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Lower oceanic crust formed at an ultra-slow-spreading ridge: Ocean Drilling Program Hole 735B, Southwest Indian Ridge

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ABSTRACT

Ocean Drilling Program (ODP) Hole 735B, drilled on Legs 118 and 176, penetrated 1508 m of oceanic layer 3 on a transverse ridge adjacent to the Atlantis II Fracture Zone, Southwest Indian Ridge. The cored sequence consists predominantly of olivine gabbro and troctolite and lesser amounts of gabbro, microgabbro, and gabbronorite rich in Fe-Ti oxides. The section contains five major blocks of relatively primitive olivine gabbro and troctolite, composed of many smaller igneous bodies. Each of these composite blocks shows a small upward decrease in Mg# [defined as 100 × Mg/(Mg + Fe^{2+})] and contains more fractionated Fe- and Ti-rich gabbros near the top. Small, crosscutting bodies of olivine gabbro and troctolite with diffuse boundaries may represent conduits through crystal mushes for melts migrating upward and feeding individual intrusions. Oxide gabbros and oxide gabbronorites are commonly associated with shear zones of intense deformation, which crosscut the section at all levels. However, oxide-rich rocks decrease in abundance downward and are nearly absent in the lower 500 m of the section. The oxide gabbros and gabbronorites appear to have formed from late-stage, Fe- and Ti-rich, intercumulus melts that were expelled out of fractionating olivine gabbros into the shear zones.

The fabrics of the recovered gabbros are consistent with synkinematic cooling and extension of the crustal section in a mid-ocean ridge environment. However, thick intervals of the core have only a weak magmatic foliation. The magmatic foliation is commonly overprinted by a weak, parallel, deformational fabric probably reflecting the transition from a largely magmatic to a largely crystalline state. Deformation in this crustal section decreases markedly downward.

Metamorphism and alteration also decrease downward, and much of the core has less than 5% background alteration. Major zones of crystal-plastic (ductile flow by dislocated creep) deformation in the upper part of the core probably formed under conditions equivalent to granulite-facies conditions when there was little or no melt present. Late-magmatic and hydrothermal fluids produced a variety of plagioclase, amphibole, and diopside veins. Late-stage, low-temperature veins of calcite, smectite, zeolite, and prehnite are present in a few intervals.

The fact that the cored section is unlike ophiolites as defined by the 1972 Penrose Conference Participants suggests that no ophiolite representing an ultra-slow-spreading-ridge environment like the Southwest Indian Ridge may be preserved.

INTRODUCTION

During the past 30 years of ocean drilling, a great deal has been learned about the upper ocean crust. Numerous holes have penetrated the upper few hundred meters of oceanic layer 2 and have yielded large amounts of data on the petrology, geochemistry, magnetic character, and physical properties of the basement. One hole, ODP (Ocean Drilling Program) Hole 504B, penetrated slightly >2000 m into basement, sampling all of the volcanic layer and the upper part of the sheeted-dike sequence. Some workers have suggested that this hole penetrated the layer 2–layer 3 boundary (Detrick et al., 1994); if so, it is the only hole in the oceans to have done so.

Despite many efforts to penetrate and sample the lower ocean crust, we still have very little information on oceanic layer 3. Gabbros interpreted as layer 3 rocks have been dredged from slow-spreading ridges, such as the Mid-Atlantic Ridge and the Southwest Indian

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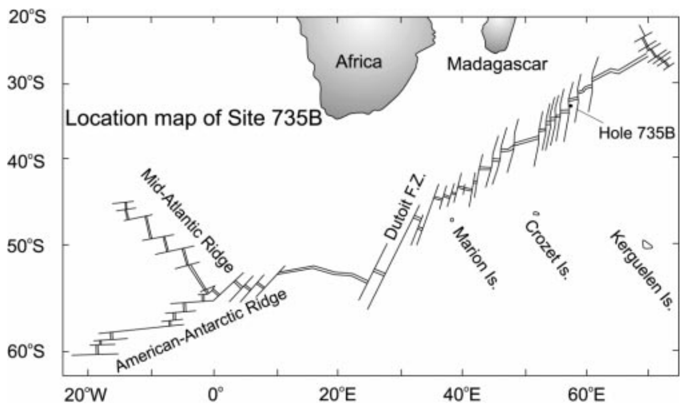

Figure 1. Southwest Indian Ridge showing location of ODP Hole 735B on the Atlantis II Fracture Zone.

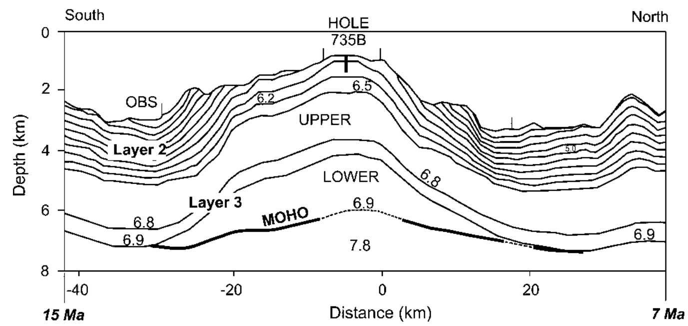

Figure 2. P-wave seismic velocity model for the Atlantis Bank and surrounding area on the north-south Line CAM 101 (Muller et al., 1997). The velocity contour interval is 0.3 km/s, and the OBS (ocean-bottom seismograph) locations are shown on the seafloor. The position of Hole 735B has been projected to the line from 1 km to the west.

Ridge (Fisher et al., 1986) and were sampled on a few DSDP (Deep Sea Drilling Project) legs (37, 45, 83) prior to ODP Leg 118. However, available samples are sparse and gave a very incomplete picture of the lower crust.

During ODP Leg 118, the *JOIDES Resolution* spudded Hole 735B on the Atlantis Bank on the eastern side of the Atlantis II Fracture Zone and drilled to a depth of 500.7 m with 87% recovery (Robinson, Von Herzen, et al., 1989). The hole penetrated a sequence of gabbros, gabbronorites, oxide gabbros, and troctolites with the seismic characteristics and physical properties of oceanic layer 3. In 1997, the *JOIDES Resolution* returned to this site and deepened the hole to 1508 mbsf (meters below seafloor), again with very high core recovery (Shipboard Scientific Party, 1999). The recovered core represents the first significant sample of in situ lower ocean crust, and its study has produced many new insights into crustal-accretion processes at ultra-slow-spreading ridges.

TECTONIC SETTING OF SITE 735

ODP Site 735 is located on the east side of the Atlantis II Fracture Zone, which offsets the Southwest Indian Ridge at long ~57°E (Fig. 1). The ridge originated with the breakup of Gondwana in the Mesozoic and, just prior to 80 Ma, joined the Central and Southeastern Indian Ridges to form the Indian Ocean triple junction (Fisher and Sclater, 1983). Once formed, the triple junction migrated steadily to the northeast, creating a number of new ridge segments and fracture zones, including the Atlantis II Fracture Zone (Sclater et al., 1981). Both the fracture zone and the adjacent crust are entirely oceanic in origin and have been unaffected by processes associated with continental breakup. Spreading on the Southwest Indian Ridge has been relatively constant over the past 30 m.y. at a half rate of 8 mm/yr (Fisher and Sclater, 1983); this half rate places the ridge at the very low end of the spreading-rate spectrum.

The Atlantis II Fracture Zone is a 199-km-long, left-lateral ridge offset that grew at a rate of ~4 mm/yr over the past 20 m.y. (Dick et al., 1991b, 1991c). The transform valley is a deep feature with relief just over 5500 m; the valley extends from 6480 mbsl (meters below sea level) at its deepest point to 694 mbsl on the shallowest part of the Atlantis Bank. The walls are very steep; the slopes range from ~25° to 40° and are typically covered with abundant talus. A turbidite sequence as much as 500 m thick covers the valley floor, which is bisected by a median ridge 1.5 km high. On the transform-valley walls, 37 dredges were carried out during the 1986 site survey and recovered a large volume of rock composed of 38% peridotite, 20% gabbro, 13% diabase, and 29% pillow lava. Peridotite was dredged from 5675 to 2548 mbsl and gabbro from 6050 to 1500 mbsl; peridotite and gabbro occurred together in eight dredges from 5652 to 3200 mbsl (Dick et al., 1991c). These lithology distributions suggest that the crust-mantle boundary lies at ~2500 mbsl on the fracture-zone wall.

Hole 735B is located on the Atlantis Bank, a flat-topped, steep-sided platform ~9 km long in a north-south direction and 4 km wide. The bank is the shallowest of a series of uplifted blocks that form a linear transverse ridge parallel to the transform. The platform has a wave-cut, commonly bare-rock, surface exposing foliated and massive gabbro, crisscrossed by a network of joints and veins. Locally, it is mantled with a thin layer of carbonate sediment. After truncation by wave action, it subsided to its present depth, presumably by normal lithospheric cooling (Dick et al., 1992).

On the basis of well-defined magnetic anomalies that cross the Atlantis Bank (anomaly 5r.2n, 11.75 Ma), this crustal segment was formed at the Southwest Indian Ridge at ca. 11.5 Ma. A U-Pb isotopic age on zircon from trondhjemite recovered in Hole 735B confirms the magnetic anomaly age (Stakes et al., 1991). The Atlantis Bank gabbros are believed to have formed beneath the ridge axis ~15–19 km from the current ridge-transform intersection (Dick et al., 1991c, 1992).

A recent survey of the area (Muller et al., 1997) suggests that the crustal thickness ranges from 5 to 6 km and that the maximum thickness is directly beneath the Atlantis Bank (Fig. 2). Despite the absence of both sheeted dikes and pillow lavas, Muller et al. (1997) postulated a 2-km-thick seismic layer 2 beneath the Atlantis Bank; they placed the Moho at a depth of 6 km below sea level. In this ultra-slow-spreading environment near the distal end of a ridge segment, it is unlikely that the lower igneous crust would be 5–6 km thick. Partially serpentinized peridotites, dredged from the west wall of the bank at water depths of ~2500 m, suggest that the gabbro-peridotite boundary is significantly higher than the seismic Moho postulated by Muller et al. (1997). Thus, the low seismic velocities beneath the Atlantis Bank probably reflect extensive serpentinization of the upper mantle.

The emplacement and unroofing of the Atlantis Bank are thought to reflect detachment faulting during a period of amagmatic spreading in the rift valley (Dick et al., 1991c, 1992). During the initial stages of faulting, the section was thinned as the upper sequence of lavas and sheeted dikes was removed, thus exposing the lower crust. This tectonic erosion was followed by block uplift as the crustal section migrated out of the rift valley and into the inside-corner high at the

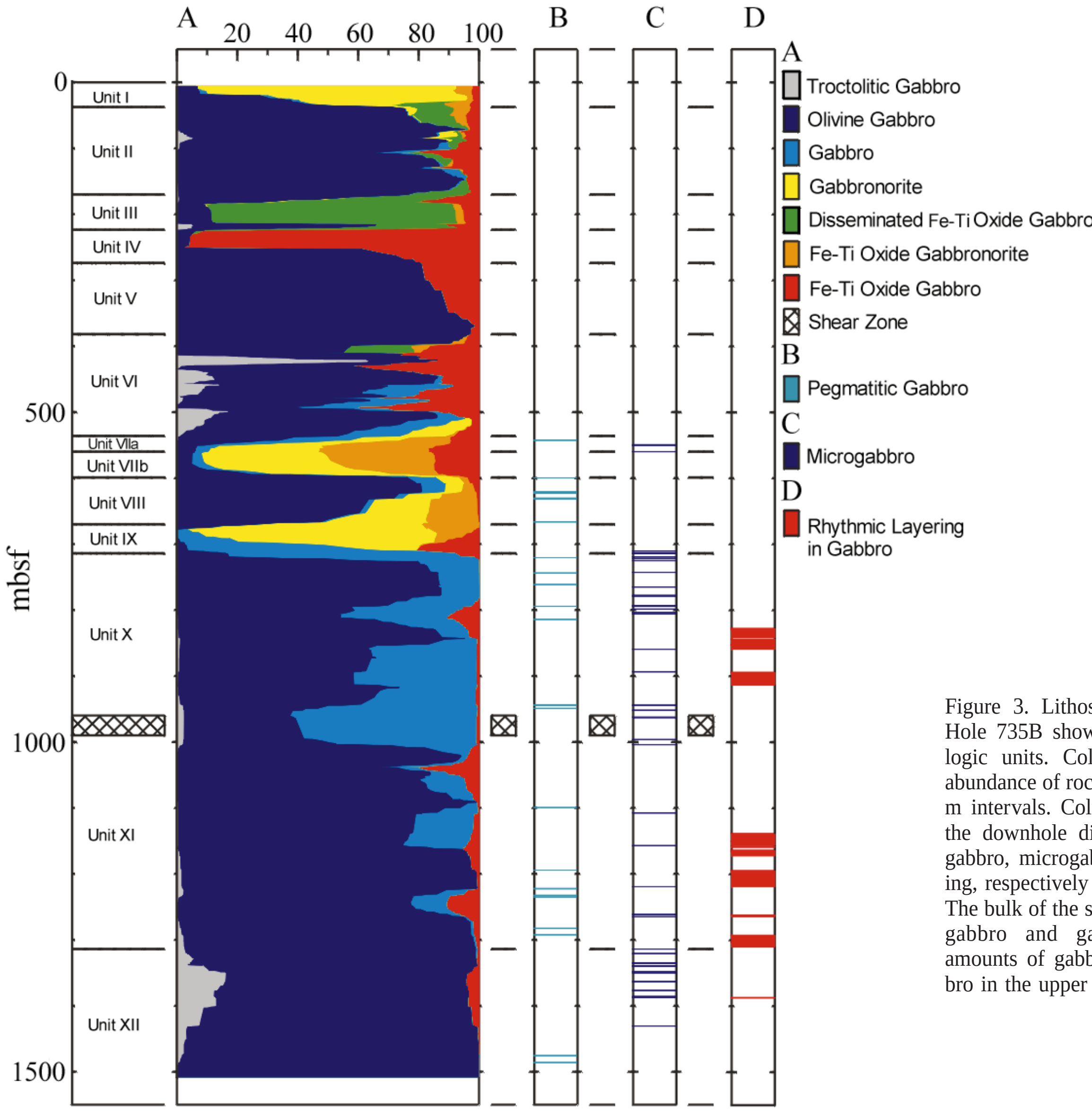

Figure 3. Lithostratigraphic column for Hole 735B showing the 12 major lithologic units. Column A is the relative abundance of rock types averaged over 20 m intervals. Columns B, C, and D give the downhole distribution of pegmatitic gabbro, microgabbro, and igneous layering, respectively (after Dick et al., 1999). The bulk of the section consists of olivine gabbro and gabbro with significant amounts of gabbronorite and oxide gabbro in the upper 700 m.

ridge-transform intersection. Uplift continued until the section reached wave base where it was eroded to form the smooth platform observed today (MacLeod et al., 1999). After truncation by wave action, the section then subsided to its current level.

In 1998, another ODP Hole (1105A) was drilled on the Atlantis Bank ~1.2 km from 735B as part of an engineering leg (179) to test the newly developed hammer-in casing. This hole penetrated 158 m and recovered 118.43 m of gabbro, olivine gabbro, oxide gabbro, and felsic rocks, similar to those in Hole 735B (Pettigrew, Casey, et al., 1999). Study of these rocks will provide valuable information on the three-dimensional structure of the bank.

LITHOLOGY OF THE LOWER OCEAN CRUST

During two legs of drilling, Hole 735B penetrated 1508 m into the lower oceanic crust with an average of 87% recovery. However, low recovery occurred primarily in the upper 100 m of the hole and in narrow shear zones at several depths; thus there were long sections in which core recovery was close to 100% (Robinson, Von Herzen, et al., 1989; Shipboard Scientific Party, 1999).

Twelve major lithologic units have been recognized in Hole 735B; they range in thickness from 44 to 354 m (Fig. 3). The bulk of the section consists of olivine gabbro and lesser amounts of gabbro and troctolitic gabbro, although gabbronorite is abundant in lithologic units I, VII, and IX. Fe-Ti oxide gabbro, Fe-Ti oxide gabbronorite, and disseminated Fe-Ti oxide gabbro are common in the upper 700 m of the section where they are typically associated with zones of crystal-plastic deformation (Dick et al., 1991a) (Fig. 4). These relatively evolved rocks are much less abundant in the lower parts of the section where deformation is also less intense. The average modal compositions of the different rock types are given in Table 1.

Most of the recovered rocks are equigranular with an average grain size between 5 and 15 mm. The principal minerals are similar in size and follow the same general trends. Where there is a disparity among the minerals, the size order is usually pyroxene > plagioclase > olivine. The grain sizes in varitextured zones range from fine (<1

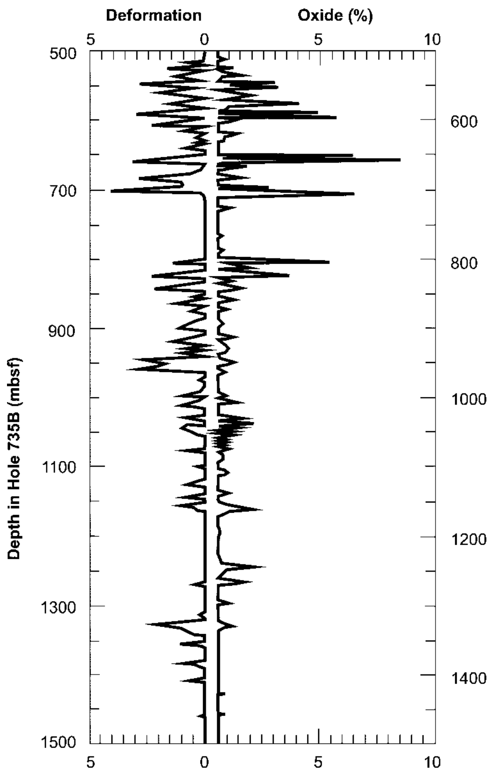

Figure 4. Downhole profile of the lower 1000 m of Hole 735B showing the relationship between intensity of crystal-plastic deformation and abundance of oxides in the core (Shipboard Scientific Party, 1999). Deformation intensity is on an arbitrary scale of 0–5.

mm) to pegmatitic (>30 mm); such zones are scattered throughout the core; grain-size peaks occur at 510, 635, 825, 1100, 1215, 1300, 1425, and 1480 mbsf (Fig. 3).

Grain-size or modal layering is rare, being present in only ~12% of the core (Fig. 3). Grain-size variations may be sharp or gradational over a few tens of centimeters whereas modal layering is typically defined by distinct changes in the proportions of olivine, pyroxene, and plagioclase. Layering may also be defined by textural changes or by weak magmatic foliations.

The dominant coarse-grained olivine gabbro is cut by numerous fine- to medium-grained bodies of microgabbro, gabbronorite, olivine gabbro, and troctolite with either sharp or gradational contacts (Bloomer et al., 1991). Sharp contacts are typically planar with distinctly finer grain sizes whereas gradational contacts swirl and curve through the host rock. These crosscutting bodies may represent channelways along which hot, relatively primitive melts fed upward into the overlying intrusions, or the bodies could be protodikes. One definite, fine-grained diabase dike with planar, chilled margins cuts the sequence at 105 mbsf, and a 0.5-m-thick interval of recrystallized diabase intercalated with highly deformed gneiss at 25 mbsf is interpreted as a dike.

Oxide gabbro, Fe-Ti oxide olivine gabbro, and Fe-Ti oxide gabbronorite make up ~15% of the recovered core, but they are abundant only in the upper 600 m of the section (Fig. 3). Fe-Ti oxides are most abundant in lithologic unit III (primarily disseminated-oxide olivine gabbro) and unit IV (massive-oxide olivine gabbro). Most of these rocks have a weak to strong penetrative foliation due to crystal-plastic deformation. They consist primarily of clinopyroxene, plagioclase and olivine, locally accompanied by hypersthene or pigeonite. Fe-Ti oxides range from <1 to 50 mod% (modal percent) and consist chiefly of ilmenite and magnetite (Natland et al., 1991; Ozawa et al., 1991). The oxides are typically anhedral and occur in thin bands or anastomosing layers that surround the silicate minerals and commonly define a foliation in the rock. They also fill what appear to be pull-apart cracks in large pyroxene and plagioclase grains. Apatite and sphene are closely associated with the oxide bands and form euhedral to subhedral crystals up to several millimeters across.

Although not voluminous (<0.5 vol%), felsic rocks are common and widely distributed in the core. These are mostly leucodiorites, accompanied by lesser amounts of trondhjemite, tonalite, and rare granite. They typically form narrow veins or small, irregular patches of uncertain origin. Many felsic veins are either hydrothermal in origin or show a hydrothermal overprint, but some of the veins and patches have sharp chilled boundaries and retain igneous textures. Most of them consist of sodic plagioclase and minor amphibole, but some contain variable amounts of quartz, diopside, sphene, and zircon.

METAMORPHISM AND ALTERATION

The cored sequence in Hole 735B preserves a complex record of metamorphism and alteration spanning a range from near-solidus to near-ambient temperatures. Granulite- and amphibolite-facies metamorphism is recorded in pyroxene and amphibole gneisses at the top of the section, and lower-temperature background alteration is widespread, particularly in the upper 1000 m. Hydrothermal veins are also abundant in the upper parts of the section and range from high-temperature diopside-rich veins to low-temperature carbonate and zeolite varieties. Background alteration generally ranges from <1% to over 40%, although it reaches nearly 100% in some narrow intervals (Fig. 5). The most abundant and pervasive background alteration occurs in the interval between 500 and 600 mbsf. In general, both metamorphism and alteration decrease downward, and below 1000 m there are long intervals of nearly fresh rock.

Five principal styles of metamorphism and alteration are recorded in the core (Robinson et al., 1991): (1) high-temperature metamorphism associated with zones of crystal-plastic deformation that produced pyroxene and amphibole gneisses; (2) static replacement of olivine and locally orthopyroxene by talc, Mg-amphibole, and secondary magnetite and marginal replacement of pyroxene by brown

TABLE 1. AVERAGE PRIMARY MODAL COMPOSITIONS (%) OF THE MAJOR ROCK TYPES IN HOLE 735B

Rock type	Olivine	Orthopyroxene	Clinopyroxene	Amphibole	Plagioclase	Opaques	Apatite
Troctolite	30	0	3	0	67	<1	0
Troctolitic Gabbro	16	<1	11	<1	73	<1	0
Olivine Gabbro	10	<1	31	<1	59	<1	0
Gabbro	3	<1	38	<1	59	<1	tr
Gabbronorite	3	4	26	1	65	1	tr
Oxide Gabbronorite	1	4	34	<1	52	9	<1
Oxide Gabbro	2	<1	40	<1	52	6	<1

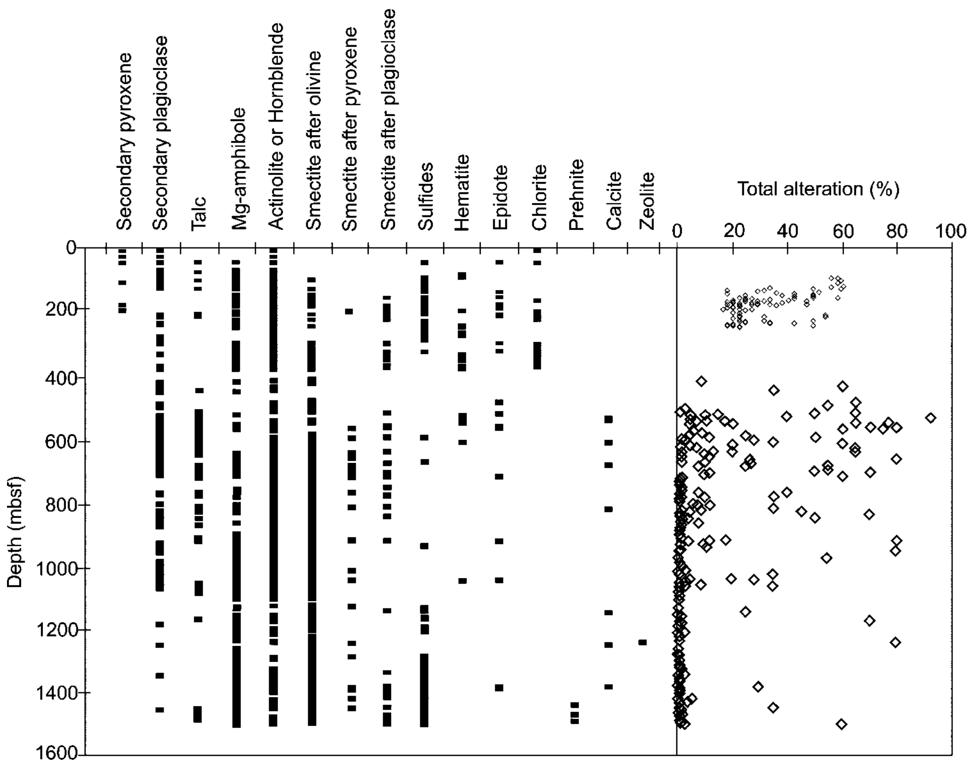

Figure 5. Intensity of background alteration and distribution of secondary minerals in Hole 735B (data from Robinson, unpublished data, and Shipboard Scientific Party, 1999).

and green amphibole; (3) infilling of hydrothermal veins formed during brittle deformation; (4) late-stage, low-temperature replacement of olivine and some pyroxene by carbonate and Fe oxides; and (5) deposition of smectite in subvertical fractures.

Granulite-facies metamorphism (>800–950 °C) is preserved in narrow zones of crystal-plastic deformation where intense shearing has produced bands of olivine and pyroxene neoblasts that alternate with plagioclase-rich bands. A few of these zones are impregnated with Fe-Ti oxides, and many have abundant brown hornblende, indicating that deformation continued as the temperature decreased and the water/rock ratios increased. Amphibole gneisses are particularly well developed in the upper 50 m of the section (lithologic unit I) but also occur in lithologic unit II and in thin shear zones lower in the section. Most of these rocks have a well-developed foliation and consist chiefly of green or brown amphibole and plagioclase, with lesser amounts of Fe-Ti oxides and brown mica. A few samples contain small amounts of actinolitic amphibole and intermediate to sodic plagioclase. Porphyroclasts of pyroxene, many of which are also replaced by amphibole, are preserved in some of the less deformed rocks.

In weakly deformed or undeformed rocks, the background alteration is much less intense and chiefly involves partial replacement of (1) pyroxene by brown and green amphibole; (2) olivine by talc, amphibole, and secondary magnetite; and (3) plagioclase by minor amphibole, smectite, or sodic feldspar. Background alteration decreases downward, and long intervals in the lower part of the core are nearly pristine.

More than 3000 separate veins were identified in the 1508-m-long section, and these make up ~2.5% of the recovered core. Most of the veins occur in the upper 500 m of the section; below this level they decrease rapidly (Fig. 6) Only a few low-temperature carbonate and smectite veins occur in the lower 700 m of the sequence.

Five major categories of veins are recognized on the basis of their mineral constituents: (1) felsic, including plagioclase and plagioclase + amphibole veins; (2) diopside and diopside + plagioclase veins; (3) amphibole veins; (4) carbonate and smectite veins; and (5) chlorite, zeolite, and prehnite veins (Fig. 6). In addition, there are a few small veins of epidote and quartz, but these are very rare. This is a rather arbitrary division because many veins are zoned with high-temperature minerals along the margins and lower-temperature minerals in the centers.

Felsic material that does not exhibit a strong hydrothermal overprint typically occurs as anastomosing veinlets and/or irregular patches as wide as 15 cm. By number, these veins constitute only ~4% of the total, but they account for 45 vol%. Most have sharp boundaries with the host rock, but some, particularly those with a hydrothermal overprint, have alteration halos 1–2 cm wide. They tend to be associated with oxide gabbros and, thus, decrease markedly in abundance in the lower parts of the section.

Dioritic veins consist chiefly of intermediate plagioclase and small amounts of amphibole and 1%–2% of accessory minerals such as apatite, zircon, titanite, and magnetite. Those with more granitic compositions contain small amounts of potassium feldspar and quartz or myrmekite and trace amounts of biotite. Veins with a hydrothermal overprint typically contain strongly zoned plagioclase, abundant brown or green amphibole, and chlorite. In some of these veins, quartz grains are partly replaced with brown smectite.

Plagioclase and plagioclase + amphibole veins are typically associated with the felsic veins and are commonly difficult to distinguish from them. In many cases, the plagioclase veins have splayed off larger felsic veins, and the plagioclase veins nearly always display a strong hydrothermal overprint. Plagioclase is the dominant mineral in these veins, and it commonly shows significant hydrothermal alteration to sodic feldspar, chlorite, zeolite, carbonate, smectite, and prehnite. Most of these veins contain at least small amounts of green amphibole, partly altered to colorless amphibole, chlorite, and secondary magnetite.

Monomineralic amphibole veins are abundant only in the upper 200 m of the section (Fig. 6) where they are closely associated with highly deformed amphibole gneisses in lithologic units I and II. A

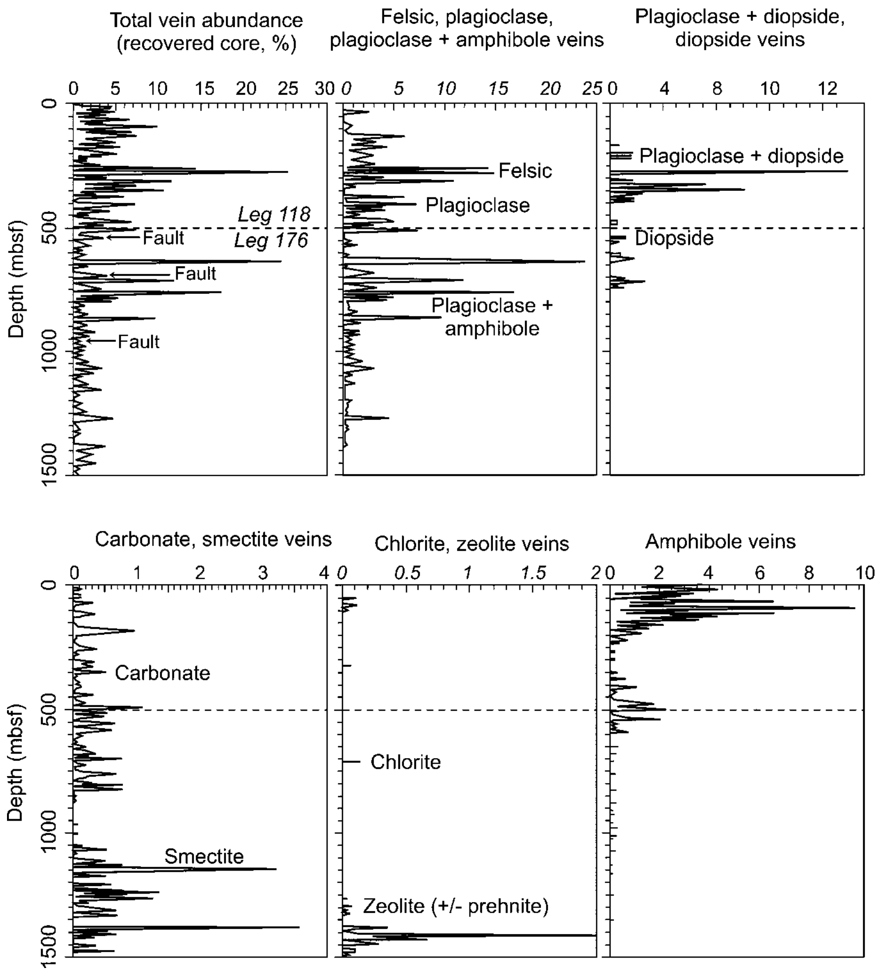

Figure 6. Downhole distribution of veins in ODP Hole 735B by the percentage of core. Note the predominance of relatively high temperature veins in the upper 750 m and the downward decrease in total vein abundance (Leg 118 data from Dick, et al., 1991; Leg 176 data from Shipboard Scientific Party, 1999).

smaller cluster occurs between ~350 and 550 mbsf; amphibole veins virtually disappear in the lower parts of the section. These veins are typically 1–2 mm wide and consist almost entirely of green or brownish-green amphibole, locally accompanied by small amounts of plagioclase, titanite, and chlorite. Most of them show little or no hydrothermal alteration although locally the amphibole is rimmed by chlorite.

Diopside and plagioclase + diopside veins are restricted to the interval between ~200 and 750 mbsf where they form several small clusters (Fig. 6). Typical examples have relatively large (up to 2 mm), euhedral to subhedral crystals of diopside along the vein margins, followed inward by mixtures of amphibole and plagioclase. A few have rims of plagioclase along the vein wall. Many of the diopside crystals are strongly zoned, filled with small, dark inclusions, and rimmed by amphibole. Late-stage, lower-temperature minerals such as prehnite, carbonate, smectite, chlorite, and various zeolites are commonly present in the vein groundmass.

Carbonate and smectite veins are irregularly distributed through the section except for a 200-m-thick interval between ~850 and 1050 mbsf (Fig. 6). Most of these are monomineralic smectite veins, ranging from hairline cracks to ~1 mm in width, although mixed smectite + carbonate veins are locally present. The carbonate veins tend to occur in narrow clusters and are almost always associated with zones of late-stage oxidation of olivine and orthopyroxene.

Zeolite veins occur only near the base of the section between ~1300 and 1500 mbsf (Fig. 6). They are typically 1–2 mm wide and consist chiefly of natrolite, prehnite, and smectite.

GEOCHEMISTRY

The rocks recovered from Hole 735B span a wide compositional range from troctolite to granite; olivine gabbro and gabbro are the most voluminous. Felsic and silicic rocks are present in very small quantities and are restricted to net veins and irregular groundmass patches. Fe-Ti oxide gabbros, on the other hand, are common and voluminous and display the most extreme lithologic and geochemical variations in the section. Magnesium numbers [defined as 100 × Mg/(Mg + Fe^{2+})] range from 87 in the most primitive troctolites to 24 in the most evolved felsic units (Fig. 7).

Troctolites, particularly those between 500 and 520 mbsf, are the most primitive rocks recovered. They are characterized by high Mg#s (>80), low SiO_2, relatively high Al_2O_3, low Na_2O and CaO (Table 2), and very low incompatible elements such as Ti, Zr, and Y. Locally, the troctolites pass imperceptibly into troctolitic gabbros and then olivine gabbros with slightly increasing SiO_2, CaO, TiO_2, Zr, and Y and decreasing Al_2O_3 and MgO. The troctolites between 419 and 520 m, however, are clearly intrusive into the olivine gabbros and form a distinct group of extremely primitive rocks.

Gabbros are almost indistinguishable geochemically from olivine gabbros except for having slightly lower MgO and slightly higher CaO, which together reflect the decrease in olivine and the increase in plagioclase.

Oxide gabbros are characterized by high Fe_2O_3 and TiO_2, relatively high Na_2O and P_2O_5, and low MgO, Al_2O_3, and CaO (Table 2). These are relatively evolved rocks with Mg#s generally between

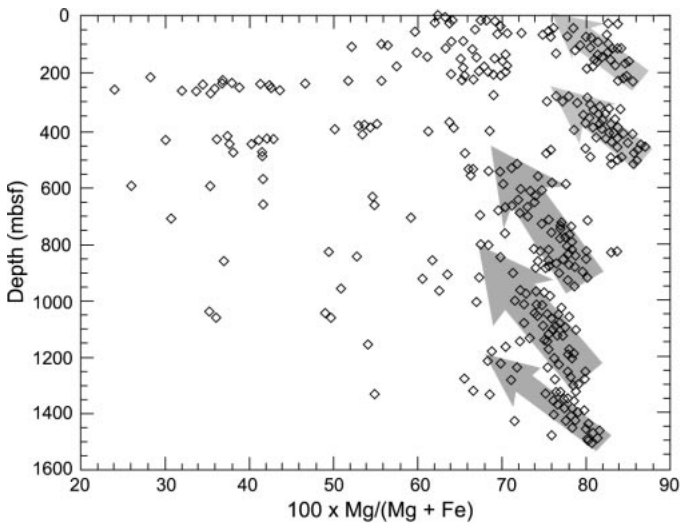

Figure 7. Mg# [defined as 100 × Mg/(Mg + Fe^{2+})] vs. depth for samples from Hole 735B. Mg#s are calculated by assuming that FeO equals 85% of the total Fe. Shaded arrows define five magmatic sequences that become more evolved upward. Each sequence is tentatively interpreted as an intrusive body made up of many smaller igneous units (after Dick et al., 1999, and Shipboard Scientific Party, 1999).

26 and 70. In the upper 500 m of the section, oxide olivine gabbros have an average Mg# of 29.6. Felsic samples have notably high SiO_2, Al_2O_3, Na_2O, and K_2O and low Fe_2O_3, MgO, and CaO. They have somewhat higher Mg#s than the oxide gabbros and the lowest Ca#s [defined as 100 × Ca/(Ca + Al)] of all the recovered rocks.

Overall, the section appears to have been constructed from as many as five major intrusions, each of which has differentiated upward from primitive to evolved compositions (Fig. 7). Boundaries between the five units lie at ~225 m, ~560 m, ~950 m, and ~1350 m depth. Although Mg#s are imperfect differentiation indices in Fe-Ti oxide gabbros, there are fairly clear fractionation patterns with depth. The very low Mg#s (<40) reflect, in part, addition of Fe-Ti oxides to the host gabbros, although a few represent highly evolved felsic rocks. However, even when these late-stage, oxide-rich rocks, which intrude or crosscut the section along shear zones, are removed from consideration, the main body of gabbro, disseminated-oxide gabbro, olivine gabbro, and troctolite shows a cyclic geochemistry (Fig. 7). In the main body of rocks, Mg#s range from a high of 87 in troctolites to a low of 63 in disseminated-oxide gabbros. It is noteworthy that the initial melts in the lower three cycles are less primitive than those in the upper two cycles (Fig. 7), a feature consistent with the observed variations in bulk-rock compositions.

The geochemical boundary at 560 m corresponds to a major fault and that at 960 m to a major shear zone (Shipboard Scientific Party, 1999).

STRUCTURAL GEOLOGY

The Hole 735B section exhibits a wide range of structural features, with considerable variation in the style and intensity of deformation. Highly deformed amphibole gneisses and mylonites alternate with essentially undeformed sections, but there is a general decrease downward in the intensity and distribution of deformation. Faults range from major features to narrow shear zones and show both normal and reverse sense of shear.

Primary magmatic foliations are locally present but are usually overprinted by crystal-plastic deformation.

Most of the rocks from Hole 735B are coarse- to medium-grained with hypidiomorphic-granular, intergranular, or subophitic textures. Where present, magmatic foliations are normally weak and are defined by the parallel alignment of platy minerals, particularly plagioclase or, more rarely, clinopyroxene. The magmatic foliations have no preferred orientation although most dip from 20° to 50° in the core (Shipboard Scientific Party, 1999).

Crystal-plastic deformation is highly localized and is most pronounced in the intervals between 0 and 50 mbsf and between 450 and 600 mbsf (Fig. 8). Most of the rocks (77%) have no crystal-plastic deformation, and only 7% have more than a weak foliation.

TABLE 2. AVERAGED MAJOR OXIDE COMPOSITIONS OF SAMPLES FROM HOLE 735B AS A FUNCTION OF ROCK TYPE AND DEPTH IN THE DRILL CORE

Rock type	Depth (mbsf)	N†	SiO_2	TiO_2	Al_3O_2	Fe_2O_3§	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
*Felsic**		3	64.06	1.62	18.49	1.80	0.05	1.27	4.93	6.24	1.43	0.11
Oxide gabbro	520–705	5	46.55	2.97	12.24	17.69	0.27	6.06	9.99	3.27	0.10	0.86
	800–960	6	47.33	2.84	12.80	14.81	0.22	7.36	11.20	2.86	0.06	0.53
	960–1320	2	48.30	2.31	15.01	13.38	0.21	6.13	10.06	3.40	0.08	1.12
Gabbro	520–705	4	52.21	0.52	16.72	7.40	0.13	7.38	12.13	3.43	0.06	0.02
	705–800	2	51.24	0.47	16.37	6.78	0.13	9.03	13.16	2.76	0.03	0.02
	800–960	7	51.04	0.43	16.38	6.93	0.14	8.97	13.21	2.84	0.03	0.03
	960–1320	6	51.75	0.38	16.37	6.45	0.13	8.77	13.15	2.97	0.03	0.01
	1320–1503	7	51.55	0.35	17.94	5.16	0.11	8.37	13.52	2.95	0.03	0.01
Olivine gabbro	520–705	12	51.50	0.44	16.18	7.78	0.14	8.85	11.91	3.13	0.06	0.02
	705–800	11	50.65	0.34	16.46	6.93	0.13	10.16	12.67	2.63	0.02	0.02
	800–960	22	50.74	0.44	15.91	7.10	0.13	10.23	12.71	2.69	0.03	0.03
	960–1320	40	51.04	0.42	16.37	7.16	0.13	9.41	12.56	2.85	0.03	0.02
	1320–1503	18	51.14	0.36	16.99	5.80	0.12	9.29	13.62	2.65	0.02	0.02
Troctolitic gabbro	800–960	2	50.95	0.36	17.29	6.19	0.12	9.26	13.05	2.68	0.08	0.02
	1320–1503	3	49.29	0.28	17.90	7.84	0.13	10.70	11.11	2.72	0.02	0.01
Troctolite	500–520	4	46.99	0.13	18.21	6.52	0.10	15.52	10.65	1.81	0.06	0.01

Note: Depth intervals correspond to the chemical-stratigraphy units (see Shipboard Scientific Party, 1999). Major element compositions are all normalized to 100%. (Data are from Shipboard Scientific Party, 1999).

* Average of 3 felsic samples.

† N = number of samples used to calculate the average; mafic rock samples have been excluded.

§ Total Fe as Fe_2O_3.

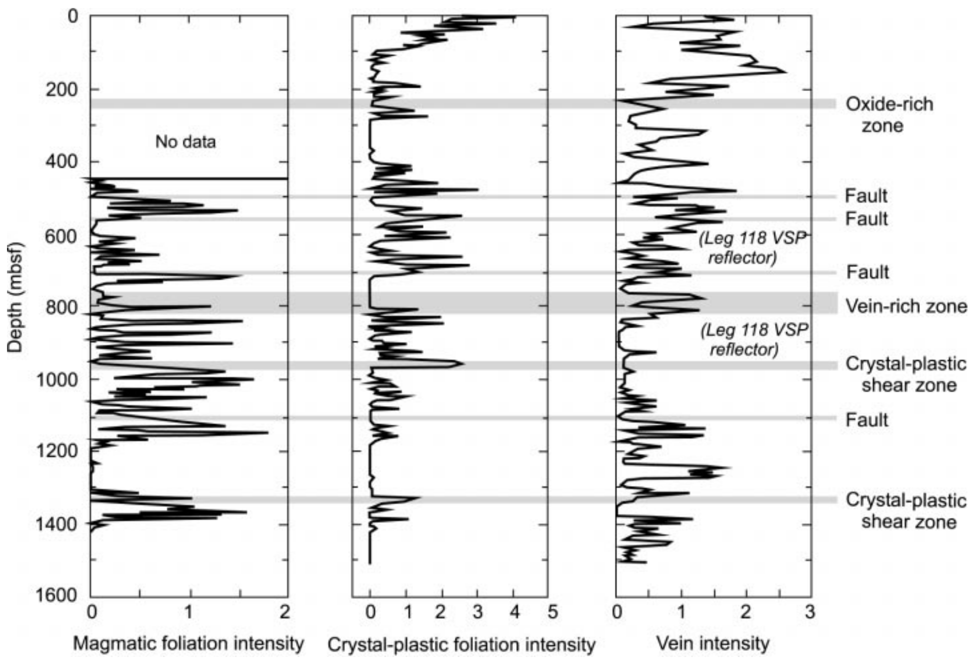

Figure 8. Downhole variations in the intensity of magmatic foliation, crystal-plastic deformation, and vein intensity in Hole 735B (Shipboard Scientific Party, 1999). VSP—vertical seismic profile.

Long intervals of core have no deformation whatsoever, and these intervals increase in number and length with depth.

More than 150 zones of intense crystal-plastic deformation have mylonitic fabrics. These zones are typically narrow bands a few millimeters to a few centimeters thick, although thicker intervals are present in the upper 50 m of the core. In most cases, the transition from mylonitic fabric to undeformed rock takes place over a few centimeters. Like the magmatic foliations, crystal-plastic foliations show no systematic variations in dip with depth in the hole; however, there is a strong preferred orientation to the deformation fabric. When oriented relative to the remanent magnetic vector, the crystal-plastic foliations dip north toward the ridge axis (Shipboard Scientific Party, 1999).

In general, the intensities of the crystal-plastic and magmatic fabrics show a good positive correlation except in areas where magmatic foliations have been completely overprinted. There are also a few zones with strong magmatic foliations that show little or no overprinting by tectonic fabrics. Shear zones with crystal-plastic deformation fabrics may show either a normal or reverse sense of shear in the core reference frame.

Both high- and low-temperature brittle deformation features are also present in the Hole 735B rocks. High-temperature brittle deformation is recorded by numerous felsic veins and magmatic breccias. Although many of these veins and breccias have a hydrothermal overprint, their original mineral assemblage (plagioclase ± clinopyroxene ± amphibole ± oxides ± biotite ± quartz ± alkali feldspar ± titanite ± apatite ± zircon) suggests a magmatic origin. Typically, the felsic material forms anastomosing vein networks and irregular patches in which individual veins have no preferred orientation.

Lower-temperature brittle deformation features are mostly discrete faults and associated cataclasites. Major faults of unknown displacement occur at 560 and 690–700 mbsf, and smaller zones of cataclasis occur at 490, 1076, and 1100–1120 mbsf. The major faults overprint granulite- and amphibolite-facies shear zones and were active during greenschist-facies conditions (Shipboard Scientific Party, 1999).

In addition to the major faults, there are more than 700 discrete ‘‘microfaults’’ or zones of cataclasis with associated breccia and gouge in the section. These are irregularly distributed in the core: most occur in the upper 750 m, and there are almost none below 1400 mbsf. Commonly, these zones of brittle deformation are filled with calcite, amphibole, and/or smectite, and many have small slickensides.

As noted above, there is commonly an association between the occurrence of crystal-plastic shear zones and the distribution of Fe-Ti oxides (Fig. 4) although some deformed intervals have no oxides and some oxide-rich zones are undeformed. This association between the shear zones and oxides suggests that crystal-plastic deformation tends to occur in zones rich in fractionated melt. However, once deformation is initiated, Fe-Ti oxide–rich melts may migrate into the shear zones, causing increased oxide concentration. Continued deformation may cause shearing and fracturing of the oxide-rich bands. An absence of annealing in the sheared and fractured oxides suggests that the late-stage deformation occurred in the solid state, well below the gabbro solidus (cf. Agar and Lloyd, 1997).

PALEOMAGNETISM

The transverse ridge on the east side of the Atlantis II Fracture Zone is crossed by a number of well-defined magnetic anomalies with the Atlantis Bank lying at anomaly 5r.2n (Dick et al., 1991c). The presence of these anomalies in an area underlain by gabbro and peridotite indicates that the lower ocean crust and (perhaps) the upper mantle are significant sources of marine magnetic anomalies.

The average natural remanent magnetization (NRM) of minicores from Hole 735B is 2.5 A/m (Shipboard Scientific Party, 1999), and there is no significant decrease downhole (cf. Pariso and Johnson, 1993) despite a significant downward decrease in the proportion of oxide gabbros. There is, however, considerably less scatter of NRM values in the lower 1000 m of the hole (Fig. 9). Downhole logs of magnetic susceptibility show numerous spikes in the record, most of which correlate closely with thin bands of oxide gabbro or felsic veins (Fig. 10).

It is clear that the gabbros sampled in Hole 735B can easily account for the observed seafloor magnetic anomalies on the Atlantis Bank (Kikawa and Ozawa, 1992). A gabbro layer 3–5 km thick with

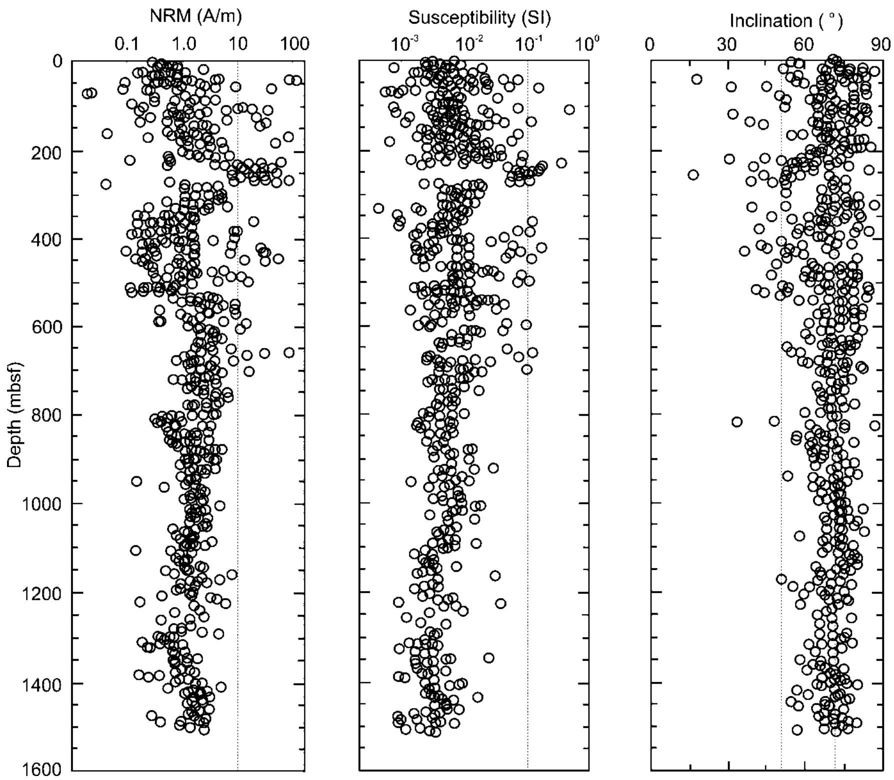

Figure 9. Downhole variations in stable thermal remanent magnetization (NRM), magnetic susceptibility, and stable inclinations in Hole 735B (Shipboard Scientific Party, 1999) (Leg 118 data after Kikawa and Pariso, 1991).

an average magnetization of 2.5 A/m could account for most seafloor anomalies observed elsewhere. Thus, it seems clear that gabbroic crust can contribute significantly to marine magnetic anomalies and locally may even dominate over the contribution of lavas and sheeted dikes. However, the rapid acquisition of thermal remanence of the Hole 735B gabbros resulting from their uplift and unroofing at the ridge-transform intersection may not be typical of the Southwest Indian Ridge as a whole. Farther from the ridge-transform intersection, the gabbros would have cooled beneath a 1–2-km-thick carapace of lavas and sheeted dikes and thus would have acquired their remanence more slowly.

Hole 735B was spudded into a negative magnetic anomaly (5r.2n), and the primary remnant magnetism has an average inclination of −71°, uncorrected for any deviation of the hole (Shipboard Scientific Party, 1999). Although there is some scatter in the upper 500 m of the section, most values cluster about the average, and there are no significant downhole trends (Fig. 9). This result indicates that the section has not been tectonically disrupted since it cooled below the Curie point at ~580 °C. However, the average inclination is ~20° steeper than that expected for the site (51°), suggesting some rotation of the section as a whole.

PHYSICAL PROPERTIES

Because the Atlantis Bank has been unroofed by some unspecified amount, its exact position in the ocean crust is not known. However, both the compressional-wave velocities and densities of the plutonic rocks are characteristic of oceanic layer 3. Compressional-wave velocities of minicores ranged from a low of 5.53 to a high of 7.83 km/s (Robinson, Von Herzen, et al., 1989). However, the average minicore velocity for the entire section is 6.78 ± 0.29 km/s, which corresponds closely to the average in situ velocity measured by vertical seismic profiling (6.4–6.5 km/s; Robinson, Von Herzen, et al., 1989). In situ velocities are normally somewhat lower than minicore velocities because of the presence of faults, fractures, breccia zones, and highly altered zones that would not normally be represented in minicores. However, both the minicore and in situ velocities are typical for gabbro and metagabbro and well within the range for oceanic layer 3 (6.5–7.0 km/s).

Bulk densities also show considerable scatter, particularly in the upper 700 m of the section (Fig. 11). The mean bulk density is 2.98 ± 0.10 g/cm^3, and the mean grain density is 2.99 ± 0.11 g/cm^3, very close to the density of typical olivine gabbro (Shipboard Scientific Party, 1999). The highest densities (up to 3.21 g/cm^3) are from oxide gabbros with abundant ilmenite and magnetite, and the lowest are from olivine gabbros with high proportions of plagioclase. The observed densities are characteristic of layer 3 gabbros.

SUMMARY AND DISCUSSION

Because it is normally covered by 1–2 km of lavas and sheeted dikes, the lower part of the ocean crust is largely inaccessible. Attempts to penetrate the volcanic carapace by drilling have proved expensive and fruitless. Because the Atlantis Bank is a segment of lower ocean crust that has been tectonically unroofed, it is readily accessible to dredging and drilling. Thus far, seven research cruises have visited the area including ODP Legs 118, 176, and 178, two survey cruises, a seismic survey cruise, and a diving cruise.

During ODP Legs 118 and 176, *JOIDES Resolution* drilled Hole 735B to a combined depth of 1508 mbsf with an average core recovery of 87%. For the first time, a significant part of the lower ocean crust has been sampled in situ; this success has allowed us to determine the stratigraphy of the crust and to assess the tectonic, magmatic, and metamorphic processes involved in crustal construction at an ultra-slow-spreading ridge.

The ocean crust is believed to be relatively thin and discontinuous at slow-spreading ridges (<10 mm/yr half rate) or near large transform faults (Reid and Jackson, 1981; Mutter and Detrick, 1984;

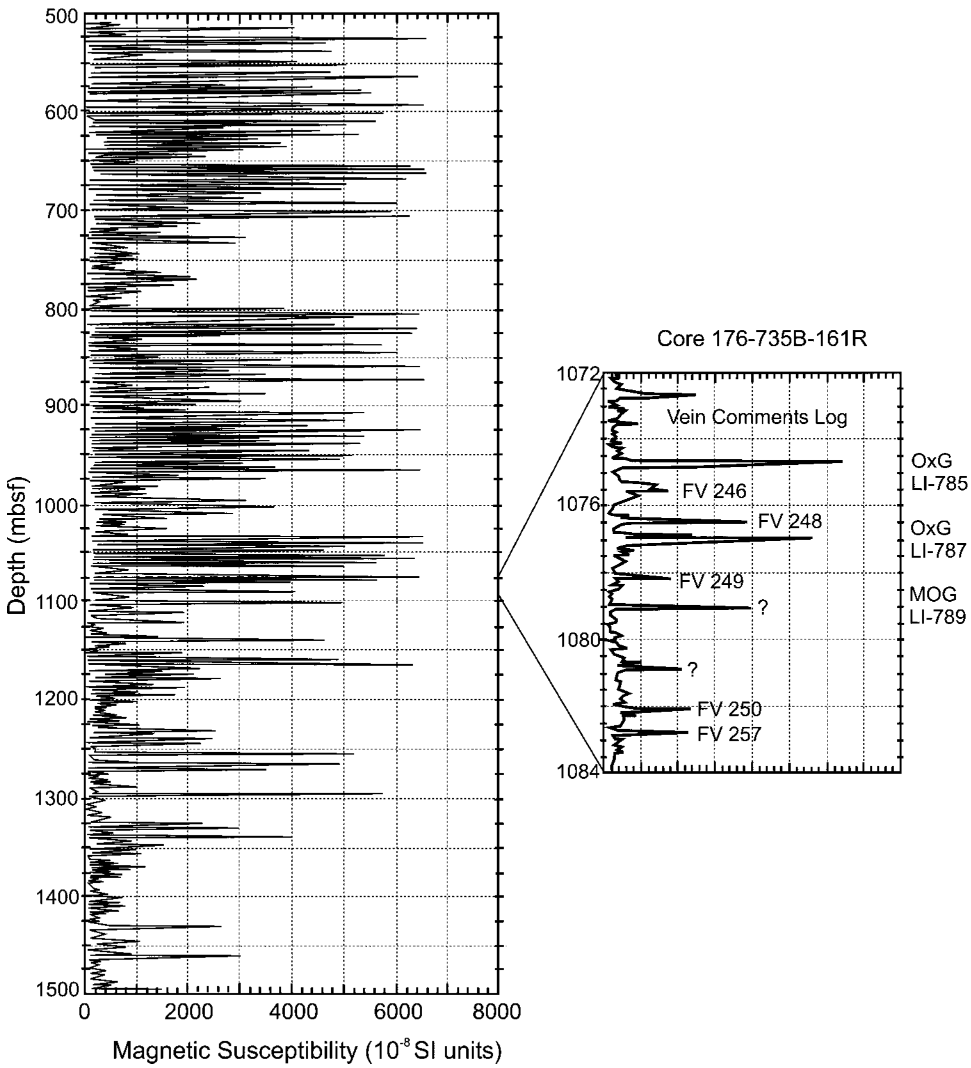

Figure 10. Magnetic susceptibility log for Hole 735B between 500 and 1508 mbsf. Enlarged part of the column on the right shows the close correlation between magnetic susceptibility and oxide layers and felsic veins. FV—felsic vein, OxG—oxide gabbro, MOG—mixed olivine gabbro (Shipboard Scientific Party, 1999).

Whitehead et al., 1984; Dick, 1989; Cannat, 1993; Bown and White, 1994; Tucholke and Lin, 1994). Large, steady-state magma chambers are absent at slow-spreading ridges (Whitehead et al., 1984; Detrick et al., 1990; Dick et al., 1991a, 1992; Bloomer and Meyer, 1992; Sinton and Detrick, 1992), and the internal structure of the crust is controlled as much by dynamic processes of tectonism and alteration as by igneous processes (Robinson, Von Herzen, et al., 1989; Dick et al., 1992; Cannat, Karson, et al., 1995).

On the basis of the seismic velocity structure beneath the Atlantis Bank, the Moho discontinuity has been placed at a depth of ~6 km below sea level (Fig. 2) (Muller et al., 1997). However, the fact that the gabbro-peridotite transition lies at a depth of ~2500 m on the western edge of the platform suggests that the crust-mantle boundary is much shallower than the Moho. If so, the low velocities below the Atlantis Bank probably reflect extensive serpentinization of upper-mantle peridotite. This inference suggests that serpentine can be a significant component of oceanic layer 3 and that the crust-mantle boundary in the oceans may not always correspond to the seismic Moho.

The bulk of the crustal section consists of olivine gabbro and gabbro with lesser amounts of troctolite and gabbronorite. Although there are many small-scale igneous units, the section appears to have been constructed from five major intrusions, each of which shows an upward fractionation from troctolite to gabbro, gabbronorite, and disseminated-oxide gabbro (Fig. 7). A striking feature of the section is the abundance of oxide-rich rocks in the upper part of the sequence and their common association with zones of crystal-plastic deformation.

The calculated bulk composition of the 1508-m-thick section indicates that the gabbros are close in composition to primitive or moderately differentiated basalts (Dick et al., 1999). However, calculated compositions for the upper, middle, and lower 500-m-thick sections show significant differences, with strong enrichment in TiO_2 and total Fe in the upper section, accompanied by a decrease in Mg#. However, except for an upward increase in Cr, trace element contents remain essentially constant through the 1508-m-thick section. This decoupling of major and trace elements appears to preclude formation of the oxide gabbros by simple upward fractionation of a large basaltic intrusion (Dick et al., 1999). Rather they must be of hybrid origin formed by intrusion of late-magmatic melts into a crystal mush of olivine gabbro. These liquids could have come from lower in the section or have been intruded laterally along the ridge axis. Mass balancing of these late-magmatic liquids with reasonable parental-magma compositions (Dick et al., 1999) suggests that there must be a considerable thickness of primitive cumulates that have yet to be sampled. These could lie deeper in the crustal section or in the upper mantle, they could have been removed by faulting, or they could be

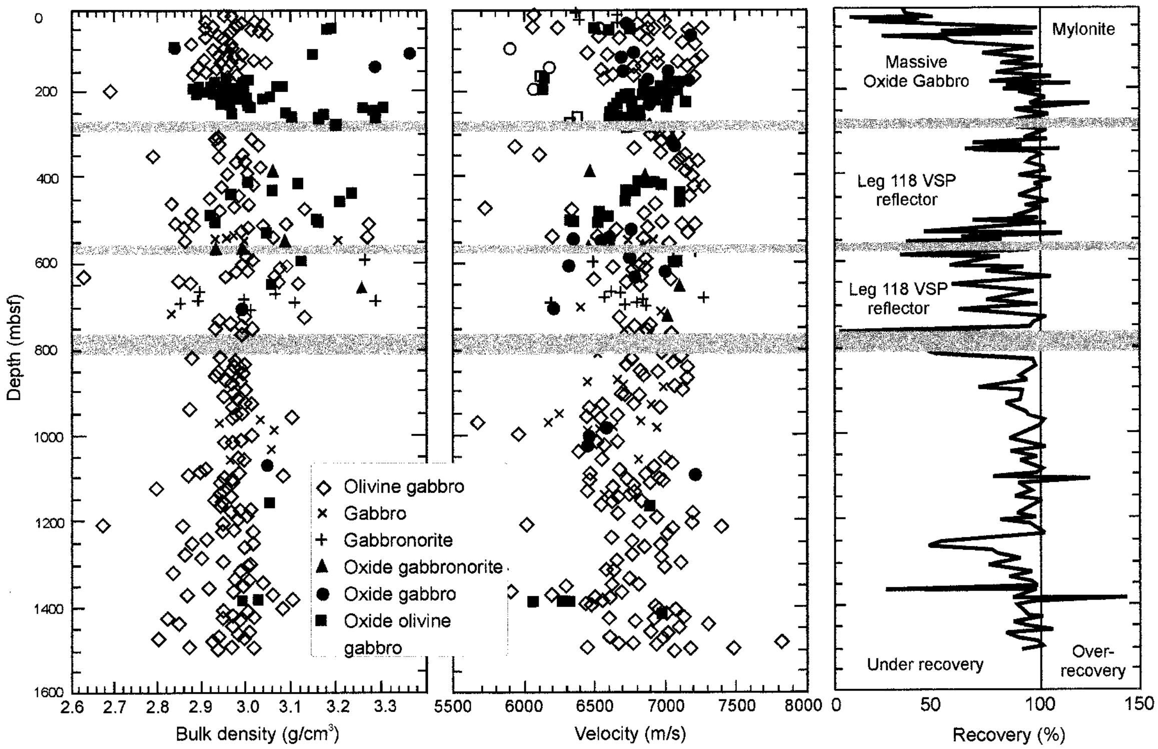

Figure 11. Downhole variations in bulk density and compressional-wave velocity for minicore samples from Hole 735B. Percent recovery is also given. Horizontal bands are oxide-rich or vein-rich zones (Shipboard Scientific Party, 1999) (Leg 118 data after Iturrino et al., 1991). VSP—vertical seismic profile.

located closer to the midpoint of the paleo–volcanic segment if the oxide-rich melts migrated along the axis.

The absence of any eruptive equivalents to the oxide gabbros (ferrobasalts) on Southwest Indian Ridge suggests that these melts represent late-magmatic liquids trapped in the crystallizing olivine gabbros. This interpretation is supported by the presence of local patches of oxide gabbro in undeformed olivine gabbro deep in the hole that may be local pockets of such melt.

The close association of oxide gabbros and crystal-plastic shear zones suggests that the crystal-plastic deformation developed preferentially in zones rich in fractionated melt. However, the abundance of oxides in some zones strongly suggests that once deformation was initiated, melt migrated into and along these zones, causing increased oxide concentrations.

Metamorphism and alteration also appear to have been strongly influenced by deformation. High-temperature (750 to 850 °C) granulite- and amphibolite-facies metamorphism is closely associated with zones of intense shearing. Because the brittle-ductile deformation and associated metamorphism took place at high temperatures, it must have occurred shortly after the rocks crystallized beneath the ridge axis. As the section migrated away from the ridge axis and cooled, brittle deformation became dominant, leading to formation of abundant veins (Robinson et al., 1991). High-temperature diopside, amphibole, and felsic veins are concentrated in the upper parts of the sequence where crystal-plastic deformation was most intense; low-temperature carbonate, zeolite, and smectite veins occur chiefly in the lower, least-deformed parts of the core. The zones of oxidative alteration are invariably associated with these low-temperature veins and must reflect migration of seawater along late-stage cracks formed after emplacement of the Atlantis Bank into the transverse ridge.

It is clear that Hole 735B sampled a section of lower oceanic crust with the seismic characteristics and physical properties characteristic of layer 3. The presence of well-defined magnetic anomalies on the Atlantis Bank clearly demonstrates that lower-crustal gabbros can contribute significantly to seafloor magnetic anomalies. Indeed, a crustal section 3–5 km thick with the average magnetization measured in Hole 735B gabbros (2.5 A/m) could account for most seafloor anomalies measured elsewhere.

The crustal section sampled in Hole 735B differs significantly from the crustal sections in ophiolites such as described by the Penrose Conference Participants (1972). Notable differences include the paucity of grain-size or phase layering in Hole 735B, the abundance of high-temperature shear zones with well-developed amphibolite gneisses, and the abundance of oxide gabbros, most of which are distributed along zones of intense shear. Wehrlites, which are common in many classic ophiolites, are absent, and the bulk geochemistry of the section is distinct from that of most ophiolites, which typically have an arc or supra-subduction zone signature. Some of the features observed in Hole 735B gabbros, particularly the abundance of high-temperature shear zones, have been reported in Alpine and Ligurian ophiolites, and more similarities may be revealed by careful comparison of the two (Ishiwatari, 1985; Lagabrielle and Cannat, 1990). However, the likelihood seems small that sections of cold ocean lithosphere formed by slow spreading—like the lithosphere at 735B—would be emplaced on land as ophiolites. Thus, there may be no direct on-land equivalent of the Atlantis Bank crust.

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