbro and felsic veins are ∼76:23.5:0.5 (Natland and Dick, 2002). Whole rock and mineral geochemistry from the olivine gabbro suite define three igneous series with thicknesses of ∼250–1000 m (Fig. 2A) (Dick et al., 2000; Natland and Dick, 2002). Within each series, whole rock Mg# increases from the base to the top of the series, indicating an upward trend to more differentiated compositions. Olivine, clinopyroxene and plagioclase mineral compositions, and whole rock Mg#, further suggest that igneous Series 3 may be composed of three sub-series (Fig. 2A) (Dick et al., 2002). Each igneous series is composed of numerous thinner (1–120 m) igneous sequences, defined by variable grain sizes, texture and mineralogy (Natland and Dick, 2002). These sequences may represent different magmatic injections, whereas the larger scale chemical zoning of the igneous series reflect progressive differentiation in an interconnected mush zone formed from these intrusions. The bulk composition of Hole 735B, and samples from the surface of Atlantis Bank, have lower Mg# than primary mantle melts, suggesting that complementary primitive cumulates are preserved out of the sampled section, either along axis, deeper in the crust, or in the upper mantle (Coogan et al., 2001a; Dick et al., 2000). Based on the