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A long in situ section of the lower ocean crust: results of ODP Leg 176 drilling at the Southwest Indian Ridge

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Abstract

Ocean Drilling Program Leg 176 deepened Hole 735B in gabbroic lower ocean crust by 1 km to 1.5 km. The section has the physical properties of seismic layer 3, and a total magnetization sufficient by itself to account for the overlying lineated sea-surface magnetic anomaly. The rocks from Hole 735B are principally olivine gabbro, with evidence for two principal and many secondary intrusive events. There are innumerable late small ferrogabbro intrusions, often associated with shear zones that cross-cut the olivine gabbros. The ferrogabbros dramatically increase upward in the section. Whereas there are many small patches of ferrogabbro representing late iron- and titanium-rich melt trapped intragranularly in olivine gabbro, most late melt was redistributed prior to complete solidification by compaction and deformation. This, rather than in situ upward differentiation of a large magma body, produced the principal igneous stratigraphy. The computed bulk composition of the hole is too evolved to mass balance mid-ocean ridge basalt back to a primary magma, and there must be a significant mass of missing primitive cumulates. These could lie either below the hole or out of the section. Possibly the gabbros were emplaced by along-axis intrusion of moderately differentiated melts into the near-transform environment. Alteration occurred in three stages. High-temperature granulite- to amphibolite-facies alteration is most important, coinciding with brittle–ductile deformation beneath the ridge. Minor greenschist-facies alteration occurred under largely static conditions, likely during block uplift at the ridge transform intersection. Late post-uplift low-temperature alteration produced locally abundant smectite, often in previously unaltered areas. The most important features of the high- and low-temperature alteration are their respective

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associations with ductile and cataclastic deformation, and an overall decrease downhole with hydrothermal alteration generally ≤ 5% in the bottom kilometer. Hole 735B provides evidence for a strongly heterogeneous lower ocean crust, and for the inherent interplay of deformation, alteration and igneous processes at slow-spreading ridges. It is strikingly different from gabbros sampled from fast-spreading ridges and at most well-described ophiolite complexes. We attribute this to the remarkable diversity of tectonic environments where crustal accretion occurs in the oceans and to the low probability of a section of old slow-spread crust formed near a major large-offset transform being emplaced on-land compared to sections of young crust from small ocean basins.

Keywords: Leg 176; mid-ocean ridges; lower crust; gabbros; alteration; deformation

1. Introduction

Because of its inaccessibility, the nature of the lower ocean crust has largely been inferred from remote sensing and by analogy to ophiolites. From its inception, a major goal of scientific ocean drilling has been to drill through the entire ocean crust into the mantle to determine directly its composition and structure. Although such a deep hole is beyond current technical capabilities, many fundamental questions can be addressed by drilling into tectonic windows where the lower crust is exposed. This was the goal of Ocean Drilling Program (ODP) Leg 118, which started Hole 735B in 1987 and drilled to 504.8 m below seafloor (mbsf), recovering 433.3 m of gabbroic lower crust [1] in a tectonic window at the Southwest (SW) Indian Ridge. ODP Leg 176 reoccupied this hole in October 1997 and drilled for 27 days to a total depth of 1508 mbsf, recovering an additional 866 m of gabbro. Crust formed at the ultra-slow-spreading SW Indian Ridge is believed to be only about 4 km thick [2]. If pillow lavas and dikes comprise 1.5–2 km of this, the lower crustal section should be no more than 2–2.5 km thick. Hole 735B is now deep enough to be regarded as representative of much of slow-spread lower ocean crust. Thus for the first time, a significant proportion of an all but inaccessible layer of the Earth has been sampled in situ, and we provide here a report of our initial findings and discuss their implication for crustal accretion in the oceans.

The section consists chiefly of gabbro with a mean density of 2.979 kg/m^3 and a seismic velocity of 6.777 km/s, both appropriate for oceanic layer 3. The stratigraphy, however, varies dramatically with depth, exhibiting large changes in igneous chemistry, deformation and alteration (Fig. 1). The chemical variations are complex, and the igneous chemistry cannot be explained by simple fractionation of an upwardly differentiating magma chamber. Rather, the igneous, structural and alteration characteristics are the product of physical processes inherent to a tectonically active ridge environment. The bulk composition of Hole 735B is too differentiated to mass balance SW Indian Ridge basalts back to the composition of a likely primary magma without the addition of a large volume of primitive cumulates. If, as may be the case, the crust–mantle boundary lies a short distance below the hole, the missing cumulates would lie out of section. Site 735 is some distance from the mid-point of the paleo-ridge segment, and the gabbros could represent moderately differentiated melts intruded down-axis from the segment center. The section drilled at Site 735 differs in many respects from those in well-known ophiolites and from gabbros sampled to date at fast-spreading ridges. These differences presumably reflect the tectonically diverse settings in which ocean crust forms, and the probabilities that ocean crust of a particular provenance is emplaced on-land. Well-preserved ophiolites formed in the slow-spreading large-offset ridge transform intersection environment like Site 735, then, may be rare or non-existent.

2. Methods

Hole 735B was cored continuously, with cores recovered every 5–9.5 m. In several instances, recovery exceeded the interval drilled, a phenomenon referred to as polling where core fails to break off during retrieval, and is recovered after drilling the next interval. The overall high recovery (86%)

compared with most basement legs (~22%) largely reflects the massive character of the rock and possibly greater drill string stability in shallow water. The Leg 176 cores were described in both hand sample and thin section. Semi-quantitative estimates were made of alteration, igneous modes, grain size, textures and intensity of deformation on a centimeter scale through all 866 m of core. Igneous mineralogy was point-counted on over 200 thin sections, and detailed semi-quantitative petrographic descriptions of rock alteration, deformation and igneous textures were made on 285 thin sections. The scientists worked in disciplinary teams, with the igneous petrologists, metamorphic petrologists and structural geologists working separate overlapping shifts. Although features were described by teams, only one individual recorded a specific measurement or observation throughout the core to insure the best possible accuracy and precision. Samples were chosen for shipboard XRF, physical properties and magnetic measurements to be as representative of each core section as possible. A consistent attempt was made not to over sample small curious features of the core, and overall the measurements are representative of the actual material drilled. Thin sections were made wherever an XRF or physical properties sample was taken. All the data were then logged into spreadsheets that are presented in electronic format in the Initial Reports [3]. The various downhole plots presented here represent but a small fraction of the available data. In order to insure consistency with earlier results, the scientific party relogged the last 50 m of the Leg 118 cores and reanalyzed some Leg 118 XRF powders.

3. Tectonic setting

The SW Indian Ridge is a highly segmented ridge representing nearly the ultra-slow-spreading end-member for crustal accretion in the oceans. Hole 735B is at Atlantis Bank, a 5 km local high situated along the eastern wall of the Atlantis II Transform. North of Atlantis Bank, the SW Indian Ridge is spreading asymmetrically 0.6 cm/yr due north and 1 cm/yr due south [6]. The hole, at 32°43′S, 57°17°E, is in 11 Ma old crust, about 18 km east of the present-day transform-slip zone and 95 km south of the SW Indian Ridge axis. At the time of accretion, however, it was only about 15 km from the active transform fault as there was subsequent transtensional extension across the transform due to a spreading direction change [6]. The top of Atlantis Bank, where the hole is located, is a wave-cut platform exposing gabbro, with less than 100 m total relief over a 25 km^2 area [7]. Seismic Moho is estimated to be approximately 5.3 km below Hole 735B [8] and is interpreted as an alteration front rather than the igneous crust–mantle boundary, based on the presence of serpentinized peridotite high on the transform wall just to the west of the hole [6].

The Atlantis Bank gabbros are interpreted as having been unroofed by a large low-angle detachment fault at the northern ridge transform intersection and then uplifted to sealevel at the northern inside-corner high of the paleo-SW Indian Ridge [6]. The Bank has since subsided to its present 700 m depth over the last 10 Ma. North of the SW Indian Ridge, on crust of the same age and distance from the paleo-transform, the volcanic carapace originally overlying the Hole 735B gabbros appears to be preserved intact [6,8]. Here, a series of E–W lineated ridges closely resemble the modern volcanic topography of the SW Indian Ridge rift valley floor. Although the seafloor has been mapped for 9 km to the east of the paleo-position of Hole 735B [9], the map area does not extend far enough to the east to reach the local high defining the mid-point of the volcanic segment. Accordingly, Hole 735B lies significantly west of the spreading segment center, rather than near its mid-point as originally suggested [6].

The exact structural position of the Atlantis Bank gabbros in the lower crust is unknown. However, fluid inclusions in the upper 500 m formed 1.5–2 km below seafloor [10]. Because this depth is close to thickness of dikes and pillows seen in many ophiolites and drilled at Hole 504B, the top of Hole 735B may not be far from the dike–gabbro transition. The appearance of troctolite in the lowermost 200 m, and the serpentinized peridotite high on the transform wall to

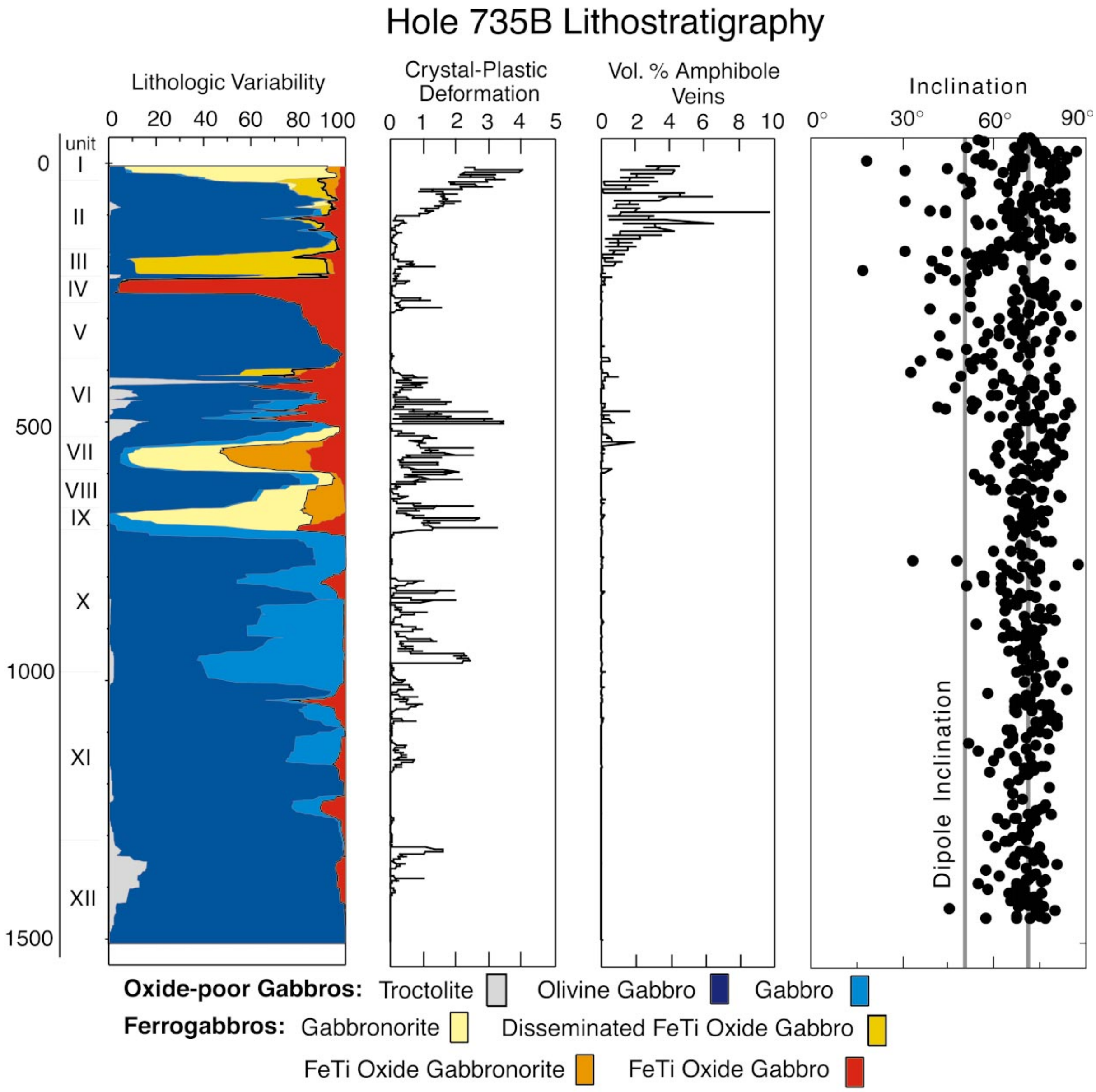

Fig. 1. Hole 735B lithostratigraphic variations [3,4]. Left: Relative abundances of igneous rocks averaged over a moving 20 m interval. Rock names follow the standard IUGS classification with modifiers to indicate oxide abundance. Middle left: Crystal–plastic deformation intensity from zero (undeformed) to five (ultramylonite). Middle right: Amphibole veins by core percentage averaged over a 2 m window. Right: Characteristic remanent inclinations. Mean inclination value (right gray line) is based on the inclination only averaging technique of McFadden and Reid [5].

the west [6], could indicate that the crust–mantle boundary is close to the bottom of the hole. However, whereas Mg-olivine-rich troctolitic gabbros are abundant near the crust–mantle boundary in some ophiolites, the lowermost Hole 735B olivine gabbros have maximum Mg/(Mg+Fe) of only about 0.82. This is considerably more iron-rich than the mantle ratio (∼0.90). Cumulates lying along a simple depositional contact with the mantle should have Mg/(Mg+Fe) close to the mantle value. However, if the gabbros represent down-axis intrusion of differentiated melts into the mantle near the transform, the crust–mantle boundary exposed on the transform wall could have virtually any orientation, and mantle peridotite could even locally overlie the gabbro. Thus, this boundary cannot be simply projected subhorizontally to the east from the transform wall to below Hole 735B without evidence of its orientation and form.

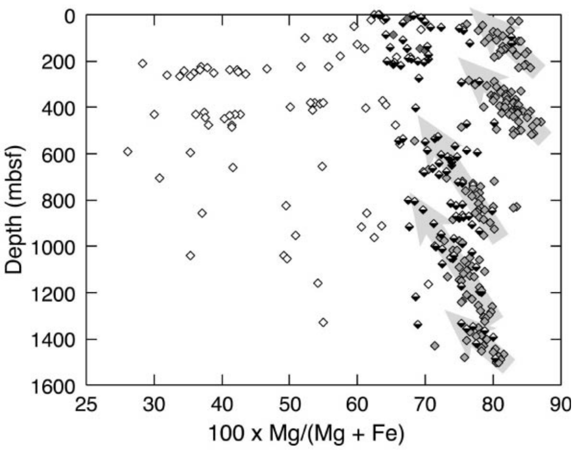

Fig. 2. Shipboard XRF whole rock gabbro molecular Mg/(Mg+Fe^{2+}) with $FeO = 0.85 \times Fe_2O_3$ [3,4]. Filled symbols: $TiO_2 < 0.4$ wt%, half-filled symbols: TiO_2 from 0.4 to 1.0 wt%, and open symbols: $TiO_2 > 1.0$ wt%.

4. Igneous stratigraphy

Gabbroic rocks containing 0.5% felsic veins and two diabase dikes (both in the upper 500 m) make up the entire Hole 735B core. A total of 953 discrete igneous intervals have been described, 457 in the lower kilometer, and there is additional subdivision possible at centimeter scales. Plagioclase (close to 60% of most rocks) and augite are the principal constituents of the gabbros. The main gabbro types are distinguished by variations in grain size and abundance of olivine, magmatic oxides (ilmenite and magnetite) and orthopyroxene. Anorthosite and clinopyroxenite occur in rare isolated patches. The average grain size ranges from coarse (5–15 mm) to very coarse (15–30 mm), with olivine, plagioclase and pyroxene generally covarying in size. Igneous contacts between lithologic intervals are 41% intrusive, 37% gradational and 6% tectonic, with 16% not recovered. Excluding tectonic and highly irregular contacts, igneous contacts dip from 0° to 90°, and average 36° with no systematic downhole trends. Modal and grain size layering are locally present, with rhythmic layering at several locations. Intervals with obvious modal or graded layering, however, constitute less than 2% of the core. Dips range from 0° to 52° and average 24°, with layers typically lying in the plane of the crystal–plastic foliation. A generally weak magmatic foliation, typically dipping from 20° to 50°, is defined by plagioclase laths and is present in 20% of the gabbros. This foliation, with few exceptions, is not present in the layered gabbros.

Of the major cumulates expected as products of differentiation of mid-ocean ridge basalt (MORB) (dunite, troctolite, olivine gabbro, gabbro, gabbronorite, oxide gabbronorite and oxide gabbro), all are present except dunite (Table 2, electronic appendix). Whereas these rocks represent a general evolutionary differentiation sequence, there is no systematic vertical change consistent with a single large upwardly differentiating magma body, nor a simple evolutionary sequence such as in layered intrusions like the Skaergaard. Rather the rock types occur in separated enclaves that interpenetrate one another throughout the hole. While ferrogabbro is most abundant in the upper 500 m, primitive and evolved gabbros are distributed irregularly throughout the section (Table 2, electronic appendix). Igneous intervals range widely in size from a few centimeters to many meters, reflecting the complex polygenetic character of the section and the many small oxide gabbro filled shear zones, intrusive microgabbros and felsic veins. The igneous stratigraphy of Hole 735B is thus characterized by extreme small-scale chemical and textural variability with multiple stages and styles of intrusion down to the hand specimen scale (e.g. Fig. 2).

The igneous stratigraphy is divided into 12 polygenetic units, including modifications to the Leg

Table 1
Hole 735B igneous lithostratigraphic units[a]

Unit I: gabbronorite, 0–37.41 m, 38 intervals
Subunit IA: massive gabbronorite, 0–27.99 m, 27 intervals
Subunit IB: olivine gabbro and gabbronorite, 27.99–37.41 m, 11 intervals
Unit II: upper compound olivine gabbro, 37.41–170.22 m, 91 intervals
Minor: *Intrusive*: microgabbro and olivine microgabbro
Synkinematic: oxide and oxide–olivine gabbro
Unit III: disseminated oxide–olivine gabbro, 170.22–223.57 m, 76 intervals
Subunit IIIA: disseminated oxide–olivine and olivine gabbro, 170.22–180.09 m, 12 intervals
Subunit IIIB: massive disseminated oxide–olivine gabbro, 180.09–209.45 m, 20 intervals
Subunit IIIC: disseminated oxide–olivine and olivine gabbro, 209.45–223.57 m, 44 intervals
Unit IV: massive oxide–olivine gabbro, 223.57–274.06 m (mylonite at upper contact), 32 intervals
Unit V: massive olivine gabbro, 274.06–382.40 m, 15 intervals
Unit VI: lower compound olivine gabbro, 382.40–536 m, 207 intervals
Subunit VIA: compound olivine gabbro, 382.40–404.01 m, 24 intervals
Minor: *Intrusive*: olivine microgabbronorite and olivine microgabbro
Synkinematic: olivine and oxide–olivine gabbro
Subunit VIB: compound olivine, oxide–olivine and disseminated oxide–olivine gabbro, 404.01–419.28 m, 43 intervals
Minor: *Intrusive*: olivine and oxide–olivine microgabbro
Subunit VIC: compound troctolitic and olivine gabbro, 419.28–433.77 m, 44 intervals
Minor: *Synkinematic*: oxide–olivine gabbro and oxide–olivine microgabbro
Intrusive: troctolite and troctolitic microgabbro
Subunit VID: compound olivine and oxide–olivine gabbro, 433.77–536 m, 96 intervals
Minor: *Intrusive*: troctolite, diopsidic olivine and troctolitic gabbro
Synkinematic: disseminated oxide–olivine and olivine gabbro
Unit VII: gabbronorite and oxide gabbronorite, 536–599 m, 35 intervals
Subunit VIIA: gabbronorite and oxide gabbronorite, 536–560 m
Minor: olivine gabbro
Subunit VIIB: gabbronorite and oxide gabbronorite, 560–599 m (fault at upper contact)
Unit VIII: olivine gabbro, 599–670 m, 22 intervals
Minor: oxide gabbronorite, gabbronorite and oxide gabbro
Unit IX: gabbronorite and gabbro, 670–714 m, 32 intervals
Minor: oxide gabbro and oxide gabbronorite
Unit X: olivine gabbro and gabbro, 714–960 m, 116 intervals
Minor: *Intrusive*: microgabbro, pegmatitic intervals, rhythmic layering
Rare: oxide gabbro
Unit XI: olivine gabbro, 960–1314 m, 164 intervals (shear zone at lower contact)
Minor: gabbro, oxide gabbro, rhythmic layering
Rare: troctolitic gabbro
Unit XII: olivine gabbro and troctolitic gabbro, 1314–1508 m, 72 intervals
Minor: *Intrusive*: microgabbro
Rare: oxide gabbro, leucogabbro

[a]Unit definitions follow Robinson, Von Herzen et al. (1989) as modified by Dick et al. (1991), and Dick, Natland, Miller et al. (1999).

118 units [4], reflecting changes in principal lithologies and various intrusive events. The product of a complex interplay of magmatic and tectonic events, this stratigraphy provides a purely descriptive breakdown of the lithologic variability of the hole conceptually different than that for layered intrusions. Some contacts are deformed, but at a few locations are simple faults, usually marked by thin mylonites such as at the bottom of Units III and VIIA. Gradational contacts, characterized by the disappearance of a distinctive mineral phase, such as orthopyroxene at the bottom of Unit IX, and abundant ilmenite and magnetite at the bottom of Unit IV, are common. Some unit boundaries are marked by the sudden appearance of an intrusive swarm, such as cross-cutting microgab-

Table 2
Results of Mass Balance Calculations for Hole 735B

	Int.	SiO_2	TiO_2	Al_2O_3	FeO	Fe_2O_3	FeO[a]	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Mg#	Ca#
0-500 meters	493	49.3	1.41	15.7	6.92	1.97	8.44	0.15	9.15	12.12	2.67	0.05	0.04	65.9	71.5
500-1000 meters	229	51.1	0.70	16.0	6.28	1.25	7.33	0.15	9.16	12.36	2.93	0.05	0.08	69.0	70.0
1000-1508 meters	231	51.3	0.50	16.6	5.39	0.89	6.19	0.13	9.33	12.96	2.80	0.04	0.03	72.9	71.9
0-1508 mbsf	**953**	**50.6**	**0.87**	**16.1**	**6.19**	**1.37**	**7.31**	**0.14**	**9.21**	**12.5**	**2.80**	**0.05**	**0.05**	**69.2**	**71.1**
Calculated Primary MORB[b]		50.3	0.91	16.4	nd	nd	7.45	nd	10.90	11.4	2.52	0.07	nd	72.3	
Hole 735B Diabase	2	49.7	1.73	14.9	7.18	2.38	9.32	0.19	7.76	11.30	3.00	0.08	0.36	59.7	67.5
Most primitive AII F.Z. Basalt		51.0	1.57	15.7	nd	nd	9.07	0.20	8.09	11.0	3.10	0.08	0.16	61.4	
Average Atlantis II F.Z. Basalt[c]	70	50.31	1.96	15.25			10.30	0.19	7.22	10.39	3.25	0.17	0.22	55.5	63.9
	V	Cr	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Bulk density				
0–500 meters	240	295	106	51	43		163	13	30		2.984				
500–1000 meters	199	119	95	75	53	0.6	166	17	44	1.3	2.981				
1000–1508 meters	177	120	100	74	43	0.7	170	12	35	2.5	2.970				
0–1508 meters	**205**	**178**	**100**	**66**	**46**		**166**	**14**	**36.5**		**2.978**				
Hole 735B Diabase	242	190	91	61	68	1	157	43	134	3.7					

See electronic table for the full computation and data inputs for this table including average interval dimensions by rock type.
Molecular ratios: Mg# = 100*Mg/(Mg+Fe) uses all iron as ferrous iron; Ca# = 100*Ca/(Ca+Na).
[a]Most primitive of 72 basalt glass analyses from 14 dredge hauls from the Atlantis II F.Z. reported by Johnson and Dick (1992).
[b]Calculated primary MORB composition from Kinzler and Grove (1993) most closely matching the Hole 735B bulk composition. Liquid composition calculated for isobaric incremental batch accumulative melting at 10 kb and 10.3% melting of a 'depleted' spinel lherzolite modelled after that of Zindler and Hart (1986).
[c]Seventy glass average for 11 dredge hauls from Johnson and Dick (1992).

bros at the top of Unit VI and abundant thin intervals of oxide gabbro at the top of Unit XI in otherwise continuous sections of coarse olivine gabbro. A summary of the igneous stratigraphy is given in Table 1 and a breakdown of average rock compositions and interval thicknesses are included in the **Epsl online background dataset.**[1]

Despite this complexity, the gabbros can be divided into three major associations: (1) oxide-poor olivine-bearing gabbros, (2) cross-cutting microgabbros, and (3) 'ferrogabbros' consisting of oxide-bearing gabbros and gabbronorites.

Coarse-grained, equigranular or vari-textured oxide-poor ($<1\%$) olivine-bearing gabbros and troctolites make up about 78% of the section. These rocks are texturally similar and exhibit a continuous gradation in olivine content from gabbro to troctolite. Vari-textured varieties are similar to the more abundant equigranular gabbros, but contain irregular coarse- and fine-grained equigranular gabbro patches at a variety of scales. These gabbros contain generally less than 1% late intergranular phases such as orthopyroxene, brown amphibole, oxide minerals and apatite. The rocks are clearly cumulates, meaning that they crystallized and separated from magma, and do not have bulk compositions appropriate for a melt (e.g. [11]). Chemically, the olivine-bearing gabbros can be separated into five units from 200 to 600 m thick. These are each characterized by an upward trend of decreasing Mg# (Mg/{Mg+Fe}), with a sharp increase in Mg# at the beginning of each overlying unit (Fig. 2). The individual chemical units defined by these trends partially overlap and each appears to be a composite, consisting of many smaller petrographically distinct intrusive intervals. The simplest interpretation is that each chemical unit represents some form of cyclic intrusion that differentiated in situ as the magma worked its way upward through a specific intrusive horizon in the section. Despite lower overall olivine contents, the uppermost two chemical units in Fig. 2 have higher average Mg#, lower TiO_2 and Na_2O, and are on average chemically more primitive than the lower three. This suggests that the upper two chemical units and the lower three chemical units could, in turn, represent two major intrusive phases characterized by different parent magmas.

Small medium- to fine-grained equigranular microgabbros, ranging in composition from troctolite to oxide gabbronorite, cross-cut the coarse-grained olivine-bearing gabbros at many intervals throughout the core. These range from several meters, to little more than a centimeter thick and span nearly the full compositional range of the coarser olivine gabbro and ferrogabbro they intrude (Fig. 3). Based on their composition (Table 2, **EPSL online background dataset**[1] appendix), most microgabbros are also cumulates retaining little trapped melt, although some of the more differentiated varieties appear to be close to a reasonable magma composition (e.g. the microgabbronorite analyzed by Hart et al. [14]). The microgabbros include the troctolites in Unit VI, which are the most primitive, high-Mg rocks in the section. These cross-cut the olivine gabbros and are chemically and texturally distinct from the coarser-grained troctolites at the bottom of the hole. Despite evidence of late reaction with Fe–Ti-rich melts, they contain Fo_{87} olivine [15]. Whereas most of the Hole 735B gabbros crystallized from moderately differentiated melts, those that produced the troctolites were fairly primitive [4,15]. Most of the microgabbro contacts with the olivine gabbros are sharp, clearly intrusive, and in hand specimen are often highly irregular in form. Typically individual grains interlock across the boundary with the finer and coarser grains intergrown, giving the contact a sutured appearance in thin section. Less abundant are simple size-graded contacts. Only five microgabbros in the lower kilometer have simple 'intrusive' contacts where individual mineral grains are broken along the contact by brittle fracture. These contact relationships suggest that in many cases, the intruded olivine gabbro was not fully solidified at the time of intrusion by the microgabbro. While contacts higher in the hole occur with shallow to moderate dips, near the base, thin sinuous microgabbros intrude coarse-grained olivine gabbro along steeply dipping to vertical intrusive con-

[1] http://www.elsevier.nl/locate/epsl; mirror site: http://www.elsevier.com/locate/epsl

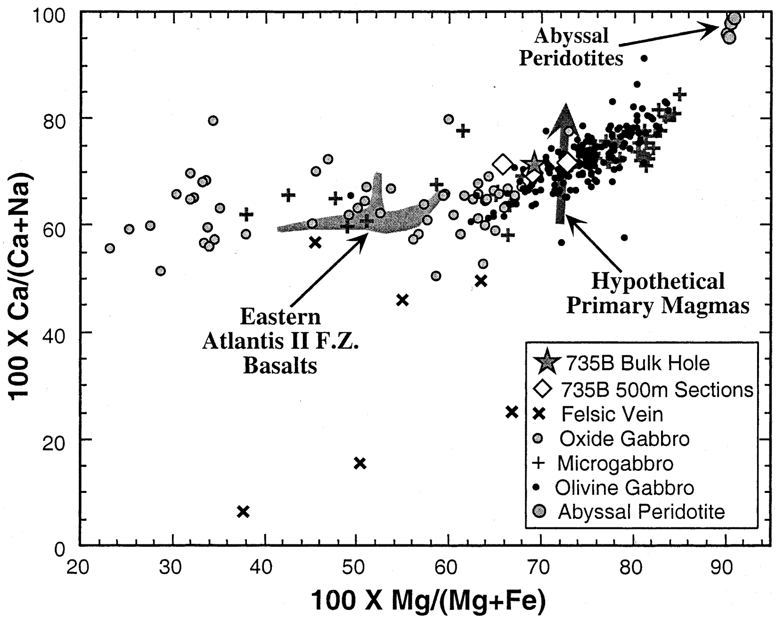

Fig. 3. Shipboard XRF whole rock gabbro molecular Mg/(Mg+Fe) and Ca/(Ca+Na), and calculated total hole and 500 m bulk compositions from Table 2. All iron as FeO. Also shown are average SW Indian and American–Antarctic Ridge abyssal peridotites [12], and the field of the Atlantis II Fracture Zone basalt glasses [4]. The hypothetical primary magma trend is for ~5–20% melts of estimated MORB mantle source compositions using various polybaric and isobaric melting models calculated from melting experiments by Kinzler and Grove [13].

tacts. We interpret the latter to represent melt transport channels through the crystallizing intrusions.

Hundreds of thin bodies of disseminated oxide (1–2 vol%) and oxide-rich (2–30 vol%) gabbronorite, gabbro and olivine gabbro, as well as several massive ferrogabbro units in the Leg 118 section, cross-cut the oxide-poor olivine gabbros. These ferrogabbros are all distinguished from the oxide-poor olivine gabbros by ilmenite and magnetite visible in hand specimen. Although the difference in modal oxide between disseminated oxide–olivine gabbro (1–2 vol%) and oxide-poor olivine gabbro (<1 vol%) is small, it is petrogenetically significant, since the former usually also contain substantially more sodic plagioclase and more iron-rich pyroxenes and olivine [16,17]. In addition, these ferrogabbros often contain significant quantities of hypersthene and brown amphibole. Usually, however, they are deficient in very late magmatic phases such as apatite and zircon. It is clear, then, that these gabbros are also largely cumulates, containing low percentages of residual melt, even though they (albeit) formed at a much later stage of differentiation than the olivine gabbros.

The relationship between ferrogabbro and oxide-poor olivine gabbro is quite varied. Modally gradational contacts are common. Many others are sharp, marked by the appearance of intergranular oxide and a change in silicate mineral proportions (generally an increase in pyroxene and often the disappearance of olivine) across a sutured boundary of interlocking grains. In many examples, the oxide gabbro lies in a zone of deformed gabbro with its contacts coinciding with the transition from deformed to undeformed gabbro. The most common types of ferrogabbro in the lower kilometer are either small oxide-rich, high-temperature shear zones cross-cutting the coarse olivine-bearing gabbros, or local undeformed patches of oxide gabbro in olivine gabbro. In many ferrogabbros, the oxide minerals locally cross-cut microcracked mineral grains and crystal–plastic deformation fabrics in olivine gabbro, or they lie along foliation planes, filling pressure shadows around pyroxene porphyroclasts and tension gashes in the rock [11]. Many of the most massive ferrogabbros in the upper 500 m appear to have an entirely igneous fabric in hand specimen, but when examined in long core sections, local oxide segregations appear to fill tension gashes and fractures. Moreover, whereas plagioclase and pyroxene grain boundaries in oxide-poor olivine gabbros tend to interlock in complex ways, pyroxene grains in many massive ferrogabbros tend to be blocky, often even rounded, suggesting that they were abraded and deformed before complete solidification.

Iron–titanium oxide-rich gabbros and gabbronorites markedly diminish in volume downhole (Fig. 1). They make up 30% of the core in the upper 500 m, 12% of the core in the lower 1000 m and less than 1% of the core in the lower 300 m. The thickest units with the most extreme enrichment in oxides, sodium, iron and titanium occur above 500 mbsf (Figs. 1 and 2, Table 1). There, Unit IV, a 50 m thick section, contains 20 intervals of massive oxide–olivine gabbro and microgabbro, averaging 10% oxide, that are interspersed with four small intervals of undeformed oxide-poor olivine gabbro. Overlying this sequence is Unit III, an apparently related but more varied 53 m thick unit of disseminated oxide–olivine gabbro. In the remainder of the hole, oxide gabbros typically form bands only a few centimeters to a few tens of centimeters thick.

A striking feature of the stratigraphy of Hole 735B is a strong downward enrichment in iron and sodium from the top of Unit III through Unit IV. In the usual case of simple differentiation of a magma body, a reverse chemical trend is expected. Units III and IV also represent a broad zone of deformation, however, with an overall crystal–plastic foliation that flattens into a plane of high shear strain with depth. The dip of this foliation correlates with the downward iron and sodium enrichment [4,18]. One explanation offered for this unique chemical trend is that melt flux and the extent of reaction between late Fe–Ti melt and olivine gabbro protolith is controlled by the influence of deformation on melt migration along the shear zone [4,18].

In summary, there is convincing evidence for local migration and intrusion of Fe–Ti-rich melts along shear zones throughout the olivine gabbros during deformation. On the other hand, there are also many local patches or layers of ferrogabbro, particularly in the lower third of the section, with no suggestion of synmagmatic deformation. In these cases, it appears that late Fe–Ti-rich melts pooled locally in situ in the olivine gabbro at the end of crystallization.

Late igneous felsic veins include leucodiorite, diorite, trondhjemite and tonalite with variable amounts of dark green amphibole, quartz and biotite. A few truly granitic veins were also recovered. The felsic veins represent the most differentiated melt compositions in Hole 735B. They range in size from a few mm to several centimeter, and cross-cut all other lithologies, usually filling crack networks forming net–vein complexes. A distinctive feature of many igneous felsic veins in the lower kilometer of the hole, evidently less common in the upper 500 m, are Fe–Ti oxide-rich reaction zones or halos in the adjacent olivine gabbro. This feature can be explained by local in situ differentiation of ferrobasalt melt and reaction with the wall rock to produce the titanomagnetite and the leucocratic vein. Some felsic veins were deformed under granulite- to amphibolite-facies conditions, and at the top of the section are locally transposed into the foliation plane in amphibolite zones [4]. Some deformed ferrogabbros are impregnated by felsic material, forming hybrids with dioritic compositions. This led to some speculation that these represent unmixing or extreme in situ fractionation of late Fe–Ti-rich melts during transport within a shear zone. Although igneous felsic veins are minor volumetrically, and decrease in abundance with depth, more than 200 were described in the lower kilometer of the hole.

5. Deformation

Macroscopic deformation in Hole 735B is generally localized in discrete shear and fault zones, with the bulk of the core (77%) being undeformed (Fig. 4). Magmatic, crystal–plastic and brittle deformation features are locally well-developed. There is a marked downward decrease in the intensity of crystal–plastic deformation, and magmatic foliations are also absent in long intervals near the bottom of the hole. Brittle fracture density, as shown by hydrothermal veins, also decreases downhole (e.g. Figs. 1 and 4). As in the Leg 118 section [4,11,17], some rocks were deformed and recrystallized while still partly molten, and there is a transition between high-temperature metamorphic and magmatic processes [3]. In many instances, crystal–plastic fabrics are crosscut by stringers of magmatic oxides and these oxides also locally cement broken silicate grains and fill cracks. Many of the most striking zones of crystal–plastic deformation, however, formed under the equivalent of granulite-facies metamorphic conditions (> 800–1000°C), when there was little or no melt present. Above 500 mbsf, the dominant sense of shear is normal, whereas below that level, there are several zones with reverse sense shear. A weak, subparallel, crystal–plastic fabric, that may record a transition from magmatic to crystal–plastic deformation, commonly overprints magmatic foliations. Many of the deformed rocks also show a continuum between crystal–plastic and brittle behavior. There are narrow zones of intense cataclasis, and several fault zones, two of which coincide with Leg 118 vertical seismic profile reflectors [3].

Although igneous textures are locally obscured by deformation, there is a strong association between magmatic foliations defined by feldspar laths and zones of crystal–plastic deformation, with long intervals of the core containing neither. Crystal–plastic and magmatic fabrics also share a common orientation (Fig. 4). Normally, because of rotation while drilling, core pieces have no azimuthal orientation. The Hole 735B cores, however, were oriented for splitting so that macroscopic foliations had a common orientation. Although this automatically produces stereo plot correlations between unrelated foliations in the core reference frame, the magnetic declinations also have a very consistent orientation (near 260° in core coordinates). Thus, assuming an original magnetic declination of 180°, magmatic and crystal–plastic fabrics both generally had an approximately E–W strike and dip toward the ridge axis.

In many intervals, primary igneous textures are overprinted by sub-solidus granulite- and amphibolite-facies deformation. Deformation is commonly localized in oxide-rich zones, suggesting that these rocks may be weaker than the enclosing olivine gabbro. This could explain the association between the abundance of magmatic oxides and crystal–plastic deformation intensity in the bottom 1 km of the hole (Fig. 4). All the major oxide concentration peaks, with the exception of the 1250 mbsf peak, coincide with crystal–plastic deformation intensity peaks. However, Unit IV, the most massive interval of oxide gabbro in the hole, for the most part, shows only weak macroscopic sub-solidus deformation. This suggests that there may be more to the association of deformation and oxides than simple sub-solidus strain localization in weaker units.

6. Metamorphism and alteration

The rocks from Hole 735B preserve a complex record of high-temperature metamorphism, brittle failure and hydrothermal alteration beginning at near-solidus temperatures and continuing down to zeolite-facies conditions. Although alteration assemblages in the Leg 176 core are broadly similar to those in the upper 500 m [4,19,20], the deeper rocks are less altered with long intervals (> 300 m) having less than 5% background alteration. Secondary minerals can be divided into three main groups (Fig. 5): (1) a high-temperature granulite- to amphibolite-facies assemblage; (2) lower temperature greenschist to the zeolite-facies assemblages; and (3) very low-temperature alteration; principally including carbonates and clays and mixed-layer chlorite–smectites.

Brown amphibole is an accessory phase in most Leg 176 gabbros and occurs intergranularly between clinopyroxene, olivine and grains of ilmenite and magnetite. In olivine gabbro, it is generally isolated, partially rimming pyroxene and olivine (< 0.1 vol%). In ferrogabbros, it is ubiquitous,

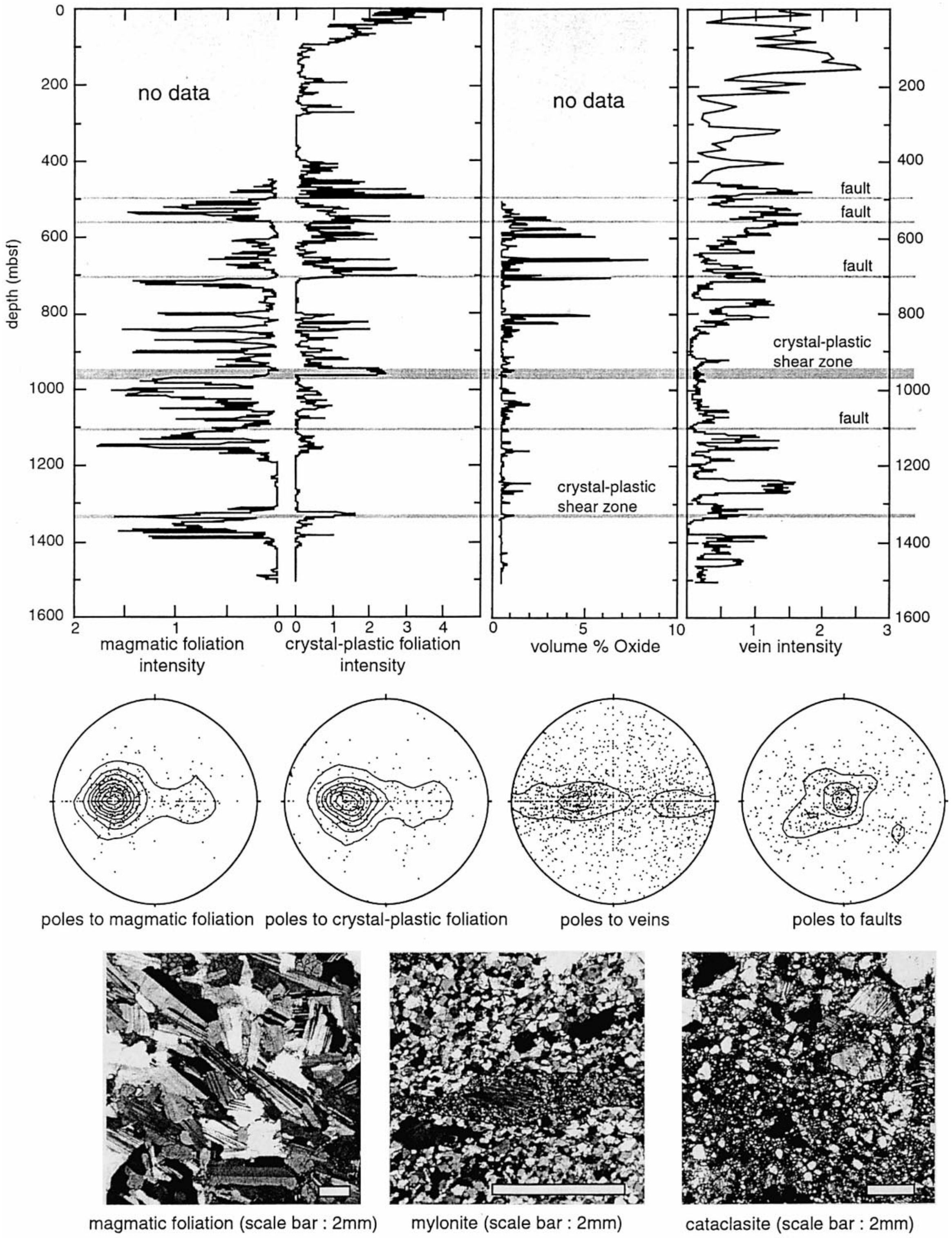
depth (mbsf)
0
200
400
600
800
1000
1200
1400
1600
no data
no data
fault
fault
fault
crystal-plastic shear zone
fault
crystal-plastic shear zone
2 1 0
0 1 2 3 4
magmatic foliation intensity
crystal-plastic foliation intensity
0 5 10
volume % Oxide
1 2 3
vein intensity
poles to magmatic foliation
poles to crystal-plastic foliation
poles to veins
poles to faults
magmatic foliation (scale bar : 2mm)
mylonite (scale bar : 2mm)
cataclasite (scale bar : 2mm)

Fig. 4. Running downhole 5 m averaged Hole 735B structural observations, including unpublished data of H. Dick for the upper 500 m. Vein intensity: 0, none; 1, <1 per 10 cm; 2, 1–5 per 10 cm; 3, >5 per 10 cm ($n=3245$ veins). The vein intensity running average is the number of veins per 31 structural intervals with the latter representing sections with near uniform veining. Stereo plots are of poles to planar features in the split core working half reference frame.
←

commonly exceeding 1 vol% and reaching 10% in a few samples. Brown amphibole in some samples grades into dark green amphibole, and whereas most of it appears to be of late magmatic origin, some may be hydrothermal or deuteric.

In hand specimen, milky white secondary plagioclase is the most abundant alteration mineral, but includes both hydrothermal and dynamically recrystallized igneous plagioclase. Hydrothermal plagioclase alteration, by itself, is very low, except near metamorphic veins, and over large intervals of the core amounts to 1% or less, usually consisting of minor amounts of actinolite or smectite along cracks and grain boundaries. Excluding dynamically recrystallized plagioclase, dark green amphibole is the most abundant alteration mineral, forming reaction rims and local replacements of olivine and clinopyroxene, and occurring in alteration halos around amphibole veins. This amphibole is found in amounts up to 20–25% above 700 mbsf, but is much less common and sparsely distributed below 750 mbsf, and all but disappears below 1175 mbsf (Fig. 5). Olivine is the least alteration resistant phase, and networks of irregular cracks cut even the freshest olivine. These cracks are lined with dark, opaque material, likely a mixture of smectites, very finely divided magnetite, fibrous amphibole and possibly talc.

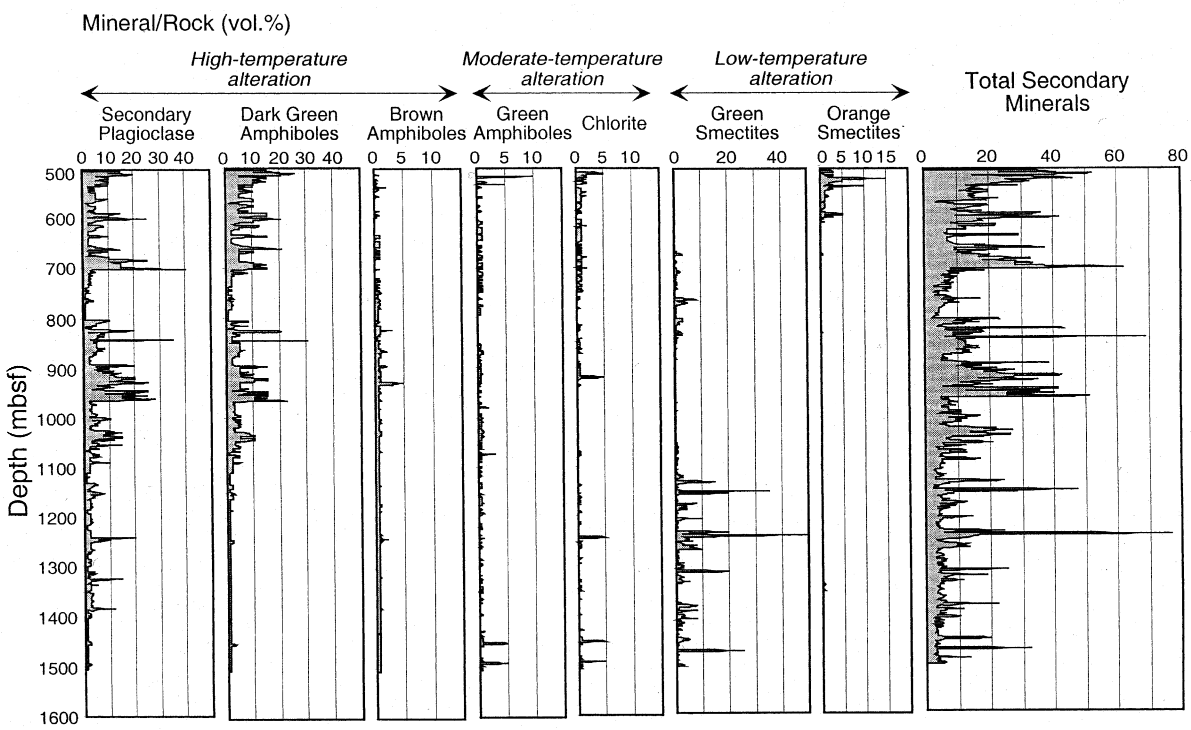

Fig. 5. Distribution of the principal metamorphic phases in the lower 1000 m of Hole 735B. Curves represent running 5 m averages of visually estimated mineral proportions checked against thin section modes. Secondary plagioclase includes both hydrothermally altered plagioclase (albitized) and dynamically recrystallized igneous plagioclase.

Where alteration is more pronounced, fine-grained mixtures of talc, magnesian amphibole and finely divided magnetite or pyrite replace the grains.

Many rocks, veins and shear zones exhibit the influence of late magmatic hydrous fluids, and in many cases, these zones have abundant amphibole. The high-temperature limit of sub-solidus alteration is represented by recrystallized gabbros, often with aggregates of equant grains with 120° triple junctions and olivine and pyroxene neoblasts typical of granulite-facies metamorphic conditions (>700–1000°C). Many of the shear zones acted as pathways for later hydrothermal fluids, resulting in the formation of amphibole and clinopyroxene as deformation continued on down into the amphibolite-facies (~450–700°C). Amphibole often partially replaces pyroxene in ductily deformed rocks down to 1100 mbsf. It forms reaction rims, tails and pressure shadows as well as discrete grains in segregations along foliation planes, and its abundance is directly correlated to that of secondary plagioclase (Fig. 5). Since the latter is mostly dynamically recrystallized plagioclase, this indicates a direct link between high-temperature hydrothermal alteration and deformation.

Alteration at moderate temperatures corresponding to the greenschist-facies (~250–450°C) is sparse. Actinolite, however, may locally comprise up to 50 vol% of the rock. It occurs almost exclusively along the margins of clinopyroxene grains where it may extend into the crystals along cleavage planes and into the adjacent plagioclase. Prehnite and epidote are the only calc-silicates recognized as vein forming minerals in hand specimen. Epidote was found in only two veins, though one of these was 12 mm wide. It also occurs sporadically as matrix alteration in the gabbro. Secondary quartz occurs rarely with other greenschist-facies minerals and there are six quartz veins near the bottom of the hole. Prehnite veins were found in the deepest part of the hole. Greenschist-facies assemblages are best developed in local breccia zones cemented by felsic material in the upper 500 m. These may be local upflow zones, overprinting networks of igneous felsic veins that formed during degassing at the end of igneous crystallization [18,20].

Low-temperature alteration (<300°C) includes the local formation of abundant chlorite–smectite minerals, carbonate veins, sulfides and oxyhydroxide minerals. Chlorite–smectite is the third most abundant alteration mineral and occurs above 600 mbsf as orange to reddish patches partially or completely replacing olivine near carbonate and clay veins. Dark green to pale bluish green clay appears deeper in the hole around clay veins, with a pronounced gap in occurrence between 800 and 1100 mbsf.

On Leg 176, we described 2792 veins representing 21 different assemblages. Total vein abundance is less than 1% as compared to 2.39% in the upper 500 m [4]. Close to half are filled with smectite and clays (1016) and carbonate (293), with most of the latter concentrated between 500 and 600 mbsf. Smectite and clay veins occur largely from 575 to 833 m and from 1054 to 1500 m and their occurrence may be related to seawater percolation in open fractures and faults at 560 m and between 690 and 700 m. Overall, the distribution of the veins corresponds well to the matrix alteration. The principal high-temperature veins decrease sharply downsection (e.g. Fig. 5). Felsic veins constitute ~0.45 vol%, amphibole-bearing ~0.24 vol% and diopside-bearing veins ~0.04 vol%, as opposed to 0.63 vol%, 0.92 vol% and 0.33 vol%, respectively, in the upper 500 m [4]. Whereas felsic veins are volumetrically most abundant, many, particularly those associated with oxide-bearing gabbros, are clearly magmatic in origin. Many of the latter have a strong hydrothermal overprint, while other felsic veins appear entirely hydrothermal in origin. Quite often, the origin of a particular felsic vein is entirely ambiguous. Though rare below 1100 m, amphibole veins are by number the second most abundant type (17% of all veins). They are almost entirely monomineralic in the Leg 176 section, though the larger ones may contain feldspar. Amphibole occasionally forms anastomosing fine vein networks, though most veins are subvertical, around 0.5 mm wide, and may be orthogonal to the foliation where present.

7. Rock magnetism

Cores from Hole 735B have a reversed polarity magnetization (mean 71.4+0.3/−3.1 [3]) with no significant downhole trend (Fig. 1). This is steeper than that expected from an axial geocentric dipole (~52°), indicating a tectonic tilt of about 19±5°. The average remanent intensity of samples from Leg 176 is ~2.5 A/m, nearly identical to the estimated in situ intensity found during Leg 118 [21]. The uniform inclination of both fresh and altered rocks suggests relatively rapid cooling accompanying unroofing at the rift valley wall [22]. Thus, the gabbros are an ideal source for marine magnetic anomalies and the 1.5 km drilled can readily account for the lineated marine magnetic anomaly found over Hole 735B [6].

8. The bulk hole composition

Table 2 gives the calculated bulk compositions of Hole 735B and its upper, middle and lower 500 m sections. The calculations are shown in the Table 2 electronic appendix and were done using the measured thicknesses of the different lithologic intervals, the shipboard XRF analyses and 452 density measurements. The composition of the upper 500 m is from Dick et al. [4]. A feature of the bulk compositions is that they are all close to those of various primitive to moderately differentiated basalts. The major element composition of many gabbros, however, is close to that of basaltic melts for most elements simply because the cotectic proportions of olivine, plagioclase and pyroxene have a basaltic bulk composition. Hence, most major elements vary little in multiply saturated MORB over a large crystallization range until iron oxide minerals appear on the liquidus [23]. Thus, the interpretation of most Hole 735B gabbros as cumulates is based on trace rather than major elements.

The calculated 500 m bulk compositions are significantly different, with nearly a factor of three enrichment in TiO_2, a strong increase in total iron, a doubling of Fe_2O_3 and a large decrease in Mg# from 72.9 to 65.9, from the lowermost to the uppermost section. Such features are normally associated with cumulate sequences produced by progressive fractional crystallization. However, molecular Ca/{Ca+Na}, which should covary with Mg# if this were the case, remains virtually constant (Fig. 3), and highly compatible Cr more than doubles. All the other trace elements, compatible and incompatible, remain virtually constant. These contrasting variations preclude simple upward progressive fractional crystallization of basaltic magma in a single intrusion from explaining the overall stratigraphy. Rather, the best explanation, consistent with the stratigraphy, appears to be a hybrid origin in which the olivine gabbros are locally intruded by late magmatic liquids, especially in the upper third of the hole. The sources of these melts (obviously compacted out of olivine gabbro intrusions similar to those comprising the bulk of the section) may either lie below or laterally out of the Hole 735B section.

Although the total composition of the lower crust is unknown, the bulk composition of the entire crust must be that of the average parental magma passing the crust–mantle boundary. Based on the composition of abyssal dunites, this must lie close to experimentally predicted primary melt compositions with respect to Mg/(Mg+Fe) ratio [24,25]. This can be inferred because dunites represent zones of focused melt flow out of the shallow mantle and therefore constrain the primary melt composition with respect to equilibrium with olivine [26–28]. The average composition of the upper crustal section (dikes and pillow lavas) originally overlying Hole 735B can be approximated from the average of basalts from Atlantis II Fracture Zone and the eastern rift valley. Although most of these samples are pillow lavas, where both dikes and pillow lavas can be compared, such as at ODP Hole 504B and in the Troodos Ophiolite, their compositions are very similar [29,30]. The Atlantis II Fracture Zone basalts are moderately differentiated, and plot far from likely parental melt compositions (Fig. 3). Therefore, they must have differentiated within the crust or the shallow mantle prior to eruption. As can be seen from Fig. 3, the bulk composition of Hole 735B itself, plotting to the left of the inferred locus of primary mantle melts, cannot mass balance any of the Atlantis II Fracture Zone basalts back to a reasonable primary composition. Accordingly, a considerable thickness of primitive cumulates complementary to the lavas, dikes and Hole 735B gabbros is missing from the drilled section.

The missing cumulates may lie below the hole, in a crustal section that remains undrilled, or they are in the underlying mantle. They may also lie out of the section, either because of faulting or because they crystallized closer to the mid-point of the paleo-ridge segment. The latter possibility is compatible with models of focused melt flow from the mantle toward the mid-point of the ridge, followed by lateral intrusion of differentiated melt down-axis in the lower crust towards Hole 735B [12,31]. This is also consistent with the small proportion of gabbro compared with basalt and peridotite dredged from SW Indian Ridge transforms, which demonstrates that if there is a normal gabbroic layer 3 anywhere beneath the ridge, it must thin dramatically near these faults [12]. Moreover, gabbro suites sampled well away from fracture zones at the Cayman Trough [32], DSDP Hole 334 west of the MAR at 36°53′N [33] and at 7°16′E on the SW Indian Ridge [34] all have average olivine compositions greater than Fo_{80}. Thus, their average compositions, unlike that of Hole 735B, plot considerably to the right of the primary magma trend in Fig. 3, with the potential of mass balancing MORB back to a primary magma composition. The possibility that the missing cumulates are in the underlying mantle section may explain why the Moho here is deep, without requiring it to be an alteration front, or requiring an anomalous thickness of gabbroic crust. However, dunites are rare from SW Indian Ridge transforms, and at the Atlantis II Fracture Zone, in particular, there are only 1.9% in 973 kg of peridotite in 16 dredge hauls [6]. This suggests that there was little melt transport in the shallow mantle near transforms [28] making this latter possibility unlikely.

9. Discussion

The innumerable late oxide gabbro bodies, their upward increase in abundance, the association of magmatic and crystal–plastic foliations with oxide abundance, and the numerous intrusions of oxide-rich melts along small shear zones distinguish the Hole 735B section from gabbros in most well-documented ophiolites or layered intrusions. Despite the abundance of the ferrogabbros, no eruptive equivalents (ferrobasalts) have been found. Instead, simple equilibrium relations show that the Atlantis II Fracture Zone basalts are complementary to the olivine gabbros [18]. This same situation has also been noted for gabbroic rocks dredged from five other SW Indian and Central Indian Ridge fracture zones where ferrogabbros are also anomalously abundant [29]. This is consistent with the supposition that the Fe–Ti-rich melts that produced the ferrogabbros were derived from late magmatic liquids squeezed from the 'mesostasis' of crystallizing olivine gabbro intrusions. Evidence for this interpretation lies in patches of oxide gabbro in undeformed olivine gabbro deep in the hole, which likely represent local pockets of late melt trapped within the olivine gabbro at the end of crystallization.

The melts producing the ferrogabbros formed by extended high-iron differentiation [35,18], and can constitute only a small residual fraction of a primary basalt magma (10–20%) since ilmenite and magnetite appear on the liquidus only after about 90% crystallization [23,36]. Moreover, since the oxidation state of MORBs is very low [37], simple normative calculations show that even the most iron- and titanium-enriched ferrobasalt liquid will produce less than 4–6% iron–titanium oxides when solidified. Thus, the thick sequences of massive oxide gabbro, with an average of close to 10% modal oxide [4] and the numerous small patches and small shears filled with oxides, are not simple ferrobasaltic intrusions. Rather, they likely represent cumulates from which late silicic melt was squeezed out to leave an oxide-rich residue, or through which ferrobasalt melt migrated by permeable flow, impregnating the protolith with excess oxides as it went.

The absence of erupted ferrobasalts complementary to the ferrogabbros and the similarity of the bulk hole composition to that of basalt suggest that the intricate igneous stratigraphy of

Hole 735B is produced by essentially closed system differentiation and redistribution of melt. The mechanism by which a large volume of late melt can be compacted out of an olivine gabbro matrix, then aggregated and finally intruded into cooler parts of the crust without eruption to the seafloor is not clear. We believe, however, that this mechanism reflects intrusion and crystallization of magmas in the dynamic environment of a slow-spreading ocean ridge where the crust is constructed of numerous small intrusions, and a steady-state magma chamber is absent (e.g. [4,35,36,38]).

One might imagine such a process as beginning where an intrusion intersects an existing fault that extends into the lower crust from the rift valley wall, or by initiation of a fault within a still partially molten body that is sufficiently rigid to support a shear stress. Where such faults cut the impermeable rocks enclosing an intrusion, the accompanying deformation, with local grain boundary sliding and cataclasis, is likely to enhance permeability and thus create pressure gradients. In such a situation, with somewhere to go, late intergranular melt will be compacted out of the crystallizing gabbro and migrate into and along the shear zones. As it moves into cooler rocks, it will crystallize and react with the enclosing gabbro. With the melt mass decreasing, ilmenite and magnetite will appear on the liquidus and precipitate, providing a mechanism to enrich oxides locally in the gabbro by adcumulus growth from migrating melt. Based on other cumulate sequences, the early flow of intergranular melt as it migrates out of the olivine gabbro will leave little textural imprint. As melt aggregates into narrow zones as it migrates into the shear zones, large fluxes might locally produce magmatic foliations due to preferred growth of plagioclase crystals in the direction of fluid flow. As melt moves along a shear zone, however, brittle–ductile and local crystal–plastic deformation will accompany permeable flow. In the end, as the rocks solidify, and at higher levels where melt is not present, deformation would continue in the crystal–plastic regime with a transition to cataclasis at shallower levels. In this way, it is possible to account for the association of oxides, crystal–plastic deformation and magmatic foliations in Hole 735B.

The absence of ferrobasalt, then, reflects the mode of melt aggregation and transport. With no steady-state magma chamber, and with ongoing deformation, late melts formed during crystallization of small mafic intrusions would either crystallize in situ or migrate by permeable flow along shear zones into cooler sections of the crust where they would freeze without erupting to the seafloor. In contrast, at the East Pacific Rise, where ferrobasalt flows are common [39,40], a nearly steady-state melt lens has been found to underlie most of the ridge [41]. Submersible sampling and ODP drilling during Leg 147 at Hess Deep recovered the uppermost gabbros crystallized beneath the rise which plausibly represent the frozen residues of such a melt lens [42]. These are largely fine- to medium-grained gabbronorite and olivine gabbronorite cumulates which crystallized from liquids ranging from ferrobasalt to ferroandesite in composition, and contain no evidence of high-temperature crystal–plastic deformation such as that found in the Hole 735B section. The East Pacific Rise, with much higher rates of mantle upwelling and melt input, also has a steep thermal profile, as indicated by the melt lens which requires temperatures of 1000°C or higher to be sustained just below the sheeted dikes. In this situation, since temperatures of around 1190°C correspond to the onset of plagioclase crystallization at the base of the crust, late Fe–Ti-rich melts, with relatively low liquidus temperatures of 1100°C or less [43], would not crystallize in the lower crust. Instead, they would tend to migrate by compaction and re-intrusion to higher levels, aggregating to form the melt lens, from which they could erupt through dikes to the seafloor. In Hole 735B, however, the presence of oxide segregations and felsic veins even near the bottom of the hole demonstrates that conditions repeatedly dropped to near 1000°C deep in the lower crust, probably following each inflation–eruption cycle.

Melt transport during deformation can account for many of the features found in Hole 735B. However, melt migration along shear zones is not the only melt migration mechanism evident in the cores. The felsic veins and their oxide-rich reaction zones clearly demonstrate fracture-controlled late-stage melt migration. In addition, the cumulus character of the olivine gabbros, which is typical of gabbros in many environments, by itself requires extensive melt migration by means of simple compaction, porous flow or solution channeling. Thus it is likely that several different modalities existed for both early and late-stage melt migration, even though their relative importance remains unknown.

The role of deformation in lower crustal petrogenesis in the Hole 735B gabbros continued into the sub-solidus regime, particularly in controlling the circulation of hydrothermal fluids and alteration. This is evident in the sharp downhole decrease in amphibole abundance and coincident drop-off in crystal–plastic deformation intensity. This suggests a strong drop in circulation of high-temperature hydrothermal fluids downhole, with only very localized penetration of fluids along vein networks at depth. Given the relative abundance of both high- and low-temperature alteration, the sparse greenschist-facies alteration is quite striking. However, this is consistent with rapid cooling from amphibolite-facies conditions to low temperatures during unroofing and block uplift at the inside-corner high [4]. The low-temperature oxidative alteration associated with zones of brittle fracture reflects slower cooling with the re-establishment of a quasi-steady-state geotherm after uplift and unroofing of the section.

The close association of oxide-rich and oxide-poor gabbro at Hole 735B and the importance of deformation-related processes in the hyper- and sub-solidus regimes are also seen in gabbros from other slow-spreading ridges, including the Cayman Trough [44], and Indian Ocean [17] and Atlantic [45,46] fracture zones. Thus Hole 735B appears representative of the lower crust sampled at slow-spreading ridges, at least that formed near large fracture zones. Hess Deep East Pacific Rise gabbros, and those in ophiolites believed to have also formed at fast-spreading ridges (e.g. Oman), on the other hand, lack intimately intercalated ferrogabbro and olivine gabbro, extensive crystal–plastic fabrics, and have a different pattern of alteration [47,48]. They contain a microscopic amphibole vein assemblage responsible for pervasive (10–50%) alteration of gabbros at temperatures of 600–700°C under static conditions in the near-axis regime. Moreover, the lack of well-defined igneous layering at Hole 735B contrasts with layering in the lower two-thirds of the Oman section and the report of layered gabbros at Hess Deep [49]. These differences, then, support the long-standing inference that accretionary processes in the lower crust are highly sensitive to spreading rate.

Hole 735B in many ways is unlike gabbro sequences in any well-described major ophiolite. Several features stand out. Massive layered gabbros and wehrlitic intrusions prominent in many ophiolites such as Oman and Troodos are missing. These could be present beneath the hole or out of section; however, they are also absent in the many gabbro dredge hauls from Atlantis II Fracture Zone [6]. Some features of the Hole 735B section, including the sparcity of layering and numerous small intrusive units, are found in ophiolites believed to be formed in slow-spreading environments, such as the Trinity or Josephine. However, several of the major features of Hole 735B have not been described in these ophiolites. These include (1) apparent synkinematic igneous differentiation resulting in intercalations of oxide and olivine gabbros at all scales, (2) the concentration of ferrogabbros near the top of the section, and (3) the sharp downward decrease of the intensity of crystal–plastic and brittle–ductile deformation. Whereas the Bay of Islands ophiolite has associated high-temperature deformation and oxide gabbro intrusion [50,51], it also has massive layering and wehrlites. The Ligurian ophiolite gabbros have some similarities to Hole 735B, notably extensive crystal–plastic deformation and coarse grain size [52]. However, they lack any connection to a sheeted dike or pillow sequence, and were intruded through old continental mantle during continental breakup [53]. Together with the well-known arc-related geochemical affinities [54], then, most ophiolites are not good analogs for Hole 735B. Although an exact on-land counterpart may not exist, the relatively small Lizard Ophiolite [55,56] may be a reasonable match; careful study of ophiolites may reveal more. The scarcity of comparable ophiolites, however, is not surprising, since obduction of ocean crust from old, cold slow-spread lithosphere is far less likely than obduction of crust from hot young lithosphere formed in small basins, fore-arcs and back-arc ocean environments.

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