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SHRIMP Pb/U zircon ages constrain gabbroic crustal accretion at Atlantis Bank on the ultraslow-spreading Southwest Indian Ridge

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ABSTRACT

Absolute ages of plutonic rocks from mid-ocean ridges provide important constraints on the scale, timing and rates of oceanic crustal accretion, yet few such rocks have been absolutely dated. We present $^{206}Pb/^{238}U$ SHRIMP zircon ages from two ODP Drill Holes and a surface sample from Atlantis Bank on the Southwest Indian Ridge. We report ten new sample ages from 26–1430 m in ODP Hole 735B, and one from 57 m in ODP Hole 1105A. Including a previously published age, eleven samples from Hole 735B yield $^{206}Pb/^{238}U$ zircon crystallization ages that are the same, within error, overlap with the estimated magnetic age and are inferred to date the main period of crustal growth, the average age of analyses is 11.99 ± 0.12 Ma. Any differences in the ages of magmatic series and/or tectonic blocks within Hole 735B are unresolvable and eight well-constrained ages vary from 11.86 ± 0.20 Ma to 12.13 ± 0.21 Ma, a range of 0.27 ± 0.29 Ma, consistent with the duration of crustal accretion observed at the Mid-Atlantic Ridge. An age of 11.87 ± 0.23 Ma from Hole 1105A is within error of ages from Hole 735B and permits previous correlations made between zones of oxide-rich gabbros in each hole. Pb/U zircon ages > 0.5 Ma younger than the magnetic age are recorded in at least three samples from Atlantis Bank, one from Hole 735B and two collected along a fault scarp to the East. These young ages may date one or more off-axis events previously suggested from thermochronologic data and support the interpretation of a complex geological history following crustal accretion at Atlantis Bank. Together with results from the surface of Atlantis Bank, dating has shown that while the majority of Pb/U SHRIMP zircon ages record the short-lived (< 0.5 Ma) phase of crustal accretion on-axis, results from several samples precede and post-date this period by > 1 Ma suggesting a complex and prolonged magmatic/tectonic history for the crust at Atlantis Bank.

1. Introduction

The accretion of gabbros at mid-oceanic ridges (MORs) builds the lower oceanic crust and, at least partially, accommodates plate separation during seafloor spreading. Details of this process are unclear but over the past two decades, several sections of in-situ gabbroic crust have been sampled in detail and, together with observations from ophiolites, a model is emerging whereby the plutonic lower oceanic crust accretes in-situ from relatively thin (1–500 m thick) sills distributed throughout the crust (Korenaga and Kelemen, 1997; Kelemen and Aharonov, 1998; Maclennan et al., 2004), in contrast to "gabbro glacier" models whereby the entire crust accretes from sills at the dike-gabbro transition and/or Moho (Sleep, 1975; Nicolas et al., 1988; Phipps Morgan and Chen, 1993; Henstock et al., 1993; Chen, 2001). Seismic observations suggest that the full crustal thickness accretes within a few kilometers of the spreading axis regardless of the full-spreading rate (Purdy and Detrick, 1986; Detrick et al., 1987; Sinton and Detrick, 1992; Sinha et al., 1998). Hence, accretion of plutonic crust at MORs is likely rapid (<<1 Ma), although there is evidence for inherited crust (Schwartz et al., 2005) and off-axis magmatism (Perfit et al., 1994; Canales et al., 2008). Melt lenses (or axial magma chambers) imaged by seismic surveys at fast- and slow-spreading ridges are small: 0.25–5.0 km wide, 100–200 m thick extending 10s of km along-axis and are underlain by narrow, steep-sided low-velocity zones that may represent mush zones where the plutonic lower crust accretes (Sinton and Detrick, 1992; Sinha et al., 1998; Dunn et al., 2000; Kent et al., 2000; Dunn et al., 2005; Singh et al., 2006). At fast-spreading MORs, these melt lenses and mush zones are common. However, at slow and ultraslow-spreading MORs, melt lenses are rare (Singh et al., 2006). Seismic tomography at 35°N on the MAR imaged a low-velocity zone at a segment center that could indicate a region with 1–4% melt on axis (Magde et al., 2000; Dunn et al., 2005). In contrast, other surveys along the MAR suggest that the axial crust is

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completely solid (Purdy and Detrick, 1986; Klingelhöfer et al., 2000). This inconsistency in seismic results supports the interpretation that at slow- and ultraslow-spreading rates the plutonic crust accretes intermittently in both space (e.g. Cannat, 1993) and time (Henstock et al., 1993; MacGregor et al., 1998). This view is compatible with inferences from earthquake seismicity (Huang and Solomon, 1988; Kong et al., 1992; Wolfe et al., 1995; deMartin et al., 2007), mechanical considerations (Chen and Morgan, 1990; Mendel et al., 1997; Buck et al., 2005; Tucholke et al., 2008), and thermal modeling (Phipps Morgan and Chen, 1993; Henstock et al., 1993) that all suggest relatively cool, brittle crust on axis to 5–6 km depth, and an axial crust that at steady state is significantly below solidus temperatures (<800 °C). Therefore, melt lenses and mush zones at slow- and ultraslow-spreading ridges are likely transient and melt may rapidly cool to subsolidus temperatures (Henstock et al., 1993; MacGregor et al., 1998).

Geochronologic dating of vertical sections of the oceanic crust has the potential to define these intrusive events (e.g. Grimes et al., 2008), constrain models of crustal accretion, and determine the relative importance of inheritance and off-axis magmatism for the construction of oceanic crust. Pb/U SHRIMP zircon ages from ODP Hole 1309D (Atlantis Massif, 30°N MAR) suggest that crustal accretion occurred over a minimum of 100–200 ka, with at least two magmatic events separated by 70 ka (Grimes et al., 2008). However, recent Pb/U TIMS dating has suggested that zircon from individual oceanic gabbro samples may crystallize over 90–235 ka (Lissenberg et al., 2009). Here, we present Pb/U SHRIMP zircon ages for ten samples from the 1508 m-deep ODP Hole 735B (Natland and Dick, 2002) and one sample from the neighboring (1.2 km to the east) 158 m-deep Hole 1105A (Casey et al., 2007), which were both drilled at Atlantis Bank on the ultraslow-spreading Southwest Indian Ridge (SWIR). We also present an additional Pb/U SHRIMP zircon age for a sample recovered by a submersible from the seafloor.

2. ODP Holes 735B and 1105A

Atlantis Bank is a bathymetric high located on the Antarctic Plate ~100 km south of the axial valley of the SWIR and immediately to the east of the Atlantis II transform fault (inset Fig. 1). At Atlantis Bank, detachment faulting has exposed lower crustal gabbro and subsidiary peridotite from >1.5–2 km depth (Vanko and Stakes, 1991; Dick et al., 2000; Arai et al., 2000; Allerton and Tivey, 2001; Kinoshita et al., 2001; Coogan et al., 2001; Matsumoto et al., 2002; Natland and Dick, 2002). ODP Hole 735B, at 57°15.960′E 32°43.392′S (Fig. 1), with a drilled depth of 1508 m provides the deepest, freshest (~70% of the core is unaltered (Party, 1999a)) and most continuous section of gabbroic rocks recovered by drilling oceanic crust (Fig. 2). ODP Hole 1105A, located 1.2 km east of ODP Hole 735B, at 32°43.1346′S, 57°16.6518′E, penetrates 158 m of gabbro and provides the opportunity to constrain the horizontal scale and timing of crustal accretion. In addition, dredging (Coogan et al., 2001), shallow coring (Coogan et al., 2001; Allerton and Tivey, 2001) and submersible sampling (Arai et al., 2000; Kinoshita et al., 2001; Matsumoto et al., 2002) has recovered gabbro for over 35 km parallel-to-spreading and greater than 20 km perpendicular-to-spreading, implying a widespread and continuous gabbroic layer at Atlantis Bank. Hole 735B is therefore an ideal locality to study the processes of gabbroic crustal accretion at an ultraslow-spreading MOR, and our observations may provide constraints on how thick, laterally continuous layers of gabbroic crust accretes at other MORs.

For ODP Hole 735B, 76% of recovery comprises gabbro, olivine gabbro, troctolitic gabbro and troctolite, while the remaining 24% of recovery comprises oxide gabbro and minor felsic dikes/vein (Natland and Dick, 2002). Ninety-seven igneous sequences are recognized in Hole 735B, the majority of which are <10 m thick with the thickest only 122-m thick (274–396 m below seafloor (mbsf)). Each sequence is thought to represent a single small intrusive pulse, which together

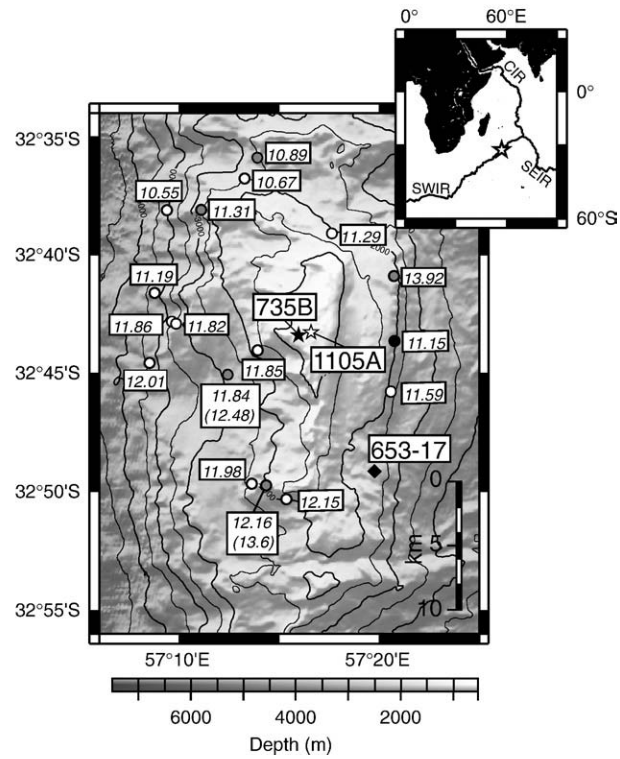

Fig. 1. Location of ODP Hole 735B on Atlantis Bank (filled star), ODP Hole 1105A (open star), sample 653-17 (black diamond) and samples dated by (Schwartz et al., 2005) (circles); grey shaded circles represent samples that contain anomalously old zircons, open circles approximate the magmatic age, black circle — sample 644-12 (see text). Numbers in italics are the $^{206}Pb/^{238}U$ ages of the samples (in Ma) from Schwartz et al (2005). If two ages were obtained from the same sample, the age of the older component is shown in parentheses. Inset shows the location of the Atlantis Bank and mid-ocean ridges in the Indian Ocean; SWIR — southwest Indian Ridge, CIR — central Indian Ridge, SEIR — southeast Indian Ridge.

make up three larger magmatic series identified on the basis of trends in bulk-rock chemistry (Fig. 2b) and equivalent trends in the compositions of plagioclase and olivine (Natland and Dick, 2002). Despite knowledge of the vertical scale of intrusive pulses, the absolute ages and therefore temporal history of crustal accretion are poorly constrained. *Natland and Dick* (2002) suggest that the steep chemical trends observed in the two upper series imply that they "were emplaced at shallow depths at the ridge axis", whereas they inferred that the more uniform composition of the deepest series represented intrusion of differentiated magma further from the spreading axis. This interpretation predicts younger crystallization ages down-hole.

Although 77% of Hole 735B is undeformed, four major tectonic blocks have been identified (Fig. 2a) that are bound by brittle fault zones active at greenschist and sub-greenschist conditions, which overprint earlier ductile granulite and amphibolite facies shear zones (Dick et al., 2000; John et al., 2004). The relative displacement of the tectonic blocks across these faults may have been significant (>1 km), such that the ages of adjacent tectonic blocks may be different. These blocks do not correlate directly with the magmatic series and assuming top-to-the-north motion consistent with detachment faulting would lead to a relative younging of ages with depth.

ODP Hole 1105A penetrates 158 m of gabbroic crust approximately 1.2 km east of Hole 735B. The recovered rock types are similar to those penetrated by 735B, such that it has been suggested that an oxide-rich section from 45–135 mbsf in Hole 1105A may correlate with the oxide-rich zone from 240–290 mbsf in Hole 735B (Casey et al., 2007). This may be a direct correlation of units formed during the same intrusive pulse, or an apparent correlation reflecting similar processes occurring on the edge of a magma chamber without representing the

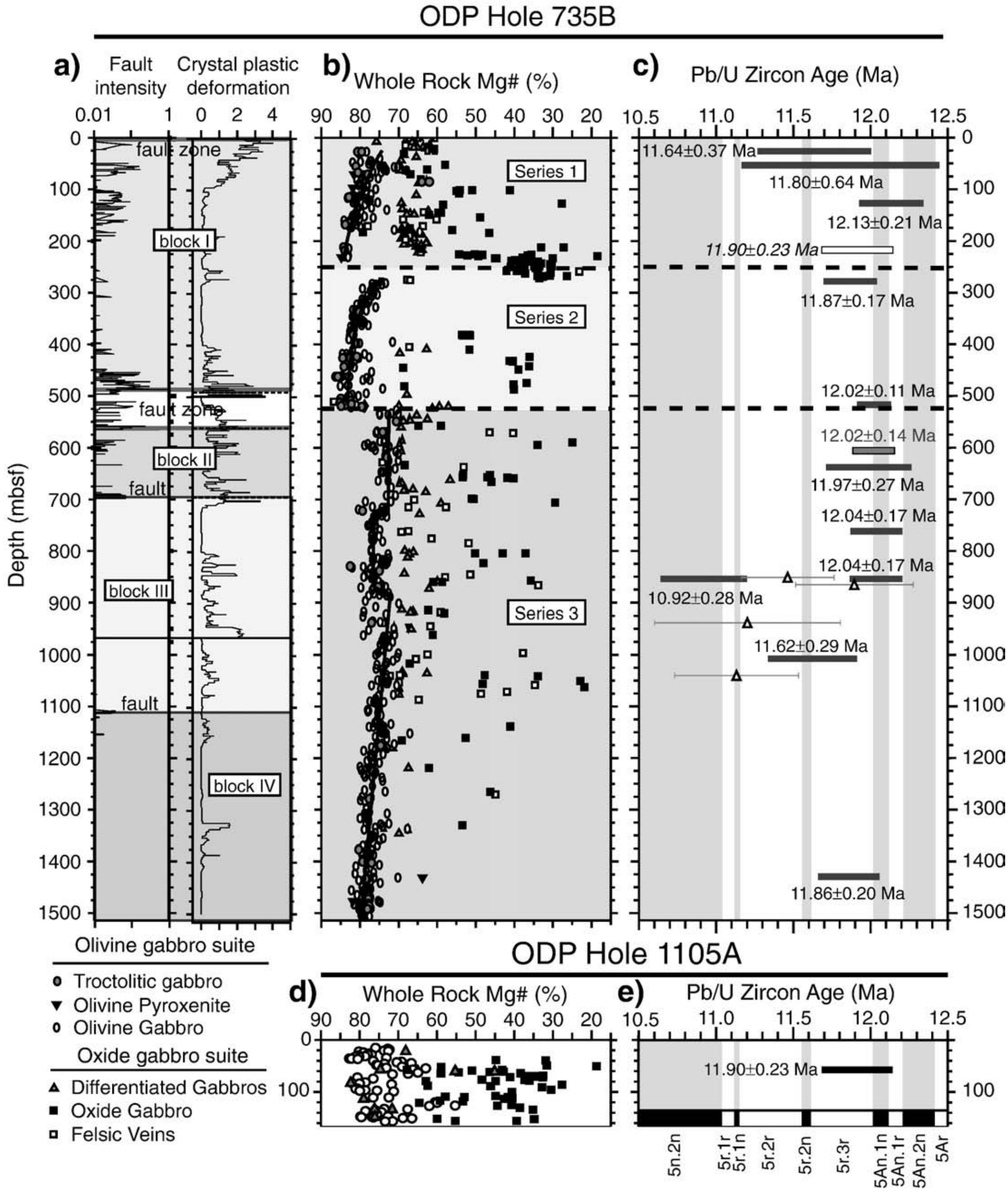

Fig. 2. Stratigraphy of ODP Holes 735B and 1105A plotted at the same scale. a) Structural data from Hole 735B, fault intensity and intensity of crystal-plastic deformation (after John et al., 2004). Tectonic blocks and the bounding fault zones are also shown. b) Mg# of whole rock analyses from Hole 735B (after (Natland and Dick, 2002)). Magmatic series are delimited by shading and horizontal dashed lines. c) Calculated ages with depth in Hole 735B, black blocks show $^{206}Pb/^{238}U$ ages from this study, dark grey block from, open block is the age from Hole 1105A plotted at the correlative depth in Hole 735B. Open triangles and error bars show $^{40}Ar/^{39}Ar$ biotite ages (John et al., 2004). All error bars are 2σ errors. Vertical light grey columns denote the duration of timing of normally polarized geomagnetic polarity intervals; intervening unshaded columns denote reversely polarized geomagnetic polarity intervals. Horizontal dashed lines show the boundaries of the magmatic series from b). d) Mg# of whole rock analyses from Hole 1105A (after (Casey et al., 2007)) e) Calculated ages with depth in Hole 1105A, legend as for c). Magnetic polarity and labeled isochrons after (Ogg and Smith, 2004).

same igneous unit (Casey et al., 2007). We date samples recovered from these zones to test the nature and significance of this correlation.

3. Previous dating of plutonic oceanic crust

3.1. Magnetic constraints

Previous dating of the accretion of vertical sections of oceanic gabbro by correlation of variations in thermal remanent magnetization (TRM) to the geomagnetic polarity timescale indicate that accretion took at least 210 ka for an ~70 m section of lower oceanic crust recovered in ODP Hole 923A south of the Kane Fracture Zone at the Mid-Atlantic Ridge (MAR) (Gee and Meurer, 2002). However, samples from ODP Hole 735B have stable reverse polarity TRM throughout the entire 1508 m of the hole (Dick et al., 2000; Worm, 2001), indicating cooling of the crust through the Curie Temperature (500–580 °C (Worm, 2001)) during the 0.400 Ma long chron C5r.3r (11.614–12.014 Ma) (Dick et al., 1991; Allerton and Tivey, 2001; Lourens et al., 2004). Given the position of Atlantis Bank ~3 km south of the boundary of C5r.2n (Allerton and Tivey, 2001), and a half-spreading rate of ~14 km/Ma (Baines et al., 2008) a magnetic age for Atlantis Bank of ~11.8 Ma is predicted.

3.2. Absolute dating

Absolute dating using (U–Pb) geochronometry can better constrain the age and rate of formation of plutonic oceanic crust. At Atlantis Massif on the MAR, Pb/U SHRIMP zircon ages from the 1415.5 m-deep ODP Hole 1309D (Grimes et al., 2008) are consistent with magnetic results from Hole 923A (Gee and Meurer, 2002), suggesting crustal accretion occurred over a minimum of 100–200 ka, with at least two magmatic events separated by 70 ka. At ODP Hole 735B, previous U–Pb dating of zircon has yielded a thermal ionization mass spectrometry (TIMS) age of 11.3 Ma (no errors presented) at 26 mbsf within the first magmatic series (Stakes et al., 1991), and a SHRIMP $^{206}Pb/^{238}U$ zircon age of 11.93 ± 0.13 Ma at 606 mbsf within the deepest magmatic series (John et al., 2004). These ages suggest crustal accretion over > 0.6 Ma, a significantly longer duration than observed at the MAR. In addition, 17 samples from the surface of Atlantis Bank have yielded SHRIMP $^{206}Pb/^{238}U$ zircon ages with precisions of 100–600 ka (Schwartz et al., 2005), with up to 25% of the ages anomalously old relative to the magnetic age. These ages suggest inheritance and incorporation of older material that crystallized in the cold, thick lithospheric mantle beneath the axial valley of the SWIR. Additional, U–Pb zircon SHRIMP dating of samples from Hole 735B may resolve intrusive events to approximately 100 ka, the timescale of events observed at the MAR (Gee and Meurer, 2002; Grimes et al., 2008), and may further constrain the importance of crustal inheritance.

Within Hole 735B additional constraints on the cooling history from thermochronologic dating have been presented by John et al (2004). $^{40}Ar/^{39}Ar$ analyses of biotite (closure temperature 365 ± 35 °C) from 851–1040 m (tectonic block III, magmatic series 3) yielded an average age of 11.42 ± 0.21 Ma. Fission track dating constrained the low-temperature evolution; titanite fission track ages (280 ± 40 °C closure interval) from yielded ages ranging from 7.4 ± 1.8 Ma to 10.2 ± 3.4 Ma; zircon fission track analyses ranged from 9.1 ± 0.6 Ma to 9.7 ± 1.2 Ma (zircon closure of 240 ± 30 °C) and apatite fission track analysis suggests a minimum cooling age (through ~110 °C) of 7.2 ± 2.6 Ma (John et al., 2004). (U–Th)/He ages for samples from the surface of Atlantis Bank and from Hole 735B suggest variable cooling histories (Schwartz et al., 2009). Several samples suggest rapid cooling to < 200 °C within 0.5 Ma of crystallization whereas other samples suggest elevated off-axis temperatures, attributed to focussed hydrothermal circulation along fault zones at ~8–9 Ma (Schwartz et al., 2009). Together, these relatively young low-temperature cooling ages suggest anomalously high off-axis temperatures at Atlantis Bank. Pb/U zircon dating at Hole 735B may further constrain the origin and nature of this anomalous cooling history.

4. Sample description

Pb/U SHRIMP zircon ages were determined for ten additional samples from 26–1430 mbsf in ODP Hole 735B, one sample from 57 m in ODP Hole 1105A (sample #1105A) and one sample collected by submersible from the surface of Atlantis Bank (sample #653-17) [Table 1]. For convenience, we refer to samples from Hole 735B by their depth, i.e. sample #26 is from 26 mbsf; full ODP sample designations and sample descriptions are given in Table 1. Samples are dated from each magmatic series and tectonic block identified within Hole 735B (Natland and Dick, 2002; John et al., 2004), therefore constraining the timescale and mechanisms of crustal accretion at this ultraslow-spreading ridge (Fig. 2). Specific samples were selected for mineral separation based on the presence of zircon in thin section, or because

Table 1
Sample descriptions.

ODP sample designation	Depth (mbsf)	Rock type	Grain size	Alteration	Tectonic block	Magmatic series	# of analyses	Age (Ma)[a]	Comments
118-735B-7D-1, piece 2A, 10–18 cm	26	Strongly foliated clinopyroxene hornblende actinolite gabbro intruded by a less-deformed zircon-bearing diorite vein	C	80%	I	1	11	11.64 ± 0.54	A 11.3 Ma age previously reported by Stakes et al, 1991. Zircon-bearing gabbro slightly deformed and intrudes highly deformed gabbros
118-735B-14R-2, piece 1D, 93–96 cm	53	Diorite vein cutting foliated gabbro	F	80%	I	1	6	11.80 ± 0.64	
118-735B-28R-1, piece 6, 56–60 cm	127	Olivine-bearing gabbro (mylonitic)	F–M	83%	I	1	10	12.13 ± 0.21	Down temperature overprinting of deformation and alteration
118-735B-57R-3, piece 1C, 44–47 cm	278	Biotite hornblende diorite hosting brecciated Ol-bearing gabbro clasts	C	30%	I	2	19	11.87 ± 0.17	
176-735B-90R-8, piece 1A, 49–54 cm	517	Hornblende quartz diorite to granodiorite dike cutting troctolite	M	15%	Fault Zone	2	15	12.02 ± 0.11	2-cm-wide vein with an alteration halo in the country rock
176-735B-104R-3, piece 1, 5–11 cm	606	Hornblende quartz diorite hosting brecciated olivine gabbro clasts	M	60%	II	3	15	12.02 ± 0.14	Dated by John et al, 2004.
176-735B-110R-4, piece 2A, 8–13 cm	638	Clinopyroxene, biotite,hornblende diorite dike cutting olivine gabbro	M	20%	II	3	8	11.93 ± 0.17	Magmatic Vein brecciates host
176-735B-126R-5, piece 2B, 85–98 cm	762	Hornblende quartz diorite, tonalite and granodiorite dike cutting olivine gabbro	M	8%	III	3	14	12.04 ± 0.17	
176-735B-137R-2, piece 3, 71–75 cm	854	Disseminated oxide, amphibole diorite dike cutting olivine gabbro	M	10%	III	3	11 3	12.04 ± 0.16 10.92 ± 0.28	12-mm-wide compound felsic vein, two age components
176-735B-154R-3, piece 3A, 52–55 cm	1008	Orthopyroxene-bearing, disseminated oxide gabbro infiltration into olivine gabbro	C	5%	III	3	4	11.62 ± 0.29	
176-735B-202R-7, piece 2, 85–94 cm	1430	Disseminated oxide amphibole diorite dike cutting olivine gabbro and troctolitic microgabbro	M	4%	IV	3	6	11.86 ± 0.20	
179-1105A-8R-4, piece 2, 21–25 cm	57	Diffuse oxide diorite dike intruding an oxide and olivine-bearing gabbro	M	14%			12	11.91 ± 0.23	
JAMSTEC sample 6 K653-17 (57°19.7745′E 32°49.0944′S)	NA	Gabbro mylonite	F	80%			8	11.27 ± 0.31	

[a] ^{207}Pb-corrected $^{206}Pb/^{238}U$ zircon error-weighted mean sample ages adjusted for Th disequilibria.

zircon was reported from nearby samples of similar composition (John et al., 2004; Schwartz et al., 2005). Analyzed samples range in composition from oxide gabbro to diorite, quartz diorite and granodiorite (Table 1), and comprise discrete felsic veins/dikes (samples #26, #53, #517, #762, #854, #1430), magmatic breccias formed by the intrusion of felsic magma into solidified gabbro (samples #278, #638), a zone of oxide gabbro infiltration into olivine gabbro (sample #1008), a protomylonitic gabbro (sample #127) and a mylonitic gabbro (sample 653-17).

Most zircon-bearing samples are more evolved than the gabbro and olivine gabbro that comprise the majority of Hole 735B. Cross-cutting relationships within ODP Hole 735B indicate that locally felsic veins and diorite represent the final intrusive phase and as zircon occurs more commonly in felsic veins they are often sampled for dating in this and other studies (Grimes et al., 2008). These felsic dikes and veins (or "oceanic plagiogranites") in Hole 735B are magmatic and intruded at temperatures from 750 °C to > 800 °C (Robinson et al., 2002). Several petrogenetic models have been suggested to explain the generation of these veins. Niu et al (Niu et al., 2002) suggest that they are the products of SiO_2-enrichment during fractionation of tholeiitic magma. Dick et al (Dick et al., 2000) suggest that they formed by "local in-situ differentiation of ferrobasalt melt[s]". Whereas, Koepke et al. (2007) suggest that these melts form by hydrous partial melting of solidified gabbros during continued magmatic accretion. In all cases, felsic magma is generated by a high-temperature (> 800 °C) magmatic event and thus crystallization ages will date these events and provide minimum ages for the country rocks these veins intrude. We note that cross-cutting relationships and the deformation history indicate at least two generations of felsic veins in 735B (Shipboard Scientific Party, 1999b), and some of the dated samples are compound felsic dykes so may record multiple intrusive events. Further, Grimes et al (2008) showed that at Atlantis Massif the ages of felsic veins, oxide gabbros and gabbronorites overlap, with several felsic vein ages older than nearby oxide gabbro and gabbronorite samples. Hence, felsic veins do not post-date all other intrusions and likely date the intrusion gabbros (within error).

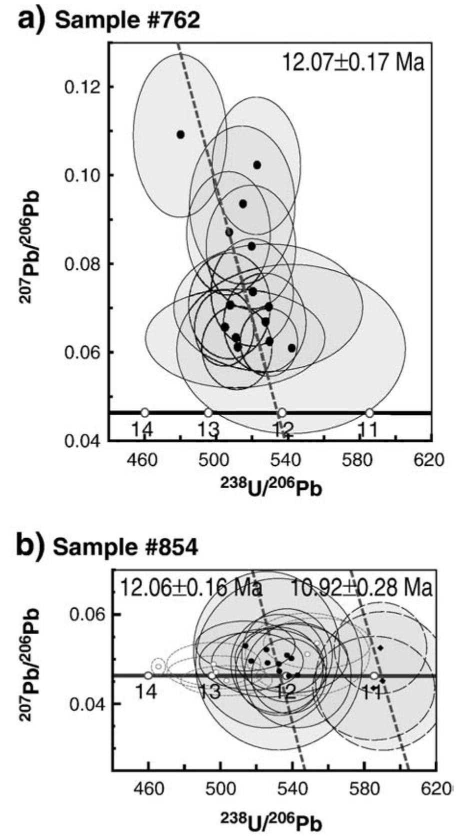

Fig. 3. Example Tera–Wasserburg diagrams. Error ellipses represent 2σ error. Best fit concordia lines are plotted assuming an upper intercept defined by common-Pb. a) Sample #762. b) Sample #854. Shaded ellipses represent the data used to calculate the reported ages, circles/solid edges correspond to the older component, diamonds/dashed edges correspond to the younger component, unshaded ellipses/open circles/dotted edges are excluded because the spot analyses overlapped highly radiogenic rims [see text].

5. Results

Zircons extracted from the samples were dated at the Stanford-USGS SHRIMP-RG facility; analytical procedure, data reduction and complete results are provided in the supplemental data (available online). Individual SHRIMP analyses had 1σ errors from 0.05–4.17 Ma, whereas 80% of analyses had spot errors < 0.50 Ma, and 50% with errors < 0.30 Ma. Tera–Wasserburg diagrams of the total ratios corrected for U–Th disequilibria (Fig. 3, Supplemental Data) show that most analyses plot on or just above Concordia. Discordance is primarily due to initial common-Pb that is thought to occur in minor inclusions or impurities in the zircon lattice possibly originating from seawater infiltration at high temperature (Hart et al., 1999; John et al., 2004; Schwartz et al., 2005). The majority of samples yield tight clusters of analyses and scatter in the data is consistent with analytical error alone (see Supplemental Data). Analyses for seven samples (#127, #278, #517, #638, #762, #1430 and #1105A) were robust and clustered to give well-constrained error-weighted mean $^{206}Pb/^{238}U$ sample ages between 11.86 Ma and 12.13 Ma to precisions of 0.11–0.21 Ma (1–2%, 2σ error) and MSWDs < 1.5 (Table 1; Fig. 2; Fig. 4). These samples likely record the main phase of crustal growth at Atlantis Bank.

After further analysis, outlined below, sample #854 gave an age consistent with the aforementioned samples, with a younger age component identified that is consistent with the age of a nearby surface sample (#653-17). The age of samples #26, #53 and #1008 were less well-constrained due to low measured U-concentration or a limited number of grains suitable for analysis (Fig. 4; Supplemental Data); however these ages may have important implications for the evolution of Atlantis Bank.

5.1. Well-constrained magmatic ages

Zircons from six of the samples (#127, #278, #517, #638, #762 and #1105A) are euhedral, have oscillatory and/or sector zoning in CL and an average Th/U ratio ~0.45 (with a full range of 0.18–0.82) (Supplemental Data). These observations are characteristic of magmatic zircons (Hanchar and Miller, 1993; Vavra et al., 1999; Whitehouse et al., 1999; Corfu et al., 2003; Hoskin and Schaltegger, 2003) and suggest that the Pb/U zircon ages reflect the timing of igneous crystallization of the samples. This inference is particularly noteworthy for sample #127, a plagioclase-rich zone of a mylonitic gabbro. In thin section, plagioclase shows grain size reduction and recrystallization at high temperature; clinopyroxene is replaced by brown amphibole. The brown amphibole is, in turn, replaced by late-stage blue-green amphibole and epidote (Shipboard Scientific Party, 1989). Despite this complex down-temperature history of deformation/recrystallization and alteration, the analyzed zircons show no evidence of deformation, recrystallization or metamorphic overgrowths. Therefore, we conclude that the zircons are unaffected by deformation and alteration of the host rock and the well-constrained weighted mean $^{206}Pb/^{238}U$ age records the original age of magmatic crystallization for this sample of 12.13 ± 0.21 Ma — the oldest $^{206}Pb/^{238}U$ sample age recorded from ODP Hole 735B.

Zircons from sample #1430, a disseminated oxide amphibole diorite dike, are noticeably different to those from other samples; they are anomalously large (some grains were > 1000 μm in length), elongate (aspect ratios often > 4) and remarkably free of zoning in CL [Supplemental Data]. The lack of zoning and the elongate crystal habit may be consistent with extremely rapid zircon growth (Hanchar and Miller, 1993; Corfu et al., 2003). Although this crystal habit could be attributed to rapid crystal growth in a water-rich hydrothermal environment (Corfu et al., 2003), the felsic dike is unaltered and the observed Th/U ratios (0.28–0.54) are characteristic of magmatic zircons. It is therefore likely that these zircons are also magmatic and date crystallization of the felsic dyke.

5.2. Samples #854 and #653-17

Spot analyses from sample #854 plot on concordia (Fig. 3b), however the ages form an array that spans >3 Ma, and differences between the spot analyses are statistically significant. CL images of zircons analyzed from this sample show grains that are euhedral and oscillatory zoned, typical of the magmatic zircons analyzed from other samples (Fig 5). In contrast to other samples, several zircons also have very dark, U (>7500 ppm U) and Th-rich (>2000 ppm Th) rims (Fig. 5). These rims were initially targeted as the high U-concentrations offered the possibility of yielding very precise ages, however, several spot analyses from these rims yielded anomalously old ages. Given these results, this sample was re-analyzed avoiding the rims. This subsequent analysis included two spots located in the cores of grains whose rims had been previously analyzed. For these two grains, the cores yielded ages significantly younger than the U-rich rims (grains 12 and 13; Table S1, Fig. 5c). Further a positive correlation between the U- and Th-concentrations and the $^{206}Pb/^{238}U$ ages of individual spot analyses that overlap rims (Fig. 5) is consistent with the age vs. U-concentration relationships observed by Williams and Hergt (2000) and McFarlane et al (2006). Possible explanations for this relationship include systematic error due to variation in the ionization of zircon caused by radiation damage, other crystallographic defects, and/or spots that overlap inclusions where U- and Th-concentrations are greater than several percent (McLaren et al., 1994). However, given that these effects cannot be corrected for, we exclude all spot analyses from sample #854 that overlap U- and Th-rich rims from further calculations and discussion.

For the remaining fourteen analyses, a probability density plot suggests two age populations (Fig. 5c). Eleven analyses provide a well-constrained age of 12.04 ± 0.17 Ma (MSWD = 0.4) that is consistent with the majority of zircon ages within Hole 735B and the magnetic age. However, three analyses are significantly younger and cluster to yield an age of 10.92 ± 0.28 (MSWD = 0.17). The three zircons that define this young age display sharp oscillatory zoning in CL (e.g. Fig. 5c) and rare-earth element (REE) concentrations (Fig. 5d) for these young zircons are identical to those of zircons that define the 12.04 ± 0.17 Ma component; further the REE patterns from sample #854 are typical of oceanic crust zircons (Hanchar and Miller, 1993; Corfu et al., 2003; Grimes et al., 2007). Hence there is little indication for later alteration or modification of the zircon (e.g. Pidgeon, 1992; Connelly, 2000), and SEM imaging of analyzed pits shows that the analyses did not intersect cracks or inclusions. Also these young zircons, have U-rich rims are so morphologically similar to zircons that define the older age (Fig. 5). Two alternative hypotheses exist; 1) these young ages record a second phase of magmatic crystallization, however this seems unlikely given that sample #854 is a thin felsic vein and the young zircon appears identical in CL to those that record an older age, or 2) the young ages record Pb-loss. Although Pb-loss is commonly associated with a disruption of zoning observed in CL (Pidgeon, 1992; Vavra et al., 1999; Connelly, 2000), this observation is not ubiquitous and the disturbance of U–Pb systematics in areas of zircon that show apparently pristine igneous character in CL has been observed (Vavra et al., 1999). For such young samples, Pb-loss may result in analyses that stretch along concordia, so the apparently young, but concordant, ages may provide a maximum age for Pb-loss. Sample #854 is not the only sample at Atlantis Bank that records an anomalously young age. Samples recovered from a transform parallel fault scarp on the eastern flank of Atlantis Bank also record similarly young Pb/U zircon ages (Fig. 1). Sample #644-12, an oxide gabbronorite recovered ~8 km to the east of Hole 735B records an age of 11.15 ± 0.46 Ma (MSWD = 0.46) (Schwartz et al., 2005), and sample #653-17 (discussed below) also yields an anomalously young age.

Sample #653-17 is a gabbro mylonite recovered ~12 km to the SSE of Hole 735B (Fig. 1). Zircons from this sample have relatively low U-concentrations, with Th/U ratios from 0.38–0.79 (Supplemental Data), consistent with igneous zircons. Although some of the zircons display sharp sector and oscillatory zoning in CL, several grains display diffuse zoning that may be consistent with annealing, alteration or deformation at moderate-to-high temperatures (Sinha et al., 1992; Pidgeon, 1992; Connelly, 2000; Corfu et al., 2003; Timms et al., 2006; Reddy et al., 2006) [Supplemental Data]. This sample has a weighted

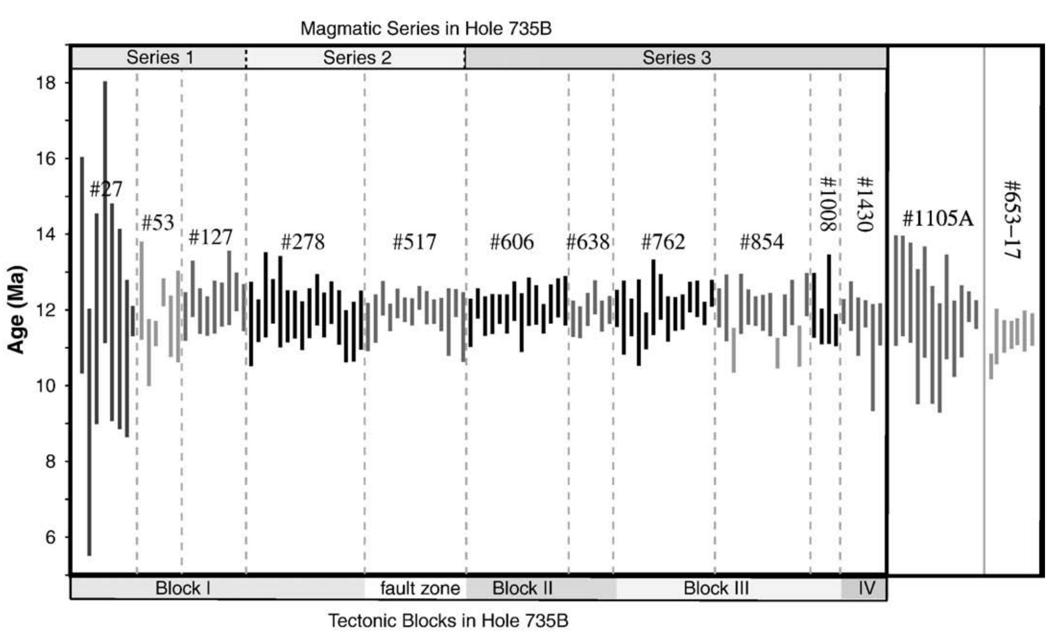

Fig. 4. Ages of spot analyses used to calculate weighted means for all samples. For samples from ODP Hole 735B, depth increases from left to right.

average Pb/U age of 11.27 ± 0.31 Ma (MSWD = 0.93). Modeling of magnetic anomalies (Baines et al., 2008) suggests a magnetic age for the sample of ~12.4 Ma (at the boundary between chrons C5Ar.1r and C5An.2n). Consequently the Pb/U age of #653-17 is > 1 Ma younger than the magnetic age. This young age together with the young age of sample #644-12 (Schwartz et al., 2005) and the young component of #854, together allude to an off-axis tectonothermal event at Atlantis Bank that effected these zircon.

5.3. Samples #26, #53 and #1008

The remaining samples (#26, #53, and #1008) gave poorly constrained ages; a detailed analysis for each sample is included in the supplementary data. The age of 11.64 ± 0.37 Ma (MSWD = 1.4) for sample #26 appears reasonably well-constrained and is within error of the 11.3 Ma age reported by Stakes et al (1991), and that of the well-constrained magmatic sample ages from Hole 735B (Fig. 2c). However, Sample #26 had very low U-concentration and the calculated age is controlled by one analysis with U > 100 ppm, so our confidence that it represents the true age of igneous crystallization is low.

Sample #53 gives a poorly constrained weighted mean age of 11.80 ± 0.64 Ma (MSWD = 5.2), due to only two concordant analyses with high U-concentrations (> 400 ppm) that are not within error. Although the younger age may reflect alteration or Pb-loss and excluding it yields an age of 12.29 ± 0.31 Ma (MSWD = 1.6) that might date the original magmatic crystallization age; an age constrained by a single grain is unreliable so we report and plot the poorly resolved weighted mean sample age obtained from all spot analyses (11.80 ± 0.64 Ma, MSWD = 5.2).

Sample #1008 yields a relatively young age (11.62 ± 0.29 Ma, MSWD = 1.1) compared to the majority of other samples analyzed (e.g. Table 1, Fig. 2c). Zircon from #1008 shows textures in CL consistent high-temperature recrystallization, diffusion or metamorphism (Supplemental Data) (Hanchar and Miller, 1993; Corfu et al., 2003) and so may record a later event following magmatic zircon crystallization. However only four zircons were suitable for dating, errors are large and the $^{206}Pb/^{238}U$ age for Sample #1008 is within error of ages calculated for the majority of other samples (Fig. 2c).

6. Discussion

6.1. The age and duration of crustal accretion in Hole 735B

The ten new Pb/U zircon ages presented here, together with the two previously reported ages (Stakes et al., 1991; John et al., 2004) make ODP Hole 735B one of the most thoroughly dated sections of in-situ oceanic crust, and allow further constraints to be placed on its evolution. Excluding the apparently young component from sample #854 and the age from Stakes et al (1991) from the following discussion, the ten samples dated in this study together with sample #606 dated by John et al (2004) yield ages within error of one another (Figs. 2c and 4). There is no resolvable variation in the ages of the tectonic blocks or magmatic series in Hole 735B suggesting that these series accreted relatively rapidly and that displacement between

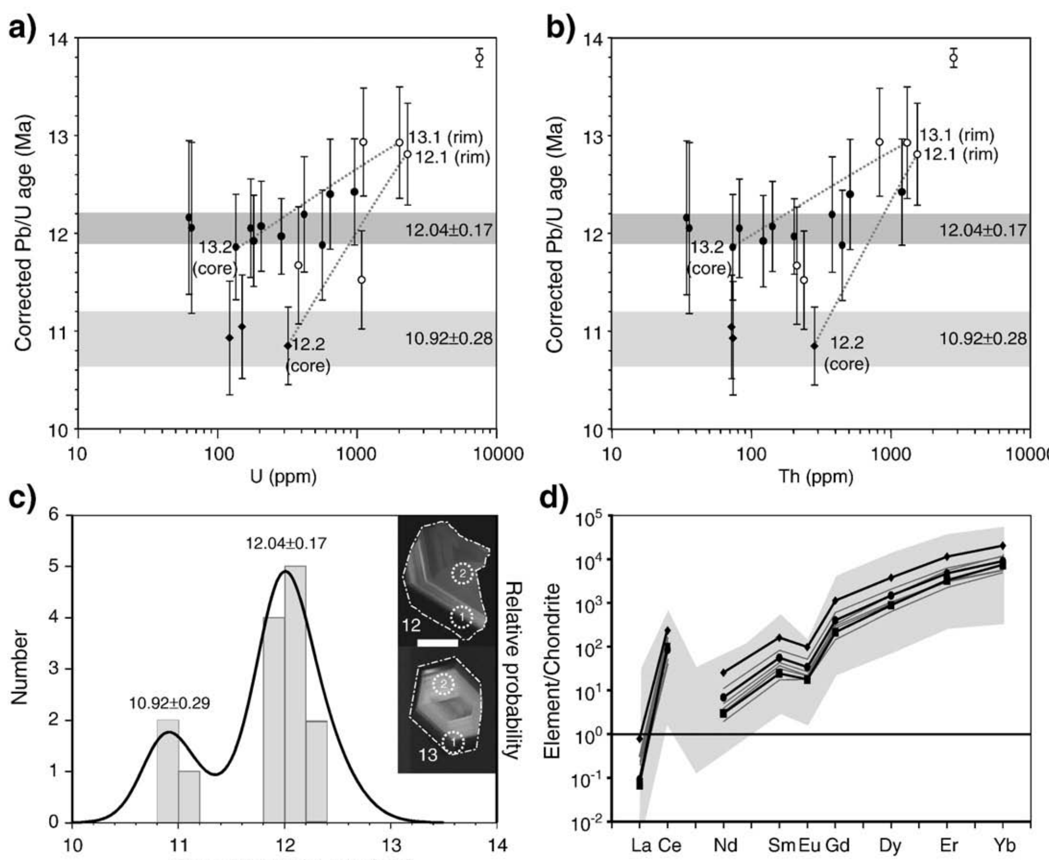

Fig. 5. Pb/U zircon age and trace element data for sample #854, a)–b) Illustrate the effect of highly radiogenic rims on the ages of spot analyses for sample #854. Analyses that overlap rims (open circles) show a positive correlation between age and the concentration of U (a) and Th (b). In contrast, the remaining analyses (filled circles and diamonds) show no correlation between age and concentration of U or Th. Analyses of cores and rims from the same grains are joined by dotted lines. c) Two age populations are observed for analyses from the cores of grains that yield significantly different ages as shown by the probability density plot and histogram of spot age. d) Rare-earth element concentrations normalized to C1 chondrite (McDonough and Sun, 1995), light grey shaded field ocean crust zircon (after Grimes et al., 2007). Dark grey lines — spot analyses from sample #854 that yield older ages. Black lines — analyses from zircon that yield anomalously young ages, where Circles spot 4.1, diamonds = spot 12.2, squares = spot 16.1.

blocks was minor. The eight well-constrained crystallization ages cluster at 11.86–12.13 Ma. These ages likely reflect the main period of crustal accretion at or near the ridge axis and are consistent with the ~11.8 Ma magnetic age of Hole 735B. A histogram and probability density function of spot analyses with 1σ error <0.3 Ma (n=63, including samples #26, #53 and #1008) demonstrates that the most precise analyses cluster closely to define an approximately symmetric, normal distribution centered at ~12.0 Ma with a width on the same scale as analytical error (Fig. 6). The weighted mean age of this population is 11.99±0.06 (0.5% error, MSWD=0.99), despite this precise age we note that the best accuracy of SHRIMP ages is limited to 1% (Black et al., 2004) so an average age estimate for Hole 735B of 11.99±0.12 Ma is more realistic.

Although when considered together the analyses define a single population, these data are from a number of samples that may have crystallized at different times. The eight well-constrained error-weighted sample ages range between 11.86±0.20 Ma and 12.13±0.21 Ma (a range of 270±290 ka, 2σ error). This range of sample ages is consistent with the >210 ka duration of episodic crustal accretion observed at the northern MAR (Gee and Meurer, 2002; Grimes et al., 2008), and the 235 ka duration of zircon crystallization accretion inferred at the Vema Transform (Lissenberg et al., 2009). However, given the error on our SHRIMP analyses, whether this accretion was accomplished by punctuated intrusive events and cooling to subsolidus temperatures in the intervening period or by accretion into a long-lived crystal mush zone remains a matter for conjecture. Further, a number of processes may affect these data at or below the scale of analytical error, 1) Schwartz et al (2005) have shown that oceanic zircon can display inheritance of older components and the potential for inheritance at or below the resolution of individual analyses cannot be ignored. 2) Lissenberg et al (2009) obtained single crystal TIMS zircon dates from oceanic gabbro that varied by 90–235 ka within individual samples. Lissenberg et al (2009) attributed this variation to protracted zircon crystallization from 800–600 °C during prolonged monotonic cooling of a gabbroic intrusion. Both of these studies show that the assumption of a single crystallization age for zircon obtained from an oceanic gabbro sample is not always valid, and variations in crystallization age can occur at or below the best analytical precision of SHRIMP analyses (1%, or 0.12 Ma for 12 Ma zircons (Black et al., 2004)). 3) In addition for such young zircon, Pb-loss may not produce discordant analyses but rather analyses will spread along concordia to younger ages, making it difficult to preclude age variations due to minor Pb-loss.

Many statistical techniques for calculating an age from multiple analyses assume that the data has a single well-defined mean; for example the error-weighted mean approach used above assumes normally distributed data with a single well-defined mean, the calculated mean and errors reflect how well that mean is defined and not the distribution or range of the observations. Thus, use of an error-weighted average is not ideal if the spread of analyses in individual samples reflects multiple discrete age components, protracted crystallization and/or Pb-loss. However, detailed analysis on each sample has shown that the spread of analyses in each sample is consistent with analytical error alone (Supplemental Data), suggesting that a single mean age can be calculated. In addition, several other algorithms used to calculate average ages for the samples gave similar estimates of the mean and confidence limits (Supplemental Data). We also note that preliminary TIMS dating of two of these samples has yielded ages that are each within 0.03 Ma of the calculated error-weighted mean SHRIMP age (M. Rioux pers. comm. 2009). Consequently, we report the error-weighted mean ages as our best estimate of the mean zircon crystallization age for each sample with the proviso that subtle and unresolvable intra-sample variations may exist but are unlikely to exceed the confidence limits on those means. Therefore, the duration of the major crustal building event may be best estimated by the range of weighted mean sample ages (270±290 Ma), with the mean age of this event in Hole 735B being 11.99±0.12 Ma.

6.2. The age of Hole 1105A and correlation with 735B

The 11.90±0.23 Ma age of the sample dated from 57 m in ODP Hole 1105A correlates well with, and is within error of, magmatic ages from Hole 735B (Figs. 2 and 4). Perhaps of most interest, given the proposed correlation between oxide-rich zones at 45–135 m in 1105A and 240–290 m in Hole 735B (Casey et al., 2007), this age correlates very well with the 11.87±0.17 Ma age of sample #278. Consequently, these felsic veins provide identical minimum ages for the oxide-rich zones that they intrude, permitting the inferred correlation between oxide-rich zones in each Hole. This suggests an along-axis continuity for >1.2 km, an inference consistent with the observation of magma chambers at slow-spreading ridges that extend for more than 7 km along-axis (Singh et al., 2006).

6.3. Apparently young ages

The apparently young age component from sample #854 and the young ages of samples 653-17 and 644-12 from normal fault scarps cutting the detachment fault (Schwartz et al., 2005) compared to the magnetic age (Fig. 7) suggest that these samples may record a tectonothermal event at or after 10.9–11.4 Ma. In addition, samples #26, #53 and #1008 yield poorly constrained ages that are relatively young,

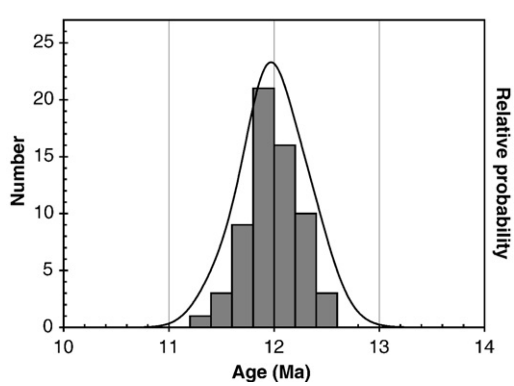

Fig. 6. A probability density plot and histogram of the ages of spot analyses, where 1σ error <0.3 Ma. The data form a single population about 12.0 Ma, with a width that is consistent with analytical error.

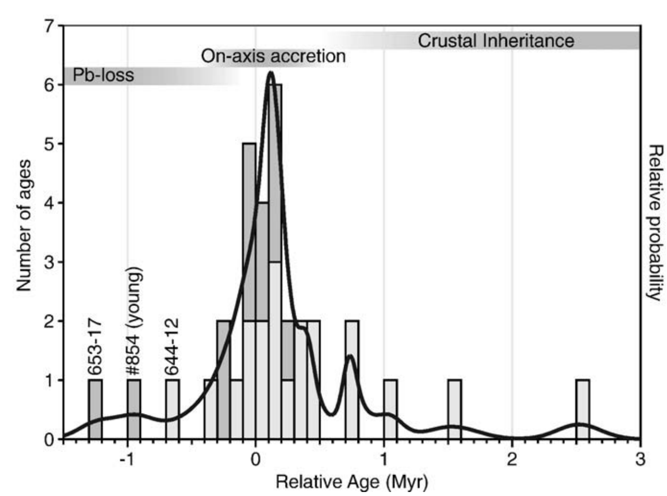

Fig. 7. Probability density functions and histograms of error-weighted mean ^{207}Pb-corrected Pb/U ages from Atlantis Bank relative to the magnetic age (after Baines et al., 2008). Dark grey boxes are ages from this study, light grey from Schwartz et al (2005). Although the bulk of ages cluster about the magnetic age (zero), a small but significant number of ages are younger and older.

therefore these zircons may record alteration following the main phase of crustal accretion. Although a late magmatic event has been hypothesized at Atlantis Bank (John et al., 2004; Schwartz et al., 2009), the young age in sample #854 is unlikely to record magmatic accretion as the felsic vein that hosts zircon is thin and most zircons record the main crust building event. For many of the other samples that yield young or poorly constrained ages, some have evidence for high-T alteration (#1008), many have poorly defined oscillatory zoning in CL (#26, #53, and #653-17) or high U rims (#53). These features may reflect later alteration or modification of the zircon that may have produced apparent Pb-loss (and possibly reduced U-concentrations (e.g. Sinha et al., 1992)). Pb-loss by volume diffusion is unlikely to have affected young and relatively low-U zircon (Cherniak and Watson, 2000; Schwartz et al., 2009), whereas other mechanisms proposed for Pb-loss have primarily been associated with radiation damage or metamict zircon and include leaching by low-T fluids (Davis and Krogh, 2000; Geisler et al., 2002), alteration by moderate-T fluids (Sinha et al., 1992; Geisler et al., 2003) and/or recrystallization/annealing/diffusion during high-T metamorphism (Hoskin and Schaltegger, 2003; McFarlane et al., 2006). Although the zircons studied here are unlikely to have accumulated significant radiation damage, we note that studies of non-metamict zircon have yielded similar, if less dramatic, results (e.g. Sinha et al., 1992). Further, the susceptibility of individual zircon grains (or domains within zircon grains) to Pb-loss is dependent on many variables including composition (U, Th and REE concentrations) (Black et al., 2004), and accumulated crystal-plastic deformation (Timms et al., 2006; Reddy et al., 2006). The chemical effects of Pb-loss and recrystallization are variable (e.g. Vavra et al., 1999) and depend on the metamorphic conditions or the composition and temperature of fluids (Sinha et al., 1992; Geisler et al., 2003; Hoskin and Schaltegger, 2003). This uncertainty in characterizing alteration of zircon and its effect on U–Pb ages is compounded for relatively young samples, in which alteration will move analyses along, rather than off, concordia. Despite these uncertainties in identifying or accounting for Pb-loss, we consider it more likely that these young ages record alteration, recrystallization and associated Pb-loss from pre-existing zircon during an off-axis thermal event at Atlantis Bank (John et al., 2004; Schwartz et al., 2009) than recording magmatic crystallization. The convolute zoning in CL, poorly defined zoning in CL, and high U rims displayed by several zircon that yield relatively young ages may be related to hydrothermal fluid flow inferred to have affected many felsic veins in Hole 735B (Robinson et al., 2002).

6.4. The proportion of anomalously old crust

The inheritance or entrainment of zircons up to 2.5 Ma older than the magnetic age, was previously reported for rocks obtained from the surface of Atlantis Bank (Schwartz et al., 2005). Up to 25% of ages from the surface are anomalously old. We do not observe anomalously old zircon ages within ODP Holes 735B or 1105A. Combining ages from this study with previously reported ages (Schwartz et al., 2005), the estimated proportion of inherited crust at Atlantis Bank is reduced to 15% (5 of 33 ages) (Fig. 7). The apparent discrepancy between these two studies may merely reflect the small number of samples analyzed, however, we note the same observations at Atlantis Massif, where one of only six samples dated from the surface yielded an anomalously old age, whereas 18 samples dated from ODP Hole 1309D did not (Grimes et al., 2008). The apparent discrepancy between surface and drill-hole samples may reflect differences in sample spacing, distribution or geological setting. While it is possible the inherited component observed in surface samples might be related to tectonic reworking along the detachment fault systems that form the majority of the seafloor in these settings. This alternative is considered to be unlikely as it would require samples to be displaced >25 km along a detachment fault system and cannot account for incorporation of inherited cores into zircons with magmatic rims that are the same age as the magnetic age (Schwartz et al., 2005). The discrepancy is more likely to reflect sample spacing; the average sampling interval within the 1.5 km-long Hole 735B is ~130 m, compared to an average of 3 km between the 17 samples dated from the surface of Atlantis Bank that cover an area of ~500 km^2 (Schwartz et al., 2005). If inherited zircons or older crust occur in relatively large but widely separated plutons we might not expect a borehole to intersect such a pluton, while the more distributed surface sampling might sample several areas of older crust and provide a more accurate estimate of crustal inheritance.

7. Conclusions

- Zircons from twelve samples, ten from ODP Hole 735B, one from ODP Hole 1105A and one from the surface of Atlantis Bank have been analyzed to determine SHRIMP ^{206}Pb/^{238}U zircon ages. The ten samples analyzed from Hole 735B together with two previous zircon ages (Stakes et al., 1991; John et al., 2004) make Hole 735B one of the best dated sections of lower oceanic crust to date.
- The majority of samples analyzed at Atlantis Bank date crustal accretion on axis (Fig. 7). In Hole 735B, ages that date crustal accretion are within error. The average age of analyses from Hole 735B is 11.99 ± 0.12 Ma (1% error), but the range of well-constrained sample ages from 11.86–12.13 Ma, may imply relatively protracted accretion during a major on-axis crust building event that lasted approximately 270 ± 290 kyr. This range is similar to previous observations from the MAR (Grimes et al., 2008; Lissenberg et al., 2009).
- For the first time, a Pb/U zircon age is presented for ODP Hole 1105A, located 1.2 km east of Hole 735B. The age of 11.87 ± 0.23 Ma is within error of ages from Hole 735B and supports previous correlations suggested between zones of oxide-rich gabbros in ODP Holes 1105A and 735B (Casey et al., 2007).
- One sample within Hole 735B and two from scarps that cut the surface of Atlantis Bank yield anomalously young Pb/U zircon ages of 10.9–11.3 Ma. These young ages may record Pb-loss or alteration of zircon and may be consistent with thermochronologic data from Atlantis Bank (John et al., 2004; Schwartz et al., 2009) that indicate a prolonged history of tectonic, magmatic or hydrothermal activity following crustal accretion at Atlantis Bank.
- The new ages reduce the estimate of the proportion of old crust at Atlantis Bank from 25% (Schwartz et al., 2005) to ~15%, although this may reflect a bias towards the relatively over-sampled ODP Hole 735B.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at DOI:10.1016/j.epsl.2009.09.002.

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