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A Brief Narrative History of ODP Hole 735B[1]

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"Facts are better than dreams."—Winston S. Churchill

ABSTRACT

The objective of returning to Ocean Drilling Program Site 735 near the Atlantis II Fracture Zone on the Southwest Indian Ridge during Leg 176 was to obtain a long section of gabbro and with it establish how the lower ocean crust forms at a slowly spreading ridge. The transition between rocks of the lower crust and upper mantle was potentially within reach. In the end, the hole was extended by more than 1000 m, achieving a total penetration of 1508 m, all but a tiny portion of it in gabbro.

We present a brief narrative history of Hole 735B, placing it in the context of planning for scientific drilling of the ocean crust over a period of more than a decade, during which our general knowledge of the structure and composition of ocean crust changed and developed. The separate contributions in this volume, of others published elsewhere, and of a scientific synthesis prepared in tandem with this report, should all be considered in relation to those plans. Drilling of the ocean crust depends on drilling technology and on decisions made at sea almost daily to make that technology work to best advantage. Success in the future will depend on a clear understanding of how to match drilling objectives with drilling technology. This is a case study of one such enterprise.

INTRODUCTION

Leg 176 was the second of two legs to occupy one hole, Ocean Drilling Program (ODP) Hole 735B, which was drilled during both 1987 and

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1997 into the gabbroic portion of the ocean crust in the Indian Ocean. The drilling was enormously successful, providing great insight into interactive processes of crustal accretion, igneous differentiation, high-temperature crystal-plastic deformation, and cooler static hydrothermal alteration of the lower ocean crust at a very slowly spreading ridge. Results have been presented in *Proceedings of the Ocean Drilling Program, Initial Reports* volumes for Legs 118 and 176 (Robinson, Von Herzen, et al., 1989; Dick, Natland, Miller, et al., 1999), the *Scientific Results* volume for Leg 118 (Von Herzen, Robinson, et al., 1991), and a number of articles in the general scientific literature. Some are now presented in this volume. Five other surveys have been conducted in the vicinity of Hole 735B, one prior to Leg 118 in 1986 and one prior to and three following Leg 176. These investigations form an important backdrop to the drilling. Additional drilling was carried out a little more than a kilometer from Hole 735B during engineering Leg 179 (Pettigrew, Casey, Miller, et al., 1999).

There is consequently material aplenty to synthesize. The planning for the drilling of Hole 735B involved many people, many documents, and many meetings. Proper understanding of the scientific results requires a summary of why the drilling was carried out in the first place and of how and in what ways it was either successful or not successful. Such an evaluation often is part of the presentation of the *Initial Reports* volume of the *Proceedings of the Ocean Drilling Program;* in this case two of those were prepared, but neither was an overview of the entire project. Consequently, we believe that the scientific reports in this volume and elsewhere are well served by a general prefatory chapter. We hope this will be useful to anyone who wishes to propose and carry out any project of similar scale in scientific ocean drilling in the future.

We have also prepared a general scientific synthesis reviewing the chemical stratigraphy of the entire core recovered during both Legs 118 and 176, integrating all shipboard and postcruise geochemical data (Natland and Dick, **Synthesis chapter,** this volume). The summaries here of survey results and of concepts of ocean crust structure are important background for that chapter.

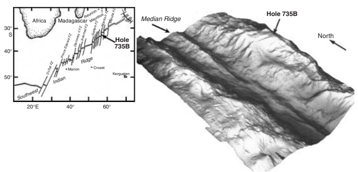
INCEPTION OF HOLE 735B

We first set down the way in which Hole 735B came to be, as there are some misunderstandings about this. The drilling was a long-term project with objectives shifting over the years, not least because of the success of the first leg, and these need to be set out as well. We were principal proponents for the drilling from the outset and participated in decisions onboard ship, somewhat peripherally during Leg 118 and more centrally during Leg 176.

Hole 735B has been described as the result of "serendipity" by those who prefer a more rigorous method of planning and conducting scientific ocean drilling than that which took place. Although Hole 735B was not the initial target of Leg 118, which set out to drill serpentinized peridotites in the transform valley, the results of the drilling are fully consistent with the original objectives of that leg and its successor. Serendipity (the faculty of making desirable but unsought-for discoveries by accident; *American College Encyclopedic Dictionary),* therefore, is not an accurate term to describe what actually happened. At the least, the drilling was not unsought. The decision to drill at Site 735 was also an *informed* one, dictated to be sure by circumstance, but there were solid reasons behind it.

In 1987, during ODP Leg 118, Hole 735B was drilled for >500 m into gabbroic rock atop a shallow platform on the eastern transverse ridge of the Atlantis II Fracture Zone, Southwest Indian Ridge (Fig. **F1**). The drilling capped a tumultuous leg that began with unsuccessful attempts to core at three other locations in the transform valley and the steep eastern wall of the transform, all of them thwarted by the impossibility of penetrating boulders and the loose surficial material of debris flows that had flooded the transform valley. The two halves of a hard rock base, constructed while sailing east to the fracture zone in the first week out of Cape Town and needing only an optimistic signal to be bolted together over the moonpool and lowered to the seafloor, sat rusting on deck. For more than a month, each of the highest-priority drilling targets was attempted, to no avail. Video monitors in various locations on the ship usually showed a great churning of rock and mud during the attempted spud-ins, but no coherent core was recovered. The holes were barely worth the expenditure of a core bit, let alone the hard rock base. In due course, a groundswell arose among members of the scientific party to pull out of the rubble-glutted ditch and try a target atop the transverse ridge, where, at least, no such material could have accumulated.

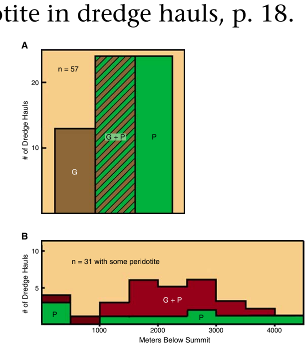
F1. Location of Hole 735B, p. 17.



At hand were the preliminary charts of a swath-mapping site survey, funded and carried out only a year earlier. The survey was one of the first ever of a transform fault using multibeam technology, and the Atlantis II Fracture Zone is still is the only one of its kind to have been surveyed by such means in the Indian Ocean. The Indian Ocean, of course, was well known as the location of numerous major rents in the seafloor, displacing segments of the Central and Southwest Indian Ridges (e.g., Fisher and Sclater, 1983). Most of these have large high-standing transverse ridges adjacent to transform valleys, similar to those of the Atlantis II Fracture Zone, from which large quantities of gabbroic and ultramafic rock had been routinely dredged (e.g., Engel and Fisher, 1969, 1975; Fisher et al., 1986). The proposal for drilling a fracture zone in the Indian Ocean, conceived in 1984 during a workshop on the Indian Ocean, was a response to the projected circumnavigation of the globe by *JOIDES Resolution,* then formally named *SEDCO/BP 471,* as part of the initial scientific plan of the new Ocean Drilling Program and the knowledge that these enticing targets would unavoidably lie in her path.

Thus, amidst the difficulties of Leg 118 the shipboard scientists fixed their attention on the heights shown on the unrolled survey charts, rather than the depths, and the principal remarkable fact about the eastern transverse ridge of the Atlantis II Fracture Zone, and the key to the eventual success of Leg 118 emerged. The ridge has a flat top that lies in only ~700 m of water. The top is so flat and shallow that the prospect of wave planation immediately came to mind, although a submerged reef was not an utter impossibility either. Whatever the case, statistics were presented to show how frequently gabbros and ultramafic rocks have been obtained by dredging at all levels of transverse ridges regardless of elevation in the Indian Ocean (Fig. **F2**). In generic form, such a target was also among the prioritized objectives for the leg. The scientific party deliberated, then voted. The Co-Chief Scientists obtained dispensation from authorities on "the beach," and *JOIDES Resolution* moved to what became Site 735.

F2. Gabbro and serpentinized peridotite in dredge hauls, p. 18.



A first glimpse of the seafloor using the video camera attached to the vibration-isolated television (VIT) frame lowered around the drill pipe and suspended just off bottom showed neither reef nor pillow lava but banded rock. Optimism rose. Coring at a short pilot hole brought up foliated gabbro, explaining the banded appearance of the outcrop and raising the level of optimism further still. A box survey with the video camera showed such rock in abundance between thin drifts of sediment. The signal was given, and the hard rock base was at last bolted together and lowered as quickly as possible to the seafloor. The almost perfectly flat bottom made the landing simple and assured the prospects for coring. No other preliminary operations were conducted; no casing was set in place. Instead, coring began as soon as the drill string could be turned around with a core bit at its end, and the funnel on the hard rock base, now perched on the seafloor, was reentered. Drilling went slowly at first until the bottom-hole assembly was safely below the seafloor, and then at an accelerating rate, one core of gabbro after another was brought on board. Reentry of the hole became routine. The material was cored with exceptional ease and astonishing recovery, nearly 87% over the entire hole. The scientific party, which for a month had made do with small chips and scraps from failed holes, was now nearly overwhelmed. The rig crew rushed to achieve the milestone of a 500-m penetration. A respite was finally provided to those describing the rocks by the staging of a comprehensive downhole logging program in the final days before leaving the site. Over the course of 17 days, Leg 118 went from being an abject failure to one of the most astounding successes in the history of drilling of the ocean crust. The first long section of the lower ocean crust ever drilled was in hand, logged, and revealing its secrets. With far more rock on board than anyone anticipated, the ship departed for Mauritius.

Open reentry holes drilled deep into the ocean crust have lives of their own, acting both as magnet to some and unwelcome burden to others. A proposal to return to Hole 735B was submitted within months of the completion of Leg 118. The Indian Ocean itself, however, was not so attractive to those with other interests. Long sojourns in the Atlantic and Pacific Oceans were in the future of *JOIDES Resolution,* and the deepening of Hole 735B, remotely situated in the Indian Ocean, did not fit with these plans. A well-attended workshop at Woods Hole Oceanographic Institute featuring archive portions of the Leg 118 core in the atrium outside the conference room launched a program of offset-section drilling of the lower ocean crust and upper mantle that eventually led to the scheduling of legs to drill gabbro and peridotite in the eastern Pacific and North Atlantic Oceans. The Southwest Indian Ridge, however, had to wait.

Again, site survey was an issue. The survey from 1986 provided a fairly broad regional context for Hole 735B, but the depth to the mantle transition, where other holes might be drilled if it became necessary to move, and the mechanism of exposure and uplift of the shallow platform—whether indeed it had been eroded at wave-base—were all unanswered questions. To be sure, simply reentering a hole does not of itself require a survey, and to some this meant that the drilling should proceed without it, allowing other surveys to be funded. Within the drilling planning structure, however, the lack of any more detailed survey information for a long time threatened the drilling. In the end, a multinational survey focused on the shallow platform was conducted *6 months after* Leg 176. Dive programs using submersibles and remotely operated vehicles organized from Japan shortly followed. A British geophysical expedition prior to Leg 176 established something about the depth to the mantle (Muller et al., 1997). The environs of Hole 735B are now perhaps the best surveyed, best sampled, and, as we believe, best understood portion of a major fracture zone anywhere in the ocean basins.

Leg 176 was finally scheduled without a new survey, sandwiched between a paleoceanographic leg in the South Atlantic and another in the far southern oceans, both of them ending or beginning at Cape Town and fully 10 years after Leg 118. In the event, Hole 735B was occupied for the entirety of Leg 176. Following a short logging program to measure temperatures and obtain an image of the hole with the Formation MicroScanner (FMS), a tool unavailable during Leg 118, we began coring, picking it up with the same high recovery experienced in 1987. On first touching the bottom of the hole with the drill, we were surprised to find that it was 4 m deeper than when last measured during Leg 118. The cause of the discrepancy remains unknown, but perhaps has to do with small differences between average lengths of stands of pipe—always assumed to be a standard 9.5 m long—used during the two legs, accumulated over the >500 m length of the hole. Over the next several weeks, an additional 1004 m of rock—all of it gabbro—was cored, carrying penetration to 1508 meters below seafloor (mbsf). This was not entirely without incident, but because the drillers were both ingenious and resourceful there were no major difficulties. Recovery again remained astonishingly high and was almost identical to that of Leg 118.

A sense of the sheer amount of rock drilled and recovered over the two legs perhaps is conveyed by comparison with the backdrop to Cape Town, the port in South Africa that served both Legs 118 and 176 (Fig. F3). Table Mountain, like Atlantis Bank, is flat topped. It consists of Precambrian Cape Granite unconformably overlain by Cambrian sedimentary rock (Haughton, 1969). An aerial tram lifts tourists from the city to the summit. At the outset of Leg 176, our conjecture was that we would very likely core deeper than the tourists ascend. Perhaps we would even reach mantle peridotite. We did the one but not the other.

F3. Table Mountain compared with penetration and recovery in ODP Hole 735B, p. 19.

With a week to go before ceasing drilling and commencing logging, while some high-strength pipe joints near the top of the drill string were being shifted, two consecutive sharp heaves of the vessel in fairly heavy seas caused the end of the temporarily suspended pipe to jam against a ledge ~100 m above the bottom of the hole. The pipe string lifted off its supports in the rig and went into compression on each downswell. On the second wave, it snapped at the guide base. In the hole the severed part of the string broke through the ledge. Several tons of steel, including the entire heavy bottom-hole assembly, hurtled downward, coming to an abrupt halt at the bottom of the hole. Only the rock around the hole prevented the falling string from collapsing under its own momentum, but it undoubtedly was forced strongly, in a tight spiral, against the wall of the hole. During the next few days, the rig crew retrieved a portion of the lost pipe but the decision during Leg 118 not to string casing from the reentry cone into the upper part of the hole severely limited the size of fishing tools that could pass from the cone into the unconnected hole beneath (Fig. F4). In the end, more than 900 m of pipe was irretrievably wedged in the hole. The drilling was over, and our opportunities to continue—perhaps into peridotite—and to log all but a small portion of the newly cored section were also lost. Thus, on the brink of truly dramatic success came the untimely demise of Hole 735B.

F4. Hard rock base installed during Leg 118, p. 20.

The reports in this volume therefore mainly summarize work on the core. This in itself has been a considerable effort, comprising first the two shipboard studies and then shore-based work of dozens of scientists—participants in both legs—funded by various agencies of the partners in the Ocean Drilling Program. However, whereas most of the studies following Legs 118 and 176 deal only or mainly with those portions of the hole drilled during either leg, our synthesis (Natland and Dick, **Synthesis chapter,** this volume) attempts to provide a synopsis of the entire core and place it properly in its geologic setting.

PURPOSE OF DRILLING

In 1987, the objective of drilling a fracture zone in the Indian Ocean was largely exploratory. Over 19 years previously, the better part of 17 legs of the Deep Sea Drilling Project and the Ocean Drilling Program had been formally devoted to drilling ocean crust produced at spreading ridges but always starting at the top in basalts. This produced a great deal of information about the chemical stratigraphy of basalts at spreading ridges, their physical and magnetic properties, and their alteration. One of the main things learned, however, was just how difficult it is to core into hard, fractured, and fragmental submarine lavas from a heaving platform using equipment originally designed for drilling in sedimentary formations from stationary rigs while searching for oil. At the outset of Leg 118, several holes had been drilled to depths of >500 m into basaltic basement at various locations in the ocean basins, but only one of them had not yet come to grief because of equipment failure or the instability of the rock. Eventually even that one, Hole 504B near the Costa Rica Rift, had to be abandoned after penetrating >1800 m of basalt pillows and dikes but before truly reaching the lower ocean crust.

The majority of the ocean crust, comprising seismic Layer 3, was presumed to be gabbro overlying mantle peridotite. Such rocks, therefore, had never yet been touched except in genuinely serendipitous fashion by the drill. In many ways, abyssal gabbro contains the keys to understanding accretion of ocean crust at spreading ridges, the mechanism of igneous differentiation influencing all abyssal tholeiites, and the deep exchanges between rocks and circulating fluids that supply high-temperature hydrothermal vents. Shallow abyssal peridotite records the process of partial melting that leads to the formation of ocean crust, the mechanism of transfer of melt from the mantle to the crust, and the scale of variability underlying the parental diversity of ridge basalts. Transitions between peridotites and gabbros and between gabbros and basalts, whether as dikes or flows, are particularly crucial places to investigate because both the physical and chemical aspects of these processes change most significantly over those critical intervals. The transitions also are places to establish a firmer understanding of the seismic structure of the ocean crust.

Transverse ridges adjacent to transform faults in the Atlantic and Indian Oceans were known to be places that afforded the drill a short and in many cases immediate path into the lower ocean crust and upper mantle. Prior to Leg 118, the major morphological attributes of transform faults had been worked out at one or two places (e.g., Karson and Dick, 1983; Fox et al., 1985; Karsen et al., 1984). Transverse ridges adjacent to transform valleys also were also known as places where gabbros and peridotites are prevalent, and this was especially well established at more than a dozen fracture zones in the Indian Ocean (e.g., Engel and Fisher, 1969, 1975; Fisher et al., 1986). However, the reasons why these rocks are exposed were uncertain, and the extent to which they represent intact ocean crust was disputed (Francheteau et al., 1976). Nevertheless, gabbros and serpentinized peridotites had been recovered in the same dredge hauls at a number of places; thus, contacts between these two rock types on the flanks of a number of transverse ridges could conceivably be reached with the drill. However, none of these transitions had actually been observed by means of either a submersible or a near-bottom remote vehicle. Whether the transitions are fundamentally igneous or tectonic in origin was unknown.

The site survey in 1986 (Dick et al., 1991b) succeeded in swath mapping the entire transform domain of the Atlantis II Fracture Zone. Full gravity and magnetic profiles were also obtained, and dredging hauled up plutonic rock at numerous places. The placement of some of these hauls suggested that contacts between gabbro and serpentinized peridotite do indeed exist on the steep inward-facing walls of the transverse ridges adjoining the Atlantis II Fracture Zone. However, a small median ridge was discovered in the deep transform valley, following the trace of the transform fault itself (Fig. F1). Virtually nothing but serpentinite was obtained in several dredge hauls of this feature. Whatever the complexities of the adjacent high transverse ridges, this small ridge was evidently comprised of nothing but abyssal peridotite. Not surprisingly, the opportunity to drill into (altered) mantle rock on this small ridge became the first priority of drilling for Leg 118. Although the high transverse ridges were of interest, those who reviewed the survey data and dictated the priorities for drilling perceived them more skeptically.

The hard realities of drilling, however, sometimes dictate their own priorities. The brief box survey with the VIT camera prior to the drilling of Hole 735B during Leg 118 was actually a small but proper milestone in the scientific investigation of fracture zones. Besides documenting a superb place to drill, the survey encompassed a substantial block of massive rock, obviously large, with strong and coherent foliation throughout. Contrast this to the closely spaced normal faults observed during dive traverses of gabbro and peridotite exposed on walls of rift valleys in the North Atlantic (Mével et al., 1991; Cannat et al., 1995; Karson and Lawrence, 1997). There also, the details of rock structure are often obscured by lack of structural continuity of outcrops, the surficial cataclasis of fault surfaces, and the prevalence and sometimes confusing distribution of talus debris. For all the detailed near-bottom work that has been done on gabbros and peridotites in the North Atlantic, no place there is known even today that provides as large a potential array of drilling targets or as easy a place to core plutonic rocks as the 25-km^2 flat summit of Atlantis Bank where Hole 735B was drilled.

Although foliated gabbros obtained by dredge and submersible had been described (e.g., Stroup and Fox, 1981; Malcolm, 1981; Fox and Stroup, 1982; Honnorez et al., 1984), the VIT survey of Leg 118 was the first documentation of the distribution of such rocks in outcrop. Drilling etched this story in high relief. Evidence for high-temperature and sometimes quite extensive crystal-plastic deformation was found throughout the core but most especially at the top (Robinson, Von Herzen, et al., 1989). All of the crystal-plastic deformation overlapped certainly the later stages of magmatic differentiation recorded by the rocks, perhaps even most of it, and extended into the high-temperature subsolidus (Dick et al., 1991a; Bloomer et al., 1991; Ozawa et al., 1991; Natland et al., 1991). By some means perhaps related to the deformation, gabbroic rocks of both fairly primitive and extensively differentiated compositions and mineralogy were juxtaposed in complex fashion, in ways not yet then seen anywhere else, up and down the core. Evocative but simplistic conceptions of dilating pop-bottle axial magma chambers or of infinite onions or leeks (e.g., Cann, 1974; Nisbet and Fowler, 1978) were inapplicable here (Dick et al., 1991a; Natland and Dick, 2001). Was this something strange, or something typical, of a slowly spreading ridge?

Then there was the question of exposure and uplift of the transverse ridge itself. Besides high-temperature crystal-plastic deformation, the cores of the upper 500 m of Hole 735B record a less pervasive and cooler but still substantial history of static metamorphism centered on an entirely separate series of veins and fractures in the rocks (Stakes et al., 1991; Vanko and Stakes, 1991). These are largely orthogonal to preexisting foliation. Amphiboles of various compositions, particularly, but also feldspars, pyroxenes, and clay minerals, line the fractures and replace minerals in rocks adjacent to the veins. After crystal-plastic deformation, the block of rock, although obviously still quite hot, was subject to a different stress field and it responded by cracking, not stretching, as high-temperature fluids coursed through it. Temperatures were sufficiently high, however, that all of this occurred while the block of rock was still in close proximity to a strong source of heat, that is, while it was still buried beneath the axial rift.

The compositions of saline fluid inclusions indicated that ~2 km of material was removed from atop the gabbros (Vanko and Stakes, 1991). This was not all eroded away, however, at the summit of Atlantis Bank. From the site survey, the overlying basalts and dikes clearly separated from the gabbros, evidently along a low-angle detachment fault that penetrated deep beneath the rift valley and were carried intact by seafloor spreading to the north, leaving the gabbros to migrate to the south. These then were soon exposed on the southern rift valley wall and shortly thereafter lifted up to sea level on the transverse ridge (Dick et al., 1991b). The detachment stage of this process corresponded to the imposition of comparatively low-angle, high-temperature crystal-plastic deformation of the gabbros. Brittle fracturing and veining occurred after this, evidently during the first stages of uplift of the plutonic section from beneath the rift valley.

A surprise was that the stable remanent magnetization of all the gabbros has a single, consistent inclination of ~71° (Kikawa and Pariso, 1991). This is ~19° higher than expected for the latitude of the site, suggesting that the rocks were tilted southward as a single block by this amount. If extended to depth, the gabbros cored are quite sufficiently magnetized to provide a source for the magnetic anomaly observed at the site. The site survey demonstrated that magnetic lineations paralleling the ridge axis strike directly across the summit of the transverse ridge (Dick et al., 1991b). The gabbros of Hole 735B thus are a component of the magnetized source for magnetic stripes (Kikawa and Ozawa, 1992; Pariso and Johnson, 1993). This obviously cannot be because of the quenching of tiny magnetites, as seen in pillow lavas. The pillows are not there. Instead, Curie temperatures were reached well after the rocks crystallized and were deformed, and even after much of the static alteration to form amphibole had taken place. Secondary magnetite formed at this later stage has to be responsible for the magnetic signature of the gabbros.

Thus, whereas the objective of extending drilling in Hole 735B during Leg 176 was formally and most simply to continue obtaining a long gabbro section, the actual heart of the venture was to extend these trends linking magmatism, deformation, metamorphism, and rock magnetization, plus some others, as far as possible into deeper rock and ideally into the upper mantle. How close to the mantle did we actually expect to come? Talcose serpentinite had been dredged from the west-facing slope of Atlantis Bank ~3 km west of Hole 735B at depths potentially within reach of the drill by the end of one more leg of drilling (Dick et al., 1991b). In the meantime, a seismic refraction study (Minshull and White 1996; Muller et al., 1997) indicated that high-velocity, unaltered mantle peridotite is present at ~5 km beneath the summit of Atlantis Bank, suggesting that perhaps serpentinized peridotite should lie between gabbro and Moho beneath the site. Formally, then, the deep target for Leg 176 was to breach the gabbro–peridotite transition, testing whether or not the peridotite is partially serpentinized. Failing that, however, we were to recover as long a gabbro section as possible in order to understand the origin of the ocean crust at this location.

NEW CONCEPTS ABOUT CRUSTAL STRUCTURE NEAR TRANSFORM FAULTS AT SLOWLY SPREADING RIDGES

The Southwest Indian Ridge is well described as fracture-zone country. Ridge segments are usually <100 km long, and in many cases they are <50 km apart (Sclater et al., 1981; Fisher and Sclater, 1983; Patriat et al., 1997). In some cases, including that of the Atlantis II Fracture Zone, the transform offsets are actually longer than the lengths of immediately adjacent ridge segments. Generally in the Indian Ocean, long-offset transforms typically have high transverse ridges, usually on both sides (Fisher and Goodwillie, 1997). The relief of transform ridges is substantial, in many cases as much as 5 km, and portions of several of them reach nearly to sea level. They dominate both the topography and the geoid along the Southwest Indian Ridge (Rommeveaux-Jestin et al., 1997).

Between Legs 118 and 176, two conceptions of the process of crustal accretion near transform faults at spreading ridges gained currency. The first is the general idea of ridge segmentation, of which transform faults are only one aspect but probably the most important one at slowly spreading ridges. Geophysical evidence now indicates that between the closely spaced transform faults at slowly spreading ridges magma supply is not uniform. Both geoidal bulls-eye patterns (Kuo and Forsyth, 1988; Lin et al., 1990; Detrick et al., 1995) and seismic studies (Tolstoy et al., 1992; Magde et al., 1997, 2000) centered on rift valleys in the North and South Atlantic show that the crust thins away from segment midpoints and toward the transform faults. Ostensibly, there is less basalt and gabbro in the crust near transform faults. This does not altogether explain the plutonic rock assemblages so commonly found on transverse ridges, but since these structures arise nearer the tapered tips of the accreted crust than the centers of segments, geophysics says that there are certainly fewer superficial rocks to offset by faulting in order to expose peridotite.

The second conception is that of asymmetric faulting on low-angle detachment faults leading to exposure of core complexes, also termed megamullions, on the transverse ridges of slowly spreading ridges (Cann et al., 1997; Tucholke et al., 1998) and of gabbroic and ultramafic rocks (Cannat, 1993; Lagabrielle et al., 1998). Although Dick et al. (1991a) considered that an assymetric detachment mechanism was responsible for separating basalts, mainly, from gabbros drilled in Hole 735B, the general structure of transverse ridges was not yet at all understood from the perspective of marine geophysics. The grooved surfaces of core complexes seen in the high-resolution bathymetry of a number of core complexes in the Atlantic Ocean, with the grooves evidently representing the striations produced by one block of rock sliding over another, were as yet unknown. Now, however, transverse ridges are known to consist at least in part of core complexes, which thus far, however, are only documented adjacent to rift valleys. Some of the grooved summits of these are quite flat although they steepen toward the rift valleys, suggesting that exhumation of the blocks is accomplished by rotation along curving detachment surfaces, rooted in the rift valleys, which roll over and flatten as the blocks gain elevation.

The postcruise surveys of Atlantis Bank where Hole 735B was drilled show that it, too, is a core complex (Dick et al., 1999; Hosford et al., 2000). This one happened to reach sea level. There, the grooved fault surface was partly skimmed off by erosion and covered with a thin patina of platform carbonates after the summit began to subside (MacLeod et al., 1998, 2000). The core-complex hypothesis explains the occurrence of intense crystal-plastic deformation at many places in the gabbros. It explains particularly why this deformation is so intense near the top of the hole. It explains why this deformation occurred at such high temperature with magmas present beneath the floor of the rift valley and prior to removal of some 2 km of overlying rock. It explains why the orientation of all of the foliation in the gabbros, when considered in relation to magnetic inclination, dips to the north toward the rift valley. Finally, it explains why magnetic inclinations up and down the core are steeper by an average of 19° than they should be for the magnetic paleolatitude at the site. Whether drilled by accident or not, Hole 735B penetrates the heart of one of these structures.

The surveys also show that Hole 735B projects to a point about midway between the center of the ridge segment lying to the north of the site and the trace of the transform fault in the transform valley. In the ideal geometrical sense, the original thickness of the crust beneath the site, before it was rent asunder by asymmetric faulting, was probably somewhat less than at the segment midpoint. This may explain why no truly primitive gabbros have been cored at the site (Dick et al., 2000) or dredged from the transform wall and why, in general, they are absent in gabbroic assemblages dredged from transverse ridges (e.g., Francheteau et al., 1976; Fisher et al., 1986; Bloomer et al., 1989).

To all of this, we add a more general consideration about the Southwest Indian Ridge. There and on the Central Indian Ridge transform offsets are numerous and usually closely spaced. Most of them do not displace ridge segments greatly; others, like the Atlantis II Fracture Zone, separate ridge segments by >150 km. The Southwest Indian Ridge itself is propagating relatively eastward into the gap created by the divergent directions of spreading of the Central and Southeast Indian Ridges (Patriat and Parson, 1989; Patriat et al., 1997). At the inception of the Atlantis II Fracture Zone when it was nearer the propagating tip, the ridge segments offsetting it were so close to the Indian Ocean triple junction that they cannot have been very far apart. The transform offset thus lengthened over time. This has been a continuing process. Magnetic profiles obtained during the original site survey (Dick et al., 1991b) revealed a slower spreading rate toward the north from the ridge segments adjacent to the fracture zone than to the south. Spreading thus has been steadily asymmetric for at least the past 20 Ma, although whether offset lengthening also resulted from propagation of nontransform offsets into the transform is uncertain. Ultimately, the ridge segments came to be >150 km apart. As the transform fault lengthened, the relief of the transverse ridges also increased, although by what mechanism is also uncertain. Nevertheless, we must construe the section cored in Hole 735B in terms of three aspects of structural asymmetry—the first being an original unequal distribution of magma along axis, the second being that associated with detachment faulting and formation of a core complex orthogonal to the ridge axis, and the third recognizing that the state of stress along the transform fault has continually but perhaps not evenly changed as it lengthened. We do not yet know how pulses in magmatism and formation of core complexes are tied to the long-term development of the Atlantis II Fracture Zone. Hole 735B represents but an instant in time in this history. We must be extremely cautious in extrapolating results from there to the broader problem of the origin of ocean crust.

CONCLUSIONS

Hole 735B nevertheless provides the only detailed lithologic perspective on the lower ocean crust obtained thus far by drilling. The payoff for the drilling lies in deciphering how the deformed, metamorphosed, and repeatedly intruded rocks of the core were emplaced at the ridge axis before all of that took place. Some of the overlapping threads of asymmetry need to be disentangled and the section reconstructed as it originally was. A start on this is made in several chapters in this volume, including our own synthesis.

Hole 735B was successful because it was spudded at a very easy place to drill and because the newly designed hard rock base provided the means to reenter the hole dozens of times. Hole 735B was eventually lost, however, because it was never designed to be exceptionally deep. Thus, a shortcut was taken to facilitate the success of the second half of Leg 118 after nearly a month of little accomplishment. No casing was placed between the hard rock base and the top of the hole. In the end, this decision proved costly since it so severely limited the options for retrieving the pipe that fell into the hole near the end of Leg 176.

Hole 735B was also too far away from the usual paths of *JOIDES Resolution* to revisit either expeditiously or repeatedly. All the promise of successful drilling portended by Leg 118 was unavailing either to secure funding for site surveys or to schedule renewed drilling until legs with other objectives in the southern oceans could be scheduled around it. Clearly, following up a similar success in the North Atlantic would not have taken 10 years. The additional difficulty now with Atlantis Bank is that the very deepest objective—coring beyond the gabbro section—has to be framed in terms of a completely new hole, whether it is placed right next to the old one, somewhere else on the platform, or even in another ocean. At least two legs of the standard 55-day duration will be required to do this properly. This would be far easier to confront logistically if Atlantis Bank was not so remote. Atlantis Bank is tantalizing because it is so easy to drill; it frustrates because no one else in the drilling community wants to take the ship into the Indian Ocean for very long.

The situation exemplifies the crossroads now facing deep drilling of the ocean crust. Its particular objectives are tied less to geographical locality than to generic types of ocean crust. Success, however, depends either on targeting places that can be drilled easily or figuring out how to drill at difficult places. The latter requires money and drilling time for testing of equipment. Money is sparse, drilling time is in competition with every other program, and truly easy places to drill are very hard to find. For plutonic rocks, we have not yet found another like Atlantis Bank. To follow up Hole 735B at Atlantis Bank or any other location and advance our understanding beyond that gained by coring gabbros for 1508 m will now require a sustained commitment to engineering development, to setting up holes properly at the outset, and to minimizing risk thereafter. To drill deeper, we shall either need to find an equivalent but closer place to drill and start from scratch or return to Atlantis Bank. Wherever we go, we shall need either to return to the location frequently or park a platform there for as much time as is required to complete the project. We will only begin to have such options when two platforms become available for drilling and we start considering drilling objectives in terms of projects rather than legs.

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Figure F1. Location of Hole 735B on the Southwest Indian Ridge and an oblique shaded-relief image of a portion of the Atlantis II Fracture Zone transform valley, showing Atlantis Bank, where Hole 735B was drilled. The relief image, from the frontispiece of the Leg 188 *Scientific Results* volume (Von Herzen, Robinson et al., 1991), is based on a multibeam survey carried out in 1986 (Dick et al., 1991b), and represents an area of ~4000 km^2. Hole 735B is in 720 m of water, and the floor of the transform valley is ~6000 m deep. The initial targets for Leg 118 were on the Median Ridge in the transform valley. FZ = fracture zone.

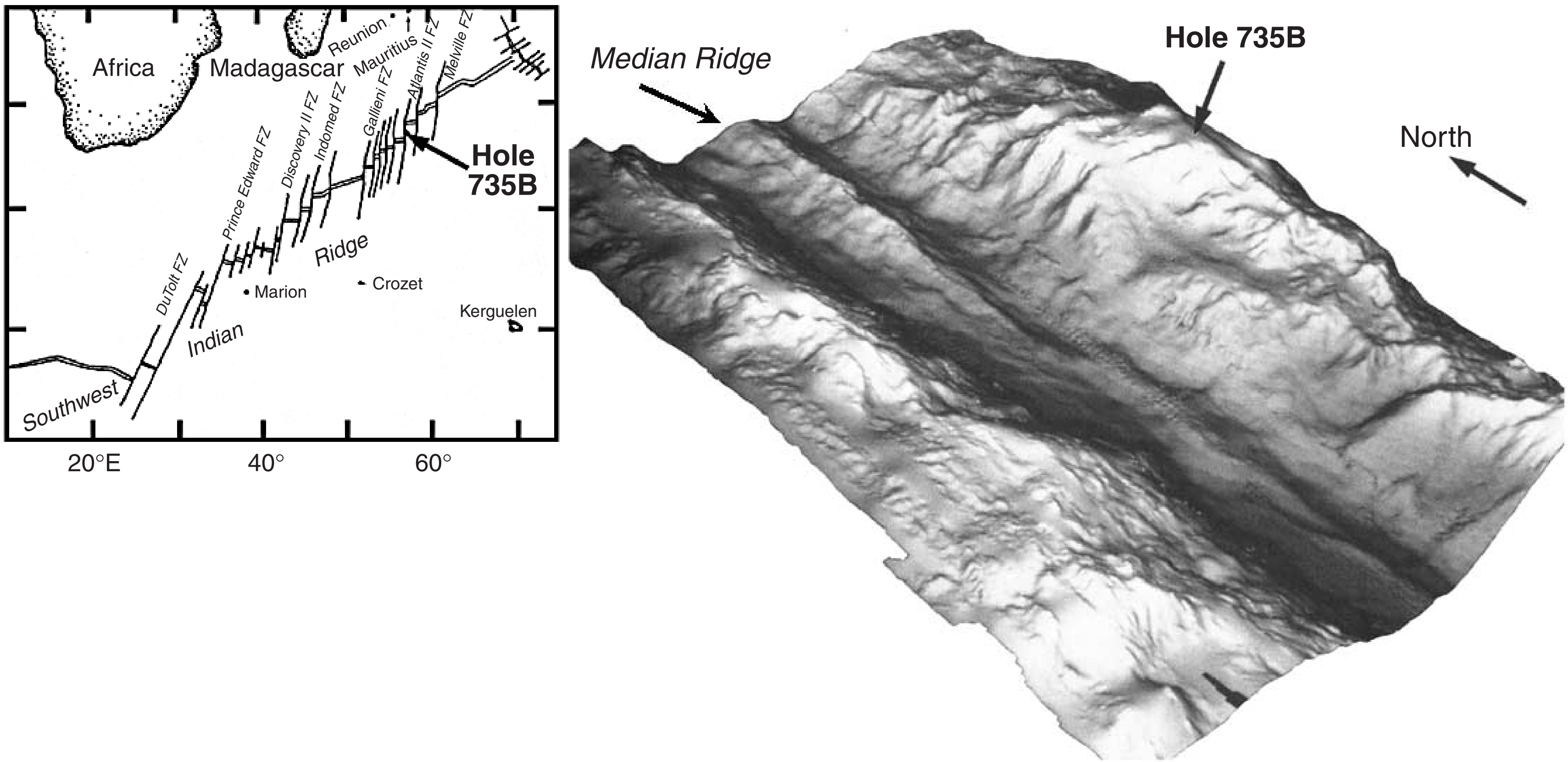

Figure F2. Histograms used during Leg 118 to show occurrences of gabbro and serpentinized peridotite in dredge hauls in the Indian Ocean. **A.** Number of dredge hauls in the Indian Ocean recovering plutonic associations (G = gabbro, P = serpentinized peridotite, G + P = both), compiled from published sources as of 1987. The compilation is for all dredge locations. **B.** Histogram showing number of dredge hauls with some peridotite from transverse ridges only, plotted vs. depth below transverse-ridge summits. The arrow gives the total penetration of Hole 735B through Leg 176, 1508 m, in gabbro, with peridotite (dashed line) somewhere deeper than that.

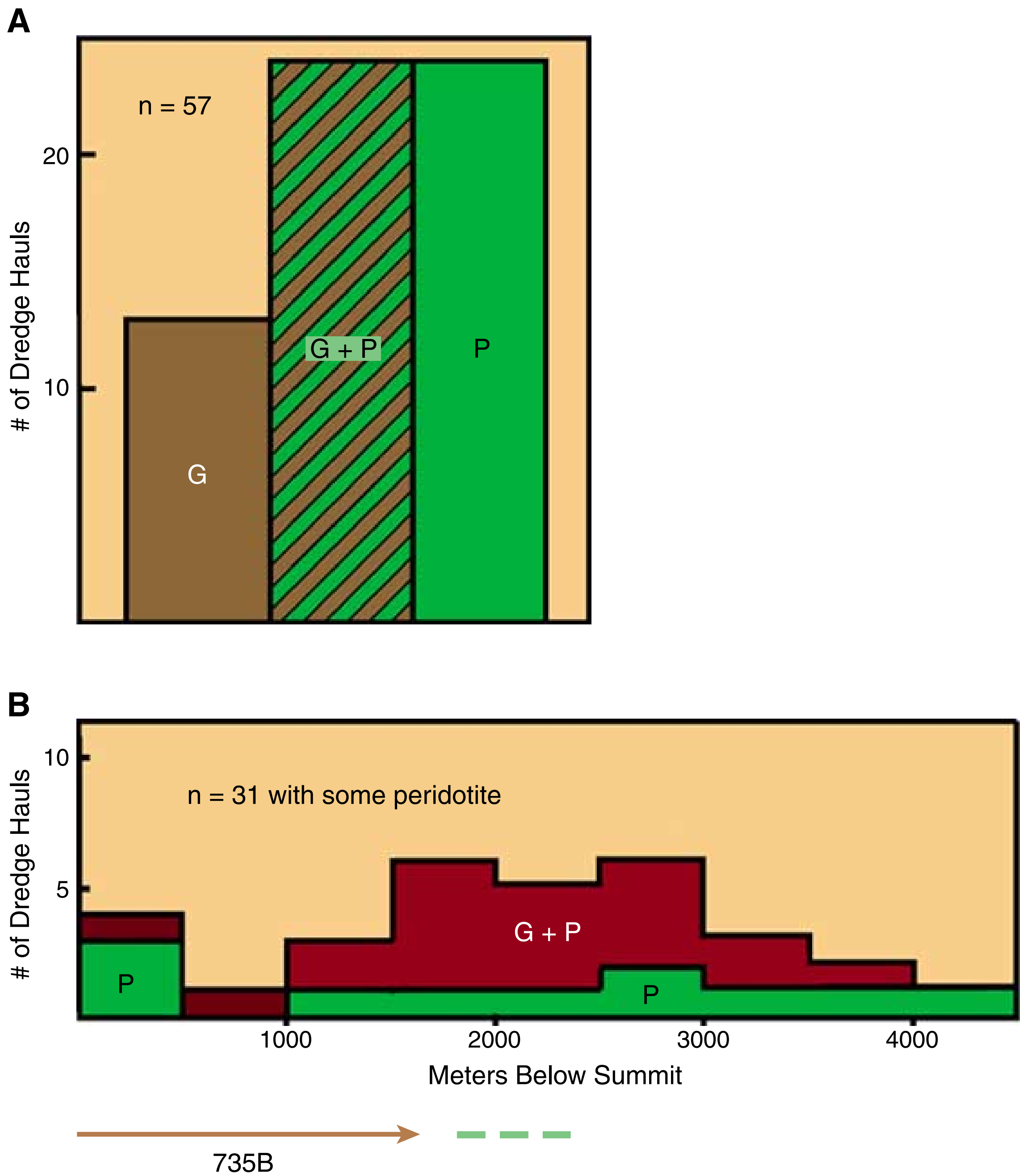

Figure F3. The landmark of Table Mountain, rising 1030 m behind the city of Cape Town, South Africa, compared with columns showing penetration and recovery in ODP Hole 735B.

Figure F4. A photomosaic of the hard rock base at Hole 735B installed during Leg 118. The smaller image to the left shows the hole itself through the open throat of the base. The base is 17 ft × 17 ft × 11 ft high and is currently host to sessile organisms (top corner). The mosaic was constructed from frames grabbed from a video sequence obtained near the seafloor using the Canadian remotely-operated vehicle, *ROPOS,* in the spring of 1998. The survey was carried out using the vessel *James Clark Ross* of the British Antarctic Survey. The figure is provided courtesy of the expedition's Co-Chief Scientists, H.J.B. Dick, P.T. Robinson, C. MacLeod, and S. Allerton.