OCEAN DRILLING PROGRAM

LEG 176 PRELIMINARY REPORT

RETURN TO HOLE 735B

Dr. Henry B.Dick
Co-Chief Scientist
Department of Geology and Geophysics
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543
U.S.A.

Dr. James H. Natland
Co-Chief Scientist
Rosenstiel School of Marine and Atmospheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, Florida 33149-1098
U.S.A.

Dr. D. Jay Miller
Staff Scientist
Internet: jay_miller@odp.tamu.edu
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, Texas 77845-9547
U.S.A.

Jack Baldauf
Deputy Director
of Science Operations
ODP/TAMU

D. Jay Miller
Leg Project Manager
Science Services
ODP/TAMU

March 1998

This informal report was prepared from the shipboard files by the scientists who participated in the cruise. The report was assembled under time constraints and is not considered to be a formal publication which incorporates final works or conclusions of the participating scientists. The material contained herein is privileged proprietary information and cannot be used for publication or quotation.

Preliminary Report No. 76

First Printing 1998

Distribution

D I S C L A I M E R

This publication was prepared by the Ocean Drilling Program, Texas A&M University, as an account of work performed under the international Ocean Drilling Program, which is managed by Joint Oceanographic Institutions, Inc., under contract with the National Science Foundation. Funding for the program is provided by the following agencies:

Australia/Canada/Chinese Taipei/Korea Consortium for Ocean Drilling
Deutsche Forschungsgemeinschaft (Federal Republic of Germany)
Institut Français de Recherche pour l'Exploitation de la Mer (France)
Ocean Research Institute of the University of Tokyo (Japan)
National Science Foundation (United States)
Natural Environment Research Council (United Kingdom)
European Science Foundation Consortium for the Ocean Drilling Program (Belgium, Denmark, Finland, Iceland, Italy, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and Turkey)

Any opinions, findings and conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation, the participating agencies, Joint Oceanographic Institutions, Inc., Texas A&M University, or Texas A&M Research Foundation.

SCIENTIFIC REPORT

The following scientists were aboard *JOIDES Resolution* for Leg 176 of the Ocean Drilling Program:

Henry B. Dick, Co-Chief Scientist (Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, U.S.A., Internet: hdick@whoi.edu)
James H. Natland, Co-Chief Scientist (Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149-1098, U.S.A., Internet: jnatland@umigw.miami.edu)
Jay Miller, Staff Scientist (Ocean Drilling Program, Texas A&M University, 1000 Discovery Drive, College Station, Texas 77845, U.S.A., Internet: jay_miller@odp.tamu.edu)
Jeffrey C. Alt, Metamorphic Petrologist (Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building, 425 E. University, Ann Arbor, Michigan 48109-1063, U.S.A., Internet: jalt@umich.edu)
Wolfgang Bach, Metamorphic Petrologist (Department of Geology and Geophysics, Woods Hole Oceanographic Institution, 360 Woods Hole Road, MS #8, Woods Hole, Massachusetts 02543, U.S.A., Internet: wbach@whoi.edu)
Daniel Bideau, Metamorphic Petrologist (Département Géosciences Marines, Institut Français de Recherche pour l’Expoitation de la Mer, Centre de Brest, BP 70, Plouzané cedex 29280, France, Internet: dbideau@ifremer.fr)
Jeffrey S. Gee, Paleomagnetist (Scripps Institution of Oceanography, University of California, San Diego, Mail Code 0215, La Jolla, California 92093-0215, U.S.A., Internet: jsgee@ucsd.edu)
Sarah Haggas, LDEO Logging Trainee (Department of Geology, University of Leicester, University Road, Leicester LE1 7RH, United Kingdom, Internet: slh19@le.ac.uk)
Jan G.H. Hertogen, Geochemist (Afdeling Fysico-chemische geologie, Katholieke Universiteit Leuven, Celestijnenlaan 200 C, B-3001 Leuven-Heverlee, Belgium, Internet: jan.hertogen@geo.kuleuven.ac.be)
Greg Hirth, Physical Properties Specialist/Structural Geologist (Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, U.S.A., Internet: ghirth@whoi.edu)
Paul Martin Holm, Igneous Petrologist (Geologisk Institut, Københavns Universitet, Øster Voldgade 10, København DK 1350, Denmark, Internet: paulmh@geo.geol.ku.dk)
Benoit Ildefonse, Structural Geologist (Laboratoire de Tectonophysique, Université Montpellier II, ISTEEM, 34095 Montpellier cedex 05, France, Internet: benoit@dstu.univ-montp2.fr
Gerardo J. Iturrino, LDEO Logging Scientist (Borehole Research Group, Lamont-Doherty Earth Observatory, Columbia University, Route 9W, Palisades, New York 10964, U.S.A., Internet: iturrino@ldeo.columbia.edu)
Barbara E. John, Structural Geologist (Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071, U.S.A., Internet: bjohn@uwyo.edu)
Deborah S. Kelley, Metamorphic Petrologist (School of Oceanography, University of Washington, Box 357940, Seattle, Washington 98195, U.S.A., Internet: kelley@ocean.washington.edu)
Eiichi Kikawa, Paleomagnetist (Global Environmental Laboratory, University of Toyama, 3190 Gofuku, Toyama 930, Japan, Internet: kikawa@edu.toyama-u.ac.jp)
Andrew Kingdon, Physical Properties Specialist (British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, United Kingdom, Internet: aki@bgs.ac.uk)
Petrus J. Le Roux, Igneous Petrologist (Department of Geological Sciences, University of Cape Town, Rondebosch, 7700, South Africa, Internet: pleroux@geology.uct.ac.za)

Jinichiro Maeda, Igneous Petrologist (Department of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, N-10, W-8 Kita-ku, Sapporo, Hokkaido 060, Japan, Internet: jinm@cosmos.sci.hokudai.ac.jp)
Peter S. Meyer, Igneous Petrologist (Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, U.S.A., Internet: pmeyer@whoi.edu)
H. Richard Naslund, Igneous Petrologist (Department of Geological Sciences, State University of New York, Binghamton, Binghamton, New York 13902-6000, U.S.A., Internet: naslund@binghamton.edu)
Yaoling Niu, Igneous Petrologist (Department of Earth Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia, Internet: niu@earthsciences.uq.edu.au)
Paul T. Robinson, Metamorphic Petrologist (Centre for Marine Geology, Dalhousie University, Halifax, Nova Scotia B3H 3J5, Canada, Internet: robinso@is.dal.ca)
Jonathan E. Snow, Igneous Petrologist (Abteilung Geochemie, Max-Planck-Institut für Chemie, Postfach 3060, 55020 Mainz, Germany, Internet: jesnow@geobar.mpch-mainz.mpg.de)
Ralph A. Stephen, Physical Properties Specialist/Downhole Tools Specialist (Department of Geology and Geophysics, Woods Hole Oceanographic Institution, MS 24, 360 Woods Hole Road, Woods Hole, Massachusetts 02543-1542, U.S.A., Internet: rstephen@whoi.edu)
Patrick W. Trimby, Structural Geologist (Department of Earth Sciences, University of Liverpool, Brownlow Street, P.O. Box 147, Liverpool L69 3BX, United Kingdom, Internet: patster@liv.ac.uk)
Horst-Ulrich Worm, Downhole Tools Specialist (BGR, Grubenhagen, 37574 Einbeck-Rotenkirchen, Germany, Internet: huworm@t-online.de)
Aaron Yoshinobu, Structural Geologist (Department of Earth Sciences, University of Southern California, 3651 University Avenue, Los Angeles, California 90089-0740, U.S.A., Internet: yoshinob@usc.edu)

ABSTRACT

Leg 176 was devoted to the deepening and logging of Ocean Drilling Program Hole 735B, atop a shallow bank along a transverse ridge of the Atlantis II Fracture Zone, Southwest Indian Ridge. During this leg, a hole initially cored to 500 mbsf on Leg 118 was deepened more than 1 km to a total depth of 1508 m. More igneous rock was cored on this leg than on any other but one, and more igneous rock was recovered by far—some 866 m, representing 86.3% recovery—than on any previous leg. The combined results of drilling during Legs 118 and 176 make Hole 735B one of the most significant accomplishments in the study of the solid Earth. For the first time, a significant proportion of one of the major layers of the Earth's crust, the all but inaccessible Layer 3 in the ocean basins, has been sampled and examined. We are now able to describe the architecture and outline the magmatic, structural, and metamorphic history of a block of the lower ocean crust that formed at this very slowly spreading ridge 11 Ma.

The gabbroic ocean crust we have drilled consists of four main blocks of relatively primitive olivine gabbro and troctolite, from 200-m to 700-m thick, each with its own internal chemical and petrological coherence. Overall, each of these bodies is composed of many smaller magma bodies, which probably represent small intrusive masses that penetrated fairly cold rock, in which case contacts are sharp, or crystal mushes, in which case contacts are diffuse or sutured. Each of the composite bodies of rock has more fractionated gabbros toward their top and more primitive rocks toward their base.

Gabbroic rocks recovered during Leg 176 display numerous magmatic crystal-plastic and brittle deformation features. The associated overprinting relationships are consistent with synkinematic cooling and extension in this mid-ocean ridge environment. However, thick intervals of the core (up to 150 m) are comparatively free of deformation and are either texturally isotropic, or contain weak to moderate magmatic foliation. Magmatic foliation is commonly overprinted by a weak parallel crystal-plastic fabric that may record the transition from magmatic to crystal-plastic deformation. Locally, however, the foliation is fairly well developed, and in one interval ~200 m thick there are many high-temperature reverse shear zones. Many of the deformed rocks show a continuum between crystal-plastic and brittle behavior, which was associated with hydrothermal alteration from amphibolite- to

greenschist-facies conditions. There are some narrow zones of intense cataclasis, and several fault zones were identified.

The gabbros of Hole 735B preserve a complex record of high-temperature metamorphism, brittle failure, and hydrothermal alteration that began at near-solidus temperatures and continued down to very low-temperature conditions. At one extreme, the high-temperature metamorphic effects are transitional to magmatic processes. Some rocks were deformed and recrystallized while they were still partly molten. Faults represented by zones of both high- and low-angle shear penetrated a crystal mush deep beneath the axial rift. Some of the most striking zones of crystal-plastic deformation probably formed under the equivalent of granulite facies metamorphic conditions (>800°-1000°C), when there was little or no melt present. Extensive intervals (>300 m), however, have less than 10% background alteration.

Rock magnetic measurements demonstrate that the entire body of rock cored during Legs 118 and 176 has a consistent average stable inclination of ~71° and no observable downhole variation. The rocks have been tilted about 20°. A preferred orientation of declinations around 260° in core coordinates suggests that gross reorientation of structural features of the core may be possible.

Physical properties were routinely measured on all cores and magnetic susceptibility measurements proved to be of particular value in outlining the occurrence and distribution of even very small intervals rich in iron-titanium oxides. The intervals are prevalent in the upper 500 m of core examined during Leg 176 (500-1000 mbsf) and correlate remarkably well with both the intensity of deformation and the average oxide percent in the gabbros, as established by visual observation of the core.

In summary, the sequence of rocks observed in Hole 735B is unlike that found in well-studied ophiolites. A full on-land counterpart to these rocks has yet to be described. Still less does this sequence of rocks resemble a layered igneous intrusion. Hole 735B, therefore, provides a first assessment of synkinematic igneous differentiation in which the upper levels of the gabbroic crust were enriched in late differentiated melts through tectonic processes, rather than simple gravitationally-driven crystallization differentiation.

INTRODUCTION

From the earliest seismic refraction studies in the ocean basins, the ocean crust has been known to have a surprisingly uncomplicated and uniform layered seismic structure (Hill, 1957; Raitt, 1963; Christensen and Salisbury, 1975). Beneath a first layer of low velocity sediments, there is a second layer, roughly 1 to 2 km thick, with an average seismic velocity of 5.1 km/s. Beneath this, following a short intervening gradient in velocity, there is a third 4- to 6-km-thick layer having an average seismic velocity of 6.8 km/s. These layers overlie material with an average velocity of 8.1 km/s at an abrupt seismic transition known as the Mohorovicic discontinuity or Moho. Earth scientists have long equated this seismic structure to a simple layer-cake sequence of sediment, pillow basalt and diabase, and a thick gabbro section overlying the Earth's mantle, with the igneous crust/mantle boundary at or near the Moho. Accretion of the lower crust is seen as resulting from crystallization from some form of near steady-state magma chamber, or crystal mush zone, where magmas accumulate beneath a sheeted dike–pillow lava sequence over the ascending mantle. Internally, a simple stratigraphy of primitive layered gabbros was believed to be overlain by more evolved isotropic gabbros, all of which were equated to seismic Layer 3. This simple hypothesis has been modified somewhat over the last 20 years. Provisions have been made for thinner crust in areas near large transforms (e.g., Mutter and Detrick, 1984; Dick, 1989) and in areas where half-spreading rates are significantly below 10 mm/yr (Reid and Jackson, 1981; Bown and White, 1994). At the same time, models of the internal stratigraphy of the lower crust have become increasingly complex, with the introduction of narrow accumulation zones (e.g., Bloomer and Meyer, 1992), ephemeral magma chambers, and a host of complexities arising from variations in thermal structure and spreading rate (e.g., Sinton and Detrick, 1992), including deep faulting and hydrothermal activity beneath slow-spreading ridges (e.g., Dick et al., 1992).

The remarkably uniform seismic structure of the ocean crust, together with a knowledge of the rate at which new seafloor forms from plate-tectonic theory, has been used to estimate the transfer of heat and mass from the Earth's deep interior to the crust, oceans, and atmosphere. Fossil sections of ocean crust, termed ophiolite complexes, preserved on land in tectonic collision zones at continental margins and island-arcs, have been used both to support this hypothesis and to allow more direct inference as to the internal structure, composition, and origin of the ocean crust. Nonetheless, it has long been known that significant differences exist between these fossil sections and what is known of the in situ ocean crust, both in the details of their rock chemistries and in the inferred thickness of many ophiolites, which are often much thinner than commonly inferred in the modern ocean (Coleman and Irwin, 1974). Thus, ophiolites have an inherently ambiguous provenance, with most attributed to a supra-subduction zone environment atypical of the world's oceans.

Hess (1962) proposed that the Moho was an alteration front in the mantle, and that seismic Layer 3 was made up mostly of partially serpentinized peridotite. In his model, the Moho was produced by auto-metasomatism of peridotite by primary water contained in the mantle as the mantle cooled into the stability field of serpentine during solid-state flow to the base of the crust. Later investigators, however, found it difficult to match laboratory observations of both seismic *P*- and *S*-wave velocities for partially serpentinized peridotite to those of Layer 3 (Christensen, 1972; Christensen and Salisbury, 1975), and rejected Hess's model in favor of a gabbroic lower crust. Recent studies now suggest, though, that the ocean crust has a complex, three-dimensional structure that is highly dependent on magma supply and spreading rates, and that it does not contain large steady-state magma chambers (e.g., Whitehead et al., 1984; Dick, 1989; Detrick et al., 1990; Sinton and Detrick, 1992; Carbotte and Macdonald, 1992). Compilations of dredge results and seismic data have suggested that a continuous gabbroic layer does not exist at slow-spreading ridges (Whitehead et al., 1984; Mutter et al., 1985; McCarthy et al., 1988; Dick, 1989; Cannat, 1993; Tucholke and Lin, 1994), and that the internal stratigraphy of slow-spread ocean crust is governed by dynamic processes of alteration and tectonism as much as by igneous processes. The exceptional abundance of serpentinized peridotite in dredge hauls from the walls of rift valleys in fracture zones and in the rift mountains away from fracture zones (Aumento and Loubat, 1971; Thompson and Melson, 1972; Dick, 1989; Cannat, 1993) raises the serious possibility that serpentinite is a major component of seismic Layer 3. Therefore, the Moho does not correspond everywhere in the oceans to the boundary between igneous crust and the mantle, but may be an alteration front, corresponding locally to the depth of circulation of sea water down cracks into the Earth's interior.

These factors—and an increasing awareness that spreading rate, ridge geometry, and proximity to mantle hot spots also have major impacts on ocean crust thickness and lithostratigraphy—make in situ observation of the lower ocean crust by drilling a necessity if the processes of ocean crust accretion and the nature of the ocean crust are ever to be understood. The Deep Sea Drilling Project (DSDP) and its successor Ocean Drilling Program (ODP) have directly sampled in situ ocean crust in a variety of spreading environments, once even drilling as deep as 2 km. This has confirmed many inferences from ophiolites as to its shallow structure and composition. The results at ODP Hole 504B, however, show that the seismic Layer 2/Layer 3 boundary may be an alteration front, rather than simply the boundary between diabase and gabbro, thus raising questions about the nature of the Moho as well. Despite the recovery of short sections of lower ocean crust and mantle by several ODP legs, no true representative section of seismic Layer 3 had ever been obtained in situ from the oceans, leaving its composition, state of alteration, and internal structure almost entirely a matter of inference.

With the completion of drilling on ODP Leg 176, however, Hole 735B comes close to this goal, representing a 1500-m section of coarsely crystalline gabbroic rock drilled in a tectonically exposed lower crustal section on a wave-cut platform flanking the Atlantis II Fracture Zone on the slow-spreading Southwest Indian Ridge. The Hole 735B cores radically change our perception of the lower ocean crust at slow-spreading ridges. They indicate that the crust formed by a complex interaction of magmatic, tectonic, and hydrothermal processes. This presents a systematic variation in igneous petrology, structure, and alteration with depth quite unlike that associated with large magma chambers, thought to exist beneath fast-spreading ridges, or presently documented in ophiolites. Given the typical 4- to 6-km thicknesses of seismic Layer 3, this 1500-m section does not adequately characterize the lower crust for all the ocean basins, but, if the lower crust at ultra-slow-spreading ridges is only about 2 km thick as predicted by modeling and seismic refraction experiments, then it is a beginning. Because no other place has had the excellent drilling conditions, high recovery, ease of guide-base placement, and superb shallow exposures of lower crust as Hole 735B, this is the one location where we know we can drill a fully representative section of the lower ocean crust, and test the nature of the Moho and the crust/mantle boundary.

TECTONIC SETTING

Introduction

Site 735 is located in the rift mountains of the Southwest Indian Ridge, 18 km east of the present-day axis of the Atlantis II Transform Fault (Fig. 1). The Southwest Indian Ridge has existed since the initial breakup of Gondwana in the Mesozoic (e.g., Norton and Sclater, 1979). Shortly before 80 Ma, plate readjustment in the Indian Ocean connected the newly formed Central Indian Ridge to the Southwest Indian Ridge and the Southeast Indian Ridge to form the Indian Ocean Triple Junction (Fisher and Sclater, 1983; Sclater et al., 1981; Tapscott et al., 1980). Steady migration of the triple junction to the northeast has since created a succession of new ridge segments and fracture zones including the Atlantis II. Thus, the Atlantis II Fracture Zone and the adjacent ocean crust is entirely oceanic in origin, free from the complications of continental breakup such as those found at some equatorial fracture zones along the Mid-Atlantic Ridge (e.g., Bonatti and Honnorez, 1976).

The spreading rate along the Southwest Indian Ridge has been relatively constant for the last 34 Ma, near 0.8 cm/yr. This is at the ultra-slow end of the spreading-rate spectrum (Fisher and Sclater, 1983). This has important implications for crustal structure at Site 735, because although crustal thickness is relatively constant with spreading rate above a half rate of 10 mm/yr, it appears to drop off rapidly at slower rates (Reid and Jackson, 1981; Jackson et al., 1982). Seismic refraction measurements at both the Arctic and Southwest Indian Ridges indicate typical crustal thicknesses of about 4 km, including normal ocean crust immediately west of Hole 735B (Jackson et al., 1982; Bown and White, 1994; Minshull and White, 1996; Muller et al., 1997). All of this indicates that, with the absence of basalt extrusives and gabbros, the depth to the crust-mantle transition should be less than 2.5 km at Hole 735B.

All the characteristic features of slow-spreading ridges, including rough topography, deep rift valleys, and abundant exposures of gabbroic and ultramafic rocks, are present on the Southwest Indian Ridge (Dick, 1989). Significantly, two-thirds of the rocks dredged from the walls of the active transform valleys are altered mantle peridotites, whereas most of the remainder are weathered pillow basalts. This exceptional abundance of peridotite, when compared to dredge collections of similar size from the North Atlantic Ocean, indicates an unusually thin crustal section near Southwest Indian Ridge transforms. Moreover, the paucity of dredged gabbro near these transforms suggests that magma chambers were small or absent there as well.

Thin crust adjacent to fracture zones is thought to reflect segmented magmatism, which produces rapid along-strike changes in the structure and stratigraphy of the lower ocean crust (Whitehead et al., 1984). Thus, the Southwest Indian Ridge is seen as consisting of a series of regularly spaced shield volcanoes and underlying magmatic centers, which undergo continuous extension to form the ocean crust (Dick, 1989). Site 735 is located some 18 km from the Atlantis II Transform Fault and is therefore situated near the projection of the midpoint of the magmatic center beneath the Southwest Indian Ridge at 11.5 Ma (Dick et al., 1991b).

Geology of the Atlantis II Fracture Zone

The Atlantis II Fracture Zone (Fig. 2) was first described by Engel and Fisher (1975) and was mapped in detail by Dick et al. (1991b). It is a 199-km, 20-Ma north–south left-lateral offset of the Southwest Indian Ridge at 57˚E longitude. The transform is marked by a 6480-m-deep transform valley, with high flanking transverse ridges shoaling to as little as 700 m. The valley walls are extremely steep for large distances, typically sloping from 25˚ to 40˚, and are covered with extensive talus and debris. The floor of the transform has a >500-m sequence of turbidites shed from the walls of the transform and is bisected by a 1.5-km-high median tectonic ridge. The ridge-transform intersections are marked by deep nodal basins lying on the transform side of the neovolcanic zones that define the present-day spreading axes, and which intersect clearly defined rift valleys with a relief of more than 2200 m and widths of 22 to 38 km. Extensive dredging showed that more than two-thirds of the crust exposed in the transform valley and its walls is plutonic rocks, principally gabbros and partially serpentinized peridotites. By contrast, only relatively undisrupted pillow lavas appear to be exposed on crust of the same age and position relative to the transform fault on the conjugate lithospheric flow line to the north (Muller et al., 1997; e.g., Fig. 3).

Well-defined magnetic anomalies were mapped over the flanking transverse ridges and transform valley, even over large areas where extensive dredging shows that basalts are absent, including Site

735. This was the first direct demonstration that the gabbros and peridotites can constitute a magnetic source layer (Dick et al., 1991b), a possibility originally raised by the laboratory work of Fox and Opdyke (1973) and Kent et al. (1978). These results were confirmed in Hole 735B by downhole logging (Pariso et al., 1991) and measurements on cores (Kikawa and Pariso, 1991; Kikawa and Ozawa, 1992; Pariso and Johnson, 1993). In fact, the gabbro massif at Site 735 is the only location in the ocean basins where the age of the magnetic anomaly (Anomaly 5r.2n, 11.75 Ma; Figs. 2–4) has been confirmed, within error, by a zircon U-Pb isotopic age date of 11.3 Ma from a trondhjemite sampled in situ in basement (Stakes et al., 1991).

Site Location

Hole 735B is located on a shallow bank, informally named Atlantis Bank, on the crest of a 5-km-high mountain range, termed a transverse ridge, which constitutes the eastern wall of the Atlantis II transform valley (Fig. 3A). The hole is situated some 93 km south of the present-day Southwest Indian Ridge axis, and is 18.4 km from the inferred axis of transform faulting on the floor of the Atlantis II Fracture Zone (Dick et al., 1991b). The bank consists of a platform, roughly 9 km long in a north–south direction and 4 km wide, which is the shallowest of a series of uplifted blocks and connecting saddles that form a long, linear ridge parallel to the transform. The top of the platform is flat, with only about 100 m relief over 20 km2. The boundary between magnetic Anomalies 5r.2n and 5r.2r crosses east–west directly over the platform just north of Hole 735B (Fig. 4).

A 4-hour video survey of a 200 by 200 m area near the hole using the shipboard Vibration-Isolated Television (VIT) system during ODP Leg 118 showed a smooth, flat, evidently wave-cut platform exposing roughly east–west foliated and jointed massive gabbro locally covered by sediment drift (Robinson, Von Herzen, et al., 1989). Using the time stamp on the video image and voice-over data on the tapes, an outcrop map was constructed of the survey area (Fig. 5). The surface consists of flat outcrops of foliated and jointed gabbro with minor relief, featureless sediment of undetermined but likely insignificant thickness, and basement with such a thin coat of sediment that outcrop textures were easily resolved through it in the video image. All of these indicate a monotonous, nearly flat hard-rock pavement. Relative depths measured by a length of weighted cable tied to the base of the VIT frame, though probably in error by a few meters, clearly showed that the southwest half of the survey area slopes gently toward the wall of the transform. Also indicated on the survey map are the estimated strike of distinct joints and fractures visible in the video image. While camera rotation and lack of orientation precluded exact and continuous measurements, the weight dragging across the seafloor, combined with the motion vector of the VIT frame deduced from the direction of ship motion, allowed orientation (within probably a 5˚–10˚ error) of many of these features. These are plotted as lines along the side of the swath path on the map adjacent to the time stamp location where the observation was made, oriented according to the estimated attitude of the joint/fracture.

The generally east–west foliation, which is orthogonal to the transform and parallel to the ridge axis, is similar in both respects to the orientation of foliated peridotites exposed on St. Paul’s Rocks. These are also orthogonal to the adjacent St. Paul’s Fracture Zone and parallel to the Mid-Atlantic Ridge (Melson and Thompson, 1971). The foliation on Atlantis Bank, projected from the position of Hole 735B westward along strike across the Atlantic Bank platform, intersects a long oblique west–northwest trending ridge coming up the wall of the fracture zone (Fig. 3A). Ridges produced by land-slips and debris flows are normally oriented orthogonal to the fracture zone. Possibly this oblique ridge, and a similar one 2 km to the north, represent the traces of inclined shear zones dipping toward the axis of the paleo-Southwest Indian Ridge exposed on the wall of the transform. The shear zone crosses over the top of the platform in the vicinity of Hole 735B. Given the once shallow water depth, the canyon between these ridges may be an erosional remnant trough between resistant foliated gneissic amphibolites (Dick et al., 1991b). A three-point solution for the dip of the shear zone, based on an east–west strike gives a dip of approximately 40˚, which is close to that observed in the amphibolites drilled in the upper 100 m of Hole 735B. The shear zone represents a ductile-fault, and thus is not a simple stratigraphic discontinuity. The rocks at the top of the shear zone at Hole 735B are largely gabbronorites that pass gradually into a zone of olivine gabbro toward its base. The shear sense determined from drill cores is normal and the rocks north of the drill site are down-thrown by an unspecified amount.

Given the position of the site, the relatively constant spreading direction over the last 11 m.y., and the ridge-parallel strike of the local foliation, the Atlantis Bank gabbros must have accreted and been deformed beneath the median valley of the Southwest Indian Ridge, 15 to 19 km from the ridge-transform intersection, around 11.5 Ma. The smooth flat surface of the platform suggests that it formed by wave erosion of a small island created when the gabbros were uplifted at the inside-corner high of the ancestral Southwest Indian Ridge at 11 Ma as a large horst block, similar to St. Paul's Rocks in the central Atlantic Ocean; the block then subsided to its present depth by means of normal lithospheric cooling (Dick et al., 1991b; Magde et al., 1995). A similar wave-cut platform, from which rounded cobbles of peridotite have been dredged, occurs on the Southwest Indian Ridge at the southern ridge-transform intersection of the DuToit Fracture Zone (Fisher et al., 1985).

The single uniform magnetic inclination measured in Hole 735B gabbros demonstrates that there is little significant late tectonic disruption of the section, although the relatively steep inclination suggests block rotation of up to 20˚ (Pariso et al., 1991). Thus the Hole 735B gabbros, which were drilled from the center of an uplifted horst block originally emplaced at an inside-corner high, formed beneath the rift-valley away from the major faults in the transform or on the rift valley walls. The section likely preserves a typical record of accretion, hydrothermal circulation, and brittle-ductile deformation beneath an active rift. However, the rocks also contain a later history, reflecting static block uplift to shallow depths and rapid cooling, but this is not the full record of thermal equilibration and alteration of mature ocean crust cooled at depth beneath an intact section of ocean floor during seafloor spreading.

The exposure and emplacement of the Hole 735B section likely occurred by unroofing at a long-lived detachment fault on the rift valley wall followed by block uplift into the inside-corner high at the ancestral ridge-transform intersection of the Atlantis II Fracture Zone (Fig. 6; Dick et al., 1991b). Similar exposure of plutonic rock has been found at several present-day ridge-transform intersections, most notably at the eastern inside-corner high of the Kane Fracture Zone in the Atlantic. There, as at the present-day northern ridge-transform intersection of the Atlantis II Fracture Zone, an intact volcanic carapace is found in the rift mountains on only one side of the rift valley spreading in the direction away from the active transform. On the other side of the rift valley, deep crustal rocks and mantle peridotite are exposed on the rift valley wall at the inside-corner high. This remarkable asymmetry is illustrated by comparing the seafloor topography around Hole 735B to that for crust of the same age situated on the opposite northern lithospheric flow line (Fig. 3B). This asymmetry is inferred to result from the periodic formation of a crustal weld between new ocean crust and the old cold lithospheric plate at the ridge-transform intersection. Because of this weld, the more rigid shallow levels of the newly formed ocean crust spread with the older plate in the direction away from the active transform. At depth, beneath the brittle-ductile transition, the plutonic section spreads symmetrically in both directions (Dick et al., 1981; Karson and Dick, 1983). At the Kane Fracture Zone, the surface of the detachment fault has been directly observed by submersible (Dick et al., 1981; Karson et al., 1987, Mével et al., 1991). Such detachment faults are suggested to form periodically by fault capture during amagmatic periods at slow-spreading ridges (Harper, 1985; Karson, 1990, 1991).

PREVIOUS RESULTS FROM HOLE 735B

The nearly intact 500-m section of gabbros recovered at Site 735 during Leg 118 provided a first look at the processes of crustal accretion and simultaneous tectonism, alteration, and ephemeral magmatism at a slow-spreading ocean ridge. Results from the leg showed that the section did not form in a large steady-state magma chamber, but instead by continuous intrusion and reintrusion of numerous small, rapidly crystallized bodies of magma. There is little evidence of the process of magmatic sedimentation important in layered intrusions. Rather, new batches of magma were intruded into a lower ocean crust consisting of crystalline rock and semisolidified crystal mush. This led to undercooling and rapid initial crystallization of new magmas to form a highly viscous or rigid crystal mush, largely preventing the formation of magmatic sediments. Initial crystallization was followed by a longer, and petrologically more important, period of intercumulus melt evolution in a highly viscous crystal mush or rigid melt-crystal aggregate.

Thus, if the 437 m of gabbro recovered from Hole 735B is representative, long-lived magma chambers or melt lenses were virtually absent throughout most of crustal formation beneath the Southwest Indian Ridge (Bloomer et al., 1991; Dick et al., 1991b; Natland et al., 1991; Ozawa et al., 1991). Melts in the highly viscous or rigid intrusions were largely uneruptable throughout most of their crystallization. This could explain the near absence of highly evolved magmas such as ferrobasalts along the Southwest Indian Ridge (Dick, 1989), as opposed to fast-spreading ridges where they are common and a long-lived melt lens is believed to underlie the ridge axis (e.g., Sinton and Detrick, 1992).

Wall-rock assimilation occurring while small batches of melt worked their way up through the partially solidified lower crust played a significant role in the chemical evolution of the section and, therefore, in the chemistry of the erupted basalt (Dick et al., 1992). This process has been largely unevaluated for basalt petrogenesis to date, but raises questions for simple models for the formation of mid-ocean-ridge basalt (MORB).

An unanticipated major feature of Hole 735B was the evidence for deformation and ductile faulting of still partially molten gabbro (Bloomer et al., 1991; Dick et al., 1991a; Dick et al., 1992; Natland et al., 1991). This deformation apparently occurred over a narrow window late in the crystallization sequence (probably at 70%–90% crystallization) when the gabbros became sufficiently rigid to support a shear stress. This produced numerous small and large shear zones creating zones of enhanced permeability into which the late intercumulus melt moved by compaction out of undeformed gabbro intervals. Migration of this late iron-rich intercumulus melt into and along the shear zones hybridized the gabbro there by melt-rock reaction and by precipitation of Fe-Ti oxides and other late magmatic phases. The net effect of these synchronous magmatic and tectonic processes is a complex igneous stratigraphy of undeformed oxide-free olivine gabbros and microgabbros crisscrossed by bands of sheared ferrogabbro. Sheared oxide gabbros, nearly identical to those drilled in Hole 735B, were also recovered at ODP Sites 921, 922, and 923 on the eastern inside-corner high of the Kane Fracture Zone (Cannat, Karson, Miller, et al., 1995). Differentiation by deformation (Bowen, 1920) is probably ubiquitous in the lower ocean crust at slow-spreading ocean ridges, and has recently been postulated for in the Lizard ophiolite (Hopkinson and Roberts, 1995). Evidence of such deformation is absent, however, in high-level East Pacific Rise gabbros drilled at Hole 894G at Hess Deep (Natland and Dick, 1996; MacLeod et al., 1996), suggesting that differentiation by deformation may be a feature that can be used to discriminate between fossil sections of ocean crust formed at different spreading rates.

At Site 735, ductile deformation and shearing continued into the subsolidus regime, causing recrystallization of the primary igneous assemblage under granulite facies conditions, and the formation of amphibole-rich shear zones (Cannat et al., 1991; Cannat, 1991; Dick et al., 1991a, 1992; Mével and Cannat, 1991; Stakes et al., 1991; Vanko and Stakes, 1991). Here again, formation of ductile shear zones localized late fluid flow with the most intense alteration occurring in the ductile faults.

One consequence of simultaneous extension and alteration in the rocks of Hole 735B is that high-temperature alteration is far more extensive than is found in layered intrusions, which are typically intruded and cooled in a near static environment (Dick et al., 1991a; Stakes et al., 1991). An abrupt change in alteration conditions of the Hole 735B gabbros, however, occurred in the middle amphibolite facies with the virtual cessation of brittle-ductile deformation (Dick et al., 1991a; Magde et al., 1995; Stakes et al., 1991; Stakes, 1991; Vanko and Stakes, 1991). Mineral vein assemblages change from amphibole-rich to diopside-rich, reflecting different, more-reacted, fluid chemistries. Continued alteration and cooling to low temperature within massive gabbro occurred under near static conditions similar to those found at large layered intrusions. These changes were probably the result of an inward jump of the master faults at the rift valley walls, transferring the section out of the zone of extension and lithospheric necking beneath the rift valley into a zone of simple block uplift at the inside-corner high of the Atlantis Fracture Zone. Hydrothermal circulation, little enhanced by stresses related to extension, was greatly reduced, driven largely by thermal-dilation cracking as the section cooled to ambient temperature.

The results from Hole 735B show the strong influence of deformation and alteration on crustal accretion at ultra-slow-spreading ridges as the critical brittle-ductile transition migrates up and down through the lower crust due to the waxing and waning of magmatism. This is in contrast to the results of the East Pacific Rise crustal section exposed at Hess Deep, where no evidence of crystal-plastic deformation was seen either in the high level gabbros from Hole 894G or in dredged gabbros. This is consistent with the presence of a near steady-state melt lens beneath the East Pacific Rise, which fixes the location of the brittle-ductile transition near the base of the sheeted dikes (e.g., Dick et al., 1991a; Sinton and Detrick, 1992).

SCIENTIFIC OBJECTIVES AND ACCOMPLISHMENTS

Stratigraphy of the Lower Ocean Crust

The first major scientific objective of the Return to Hole 735B by ODP Leg 176 was the recovery of a representative section of gabbroic Layer 3 to determine its stratigraphic variation with depth. This was accomplished by deepening the hole to 1.5 km with an overall recovery of 87%, in an environment (ultra-slow-spreading ridges) where the lower crust is believed to be only about 2 km thick. The recovery was the highest for any hard rock hole in history—by a wide margin—and is the first ODP hole in the ocean lithosphere where there can be no debate about it representing what was drilled. Such recovery, and the detailed logs made of the core aboard ship, will allow detailed mass balances to be calculated using the chemistry of the section—a significant step forward in reconstructing the bulk composition of the ocean crust as a whole, and one needed for realistic models of crustal recycling and global geochemical fluxes.

Present models for the ocean crust also suggest that there are radical differences in the stratigraphy of the lower crust according to spreading rate, proximity to hot spots, local ridge geometry, and proximity to fracture zones. Demonstrating the extent to which these differences are genuine and how they are manifested in the lower ocean crust are major objectives of the proposed lower crustal and shallow-mantle drilling program of the internationally coordinated effort to study the accretion of the ocean crust at mid-ocean ridges (InterRidge). This involves both drilling a representative section of slow-spread lower crust at Site 735, and further offset drilling in tectonically exposed East Pacific Rise lower crust to obtain a composite section for the fast-spread end-member.

Deep crustal sections exposed in ophiolites are highly variable, both between different ophiolites (e.g., Coleman, 1977) and within a single ophiolite (e.g., Nicolas et al., 1996). Because many ophiolites are associated with the formation of ocean crust in island-arcs, fore-arcs, back-arc basins and small oceanic rift basins, it also is not known to what extent they provide a valid analog to modern ocean crust formed beneath the major ocean basins. The criteria for discriminating primary tectonic variables, such as spreading rate and proximity to transforms, are also largely conjectural. This section of ultra-slow-spread lower crust provides objective criteria for evaluating the provenance of individual ophiolite complexes because its proximity to transform offsets and its position in the paleo-ridge segment are precisely known. This can be a major asset to reconstructing paleo-geographies and the nature of remnants of fossil ocean basins.

Perhaps the most significant finding, however, is that the crustal section drilled is not matched by that in any known ophiolite. Some of its attributes, including the lack of well developed layering, the presence of small 100- to 500-m intrusions, are similar to structural characteristics from ophiolites formed in slow-spreading environments, such as the Trinity ophiolite or the Josephine ophiolite. However, several of the major features of the section have not been described in these ophiolites. These include: (1) the occurrence of innumerable discrete large and small sheared oxide-rich gabbros intruding undeformed olivine gabbro, and (2) that, strikingly, these decrease downward in abundance through the section; (3) a baseline igneous stratigraphy of successive small “isotropic” olivine gabbro intrusions, the chemistry of which becomes less primitive with depth; (4) synkinematic igneous differentiation of the section, involving intrusion of late iron-rich melts from below into the olivine gabbros at the top of the section along faults and shear zones leading to a Fe-Ti-rich upper section and a lower depleted section; (5) abundant crystal-plastic and brittle-ductile deformation at the top of the section that decreases downward rather than increases as has been described repeatedly in ophiolites.

Together with the well known geochemical affinities of ophiolites for the arc-environment, these “slow-spreading ophiolites” are not good analogs for the Hole 735B section. Nor are “fast-spreading ophiolites” and ocean crust good analogs. The upper gabbros cored during Leg 147 in Hess Deep, and the gabbros of ophiolites inferred to have originated at fast-spreading centers, such as the Oman ophiolite, do not have the extensive crystal-plastic fabrics of the rocks from Hole 735B. The lack of well defined, planar, and continuous igneous layering at Hole 735B also contrasts with the presence of layered gabbros in the lower two-thirds of the gabbros at Oman.

Although these new observations from Leg 176 are generally consistent with the paradigm of the spreading-rate dependence of crustal accretion at ocean ridges, particularly when combined with the recent results of ODP drilling at Hess Deep, they also demonstrate that ophiolite complexes do not fully characterize the evolution of the ocean crust. Penetration and recovery rates at Hole 735B were constant and very high throughout both Legs 118 and 176. Drilling stopped because of a pipe failure during unanticipated weather, not because of hole conditions. Thus, the results of Leg 176 demonstrate the need for future ocean drilling in the lower ocean crust, set the stage for penetrating it to the mantle, and confirm that this can be done using our current drilling platform.

The Nature of Seismic Layer 3

The second major objective of deepening Hole 735B was to test whether the Moho is coincident with the crust/mantle boundary. Based on an ocean-bottom seismometer (OBS) refraction study, Muller et al. (1997) found that the “seismic” crustal thickness north and south of Atlantis Bank, on which Site 735 is located, is 4 km with a normal-thickness Layer 2 of about 2 km (Fig. 7). These are consistent with crustal thicknesses predicted and observed for ultra-slow-spreading ridges, including the Southwest Indian Ridge (Reid and Jackson, 1981; Jackson et al., 1982; Bown and White, 1994). Beneath Atlantis Bank, however, the projected depth to Moho is 5 ±1 km, although both drilling and dredge results, to date, show that the bank exposes only gabbroic rock. Compositions of basalts dredged from the conjugate site to the north, exposing crust of the same age as Atlantis Bank, suggest a crustal thickness of 3 ± 1 km (Muller et al., 1997). Thus, Muller et al. (1997) agree with the predictions based on sparse geologic evidence (Dick et al., 1991b; Dick, 1996) that the crust is thin beneath Atlantis Bank and that seismic Layer 3 at that location is largely composed of partially serpentinized peridotite, with the base of that layer being an alteration front. We hoped that deepening Hole 735B to 1500+ m would penetrate the crust/mantle boundary and penetrate partially serpentinized peridotite far above the Moho. Obviously the plus sign was important here. If this prediction eventually proves true, then the drilling might demonstrate whether, in at least one place, the Moho is an alteration front rather than the crust/mantle boundary. This continues to be a major objective for the drilling program, because, if true, it puts in question the universal use of this seismic boundary for estimating crustal thickness in the ocean basins.

Stratigraphy of the Uppermost Mantle

A third major objective of Leg 176 was deepening Hole 735B well below the crust/mantle boundary to document the shallow mantle stratigraphy beneath the crust to as great a depth as possible. This would have allowed determination of the pattern and nature of mantle flow immediately beneath the ridge axis, the extent of mantle melting beneath a ridge segment, the mechanism of mantle melt transport to the base of the crust, and the nature of the primary magmas. The present setting of Hole 735B, 18 km from the trace of the Atlantis II Transform and within the center of a major tectonic horst block, is an ideal place to observe this stratigraphy with minimum overprinting by late faulting.

Despite reaching our goal of deepening Hole 735B to a target depth of 1.5 km, we did not penetrate the crust/mantle boundary. Several different factors, including a very high mantle Bouguer Anomaly, several vertical seismic profile (VSP) reflectors immediately beneath the bottom of the hole, and very primitive troctolites found at the base of the Leg 118 section, initially suggested that the crust/mantle boundary might have been encountered immediately beneath the old hole. Instead, we encountered something quite different, drilling into less-primitive gabbros immediately below 500 meters below seafloor (mbsf), and from that point going down through a succession of small gabbro intrusions. With depth, there were a number of systematic changes in the degree of alteration, nature of deformation, and rock chemistry that indicate that the section is not seriously disrupted or imbricated. At the bottom of the hole during Leg 176, we encountered rapidly increasing olivine contents and coarse troctolitic gabbros, which again have raised hopes that we were near a major change in lithology—perhaps the crust/mantle boundary. But this is purely hope and speculation at this time. The crust/mantle boundary could be a few hundred meters below the present bottom of the hole, or several kilometers. Because the overall stratigraphy of the lower ocean crust at this location has proved not to have a direct ophiolite analog, we have entered uncharted depths in the Earth.

IGNEOUS PETROLOGY

Description of the Hole 735B section required logging the features of 866 m of rock from a 1-km section of the lower ocean crust, and integrating those observations with those made previously from the overlying 500-m section drilled during Leg 118. This was more than double the highest previous recovery of any hard-rock leg, and some seven times the amount logged during Leg 147 in similar materials at Hess Deep. To accomplish this, the scientific party divided into specialist igneous, metamorphic, and structural teams, rather than into alternating watches. The teams, in turn, divided core description into specific tasks, with one individual responsible for logging a specific observation. This method proved remarkably efficient, allowing a greater number of observations to be made, a greater amount of data to be recorded, and a greater amount of core to be described than previously achieved.

The greatest value of this approach, however, is a dramatic improvement in consistency of observation. As can be seen from the comparisons made using independent observations on thin sections to check the macroscopic observations made on the core, there is a remarkable consistency of observation, both with respect to precision and with respect to accuracy. For example, three individuals estimated the modal abundance of plagioclase (Maeda), olivine (Le Roux) and pyroxene (Holm) in each of the 457 discrete igneous intervals described, whereas modes were independently determined by point counting on 220 representative thin sections (Meyer). Averaged for the hole, the macroscopic modal analysis gave: 59.5% plagioclase, 30.1% augite, 8.8% olivine, 0.33% orthopyroxene, and 0.76% oxide, point counting gave 58.9% plagioclase, 30.6% augite, 8.2% olivine, 0.62% orthopyroxene, and 0.79% oxide. The difference in orthopyroxene abundance is attributable to the fact that half of it occurs as rims around olivine and cannot be distinguished macroscopically. These consistent observations, in turn, allowed direct comparisons between independently observed features of the core. Oxide abundances, for example, logged on a centimeter scale down the entire core (Naslund), proved to have a remarkable positive correlation with the degree of crystal-plastic (Hirth) and magmatic foliation (Yoshinobu). This observation, as will be seen, is important to understanding the evolution of the lower crust at Hole 735B.

The Hole 735B core between 504 and 1508 mbsf was divided by the igneous team into 457 discrete igneous intervals, numbered from 496 to 952 following the succession from the upper 500 m of Hole 735B (Dick et al., 1991a). These were distinguished on the basis of igneous contacts, variations in grain size, and the relative abundances of primary mineral phases (Fig. 8). Individual contacts were then described and logged (Snow). The major lithologies in Hole 735B were gabbro and olivine gabbro, composing 14.9 and 69.9 vol% of the core, respectively. The distinction between the two is arbitrary, set at 5% olivine following the International Union of Geological Sciences (IUGS) classification, and there is complete gradation between them. The separation, however, allowed distinction of areas of lesser olivine content in the core. Generally, this is an equigranular rock (Fig. 9A, 9D), rarely containing a weak magmatic foliation commonly overprinted by crystal-plastic deformation (Fig. 9D). Most commonly, though, it is varitextured, with irregular coarse, medium, fine, and even pegmatitic patches (Fig. 9E, 9F).

The average grain size of samples varies from fine grained (<1 mm) to pegmatitic (>30 mm), with average grain sizes generally in the range of coarse (5–15 mm) to very coarse (15–30 mm). The relative grain sizes for the major minerals are in the order augite > plagioclase > olivine, but are generally similar. Pegmatitic intervals occur sporadically through the core (Fig. 9E). Peaks in average grain size occur at 510, 635, 825, 940, 1100, 1215, 1300, 1425, and 1480 mbsf, and the grain size data for augite, plagioclase, and olivine all follow similar trends.

Weak modal and grain size layering is present in 22 intervals (12 vol% of the core). The types of layering observed include: (1) grain size layering characterized by either sharp breaks in grain size or gradational variations in grain size (Fig. 10A), (2) modal layering marked by distinct changes in the abundance of plagioclase, olivine, clinopyroxene, and Fe-Ti oxide (Fig. 10B, 10C), (3) magmatic foliation (igneous lamination) defined by the preferred orientation of plagioclase and in some cases olivine and clinopyroxene, and (4) layering defined by textural changes such as layers with crescumulate texture. In several intervals, layer types 1 and 2 occur in rhythmic sequences.

The olivine gabbro is locally crosscut by fine- to medium-grained microgabbros whose contacts range from sharp, with a definable slight finer grained margin, to irregular grading and swirling up through and into the adjoining olivine gabbro (Fig. 9B). These range in composition from primitive troctolites in lithologic Unit IV and Unit XII at the top and bottom of the Leg 176 section, to microgabbro and gabbronorite, though the majority are olivine microgabbros, which are nevertheless similar to the olivine gabbros they frequently cut. The origin of these bodies is speculative, as they could represent channels along which relatively hot primitive melt was fed up into the succession of gabbro intrusions, or they could be protodikes through which the typically primitive magmas of the Southwest Indian Ridge erupted to the seafloor.

Oxide-rich gabbros, including oxide olivine gabbro, make up 7 vol% of the recovered rocks, and gabbronorites and oxide gabbronorites make up approximately 8 vol%. These intervals range considerably in size, but decrease noticeably downward in the section and never occur in the abundance they have in the upper 500 m of the hole. There is nothing like the nearly 100-m-thick polygenetic units of sheared disseminated oxide olivine gabbro and oxide olivine gabbro found in Units III and IV between 170.22 and 274.06 mbsf. The latter require a very large flux of melt that has passed through them to account for the massive precipitation of intercumulus Fe-Ti oxides (Natland et al., 1991; Dick et al., 1991a), whereas the former could easily have crystallized from locally derived iron-rich melts sweated out of the crystallizing olivine gabbros. The oxide-rich gabbros in the lower two-thirds of Hole 735B are found as innumerable undeformed and sheared irregular patches and veins in olivine gabbro (Fig. 9C), and as consistently deformed larger intervals several meters or more thick. A consistent and impressive feature of these rocks is their overall positive correlation with areas of magmatic and crystal-plastic foliation as detailed in the structure section, and with the percent oxide found in the core. This is noteworthy, because most of these rocks are cumulates and do not represent a liquid composition. Moreover, as discussed in detail when they were previously described from the Leg 118 section, the liquids with which they are in equilibrium are far more evolved than any pillow basalt that has been dredged along the Southwest Indian Ridge (Dick et al., 1991a).

Dick et al. (1991a) have proposed that this is because the oxide gabbros represent intrusion of late iron-rich melts that have migrated out of the olivine gabbros and into and up shear zones penetrating or originating in partially molten lower crust (synkinematic igneous differentiation). When such melts migrate up section and down temperature, they must decrease in mass as they migrate. In the case of a late Fe-Ti-rich melt near the end of crystallization of the gabbros when they were sufficiently rigid to support a shear stress (80%–90% crystallinity), these liquids would precipitate abundant ilmenite and magnetite as they cooled. Thus, the greater the fluid flux through any area, the greater the enrichment in these oxides, hence a correlation exists between the degree of strain and the amount of precipitated oxide. The correlation between oxides and deformation throughout Hole 735B can be interpreted as evidence that deformation and the formation of shear zones have controlled the flow and transport of late intercumulus melt from depth to the top of the section.

A wide variety of felsic rocks were described (Niu), constituting 0.5% of the core. The majority are leucodiorite, but diorites, trondhjemite, tonalite, and a very little granite occur. They are largely net-veins, and rarely were sufficiently massive (5 cm) to be described as an igneous interval. Although many of these veins are clearly of igneous origin, having primary igneous textures and sharp intrusive contacts, many have experienced subsequent high- and low-temperature alteration and developed diffusive or reactive contacts with the host gabbros. Still others may be hydrothermal or metamorphic in origin.

Seven additional major lithologic units (VI to XII) were identified below the Leg 118 section, based on modal mineralogy and the relative abundance of rock types: VI—compound olivine gabbro, which continues from 382 mbsf in the Leg 118 core to 536 mbsf; VII—gabbronorite and oxide gabbronorite from 536 to 599 mbsf; VIII—olivine gabbro from 599 to 670 mbsf; IX—gabbronorite and gabbro from 670 to 714 mbsf; X—olivine gabbro and gabbro from 714 to 960 mbsf; XI—olivine gabbro from 960 to 1314 mbsf; and XII—olivine gabbro and troctolitic gabbro from 1314 mbsf to the bottom of the drilled hole at 1508 mbsf. These are shown in Figure 8. The stratigraphy, at first glance, would seem to resemble that of a large layered intrusion, with the proportion of rocks crystallized from differentiated and evolved liquids increasing upward. However, this is entirely misleading. The complex contains little layering, and none that resembles that characteristic of a layered intrusion. Rather it consists of a series of individual olivine gabbro intrusions, best defined geochemically, which are crosscut repeatedly at higher levels in the crust by oxide-rich gabbros. Thus the lower ocean crust here is differentiated kinematically by intrusion of late melts into the top of the section. In fact, as discussed in the geochemistry section, despite irregularly increasing olivine content, the lower olivine gabbros are less primitive, more titanium and soda rich, than those crosscut by the evolved intrusives higher in the section.

The average phase proportions in Hole 735B troctolites and olivine gabbros closely resemble cotectic proportions observed in low pressure experiments on mid-ocean-ridge basalts, suggesting that the main body of olivine gabbro crystallized at relatively shallow depths (<6 km) and solidified after efficient expulsion of residual melts. The more evolved Fe-Ti oxide-bearing gabbros do not have good experimental cotectic analogs. The strong correlation between deformation and oxide-rich gabbros in the Hole 735B section suggests that: (1) lenses of late-stage magma may have acted as zones of weakness along which deformation was concentrated; (2) late-stage magmas may have been concentrated in zones that had been previously sheared, because these zones have greater high-temperature permeability; or (3) active shear zones acted as conduits for melt transport through the section. The high concentrations of oxides present in some samples require that large volumes of melt were transported through these zones.

METAMORPHIC PETROLOGY

The metamorphic petrology working group logged 2792 veins as well as groundmass alteration assemblages on a piece-by-piece basis downcore. This was supplemented by an examination of some 243 thin sections of the Leg 176 cores. The individual observations were made by two teams of two investigators, with one team identifying, measuring, and logging veins (Alt and Kelley) and the other characterizing and logging alteration in the groundmass of the gabbros (Bach and Bideau). The same types of observations, and others, were then made independently on the thin-section suite by a fifth investigator (Robinson), who separately confirmed and expanded the observations of the macro-description teams. In hand sample, plagioclase alteration was based on the extent of a milky white appearance. This did not distinguish between hydrothermally altered plagioclase and plagioclase recrystallized by the high-temperature granulite facies deformation, which was pervasive in many sections of the core. Thus the total background alteration logged downhole is significantly greater than that seen in thin section, where secondary plagioclase due to hydrothermal alteration was more readily distinguished from that produced by dynamic recrystallization. Otherwise, the thin section observations were remarkably consistent with the observations of alteration in hand specimen. The thin section observations are presented in Figure 11. Total alteration and vein abundances downhole are plotted in Figure 12. This uses additional data on vein abundances for the upper 500 m (H.J.B. Dick, pers. comm., 1997).

The gabbros recovered during Leg 176 range from fresh to 40% altered, although there are many small intervals where alteration is far more extensive. Typically, however, there is less than a few percent total hydrothermal alteration through long sections. The most intensely altered portion of the core occurs between 500 and 600 mbsf, where amphibole in addition to secondary recrystallized plagioclase is most abundant, and the primary minerals are on average 10% to 40% altered. This contrasts sharply with the amphibolite gneisses at the top of Hole 735B, where total alteration was more intense, coming close to 100% (e.g., Robinson et al., 1991; Stakes et al., 1991). Calcite veins, associated with low temperature oxidation of the rocks, are also abundant between 500 and 600 m, evidently reflecting ongoing alteration at low temperatures due to the presence of open fractures. A second zone of intense recrystallization occurs between 800 and 1030 mbsf, where many of the rocks exhibit high-temperature plastic deformation, and veins are rare. Two less altered zones are located in an interval of abundant smectite veins at 1300–1500 mbsf. Below 1030 m, the intensity of alteration is generally much less than 10%.

The Leg 176 gabbros preserve a complex record of high-temperature metamorphism, brittle failure, and hydrothermal alteration that began at near solidus temperatures and continued down to very low-temperature conditions. The highest temperature metamorphic effects are transitional with magmatic processes: they most likely overlap both temporally and spatially, and in places distinguishing the effects of these two processes is difficult. This is particularly true of the felsic vein assemblages, which range from clearly magmatic to apparently exclusively hydrothermal. It was not unusual to find plagioclase and diopside veins, and combinations thereof, on splays from apparently igneous felsic veins (Fig. 13). In general it would appear that the locus of felsic veins also served as a conduit for late fluids, possibly often of magmatic origin, often leaving a heavy overprint on the igneous assemblages, which extended to partial replacement of some veins with clays.

Granulite facies metamorphic conditions (>800˚–1000˚C) are clearly marked by localized, narrow zones of crystal-plastic deformation that cut igneous fabrics. These intervals are characterized by anastomosing layers of olivine and pyroxene neoblasts that are bounded by plagioclase-rich bands. In some places, the high-temperature shear zones are associated with impregnations of oxide gabbros; in many cases, these zones have abundant recrystallized brown hornblende, indicating that deformation continued down to amphibolite facies metamorphic conditions. Other high-temperature effects probably resulting from late-stage magmatic activity include the formation of plagioclase+amphibole veins and diopside-rich veins, which in some intervals are progressively transposed into localized zones of high-temperature shear. Many of these rocks, veins, and shear zones reflect the effects of late magmatic hydrous fluids, but these zones also acted as pathways for later hydrothermal fluids at various temperatures.

Static high-temperature alteration is commonly associated with vein formation, and it is patchy throughout the section. Extensive intervals (>300 m) are marked by less than 10% total background alteration. This alteration is generally manifested by coronitic alteration halos around olivine grains, and the common replacement of clinopyroxene by variable amounts of brown amphibole. In more evolved rocks, magnesium-amphibole±talc typically replaces orthopyroxene. The secondary minerals most likely formed under low water-to-rock ratios over a range of temperature, from >600˚–700˚C down to much lower temperatures.

Ingress of high to moderate temperature fluids (400˚–550˚C) was facilitated by subvertical amphibole veins that are probably related to cooling and cracking of the rocks in the subaxial environment (e.g., Fig. 14). However, the abundance of amphibole veins decreases markedly with depth, as does the alteration, and below 600 mbsf amphibole veins are rare. In the Leg 118 section of Hole 735B amphibole veins and groundmass alteration were associated with zones of deformation at the top and bottom of the hole, with a sharp drop in abundance in undeformed intervals. The greatest alteration, often with complete replacement of mafic phases by amphibole and the highest vein abundances, was situated in the upper 100 m in a zone of intense deformation (Dick et al., 1991a; Stakes et al., 1991). A second more irregular zone of deformation and alteration was present in the bottom 100 m, where generally replacement of mafic phases by amphibole was only partial. Although this lower zone of deformation and associated amphibole alteration continued into the upper 100 m of the Leg 176 section, this is not observed in deeper intervals of the core, where foliated gabbros largely underwent crystal-plastic deformation at high temperatures. Microcracks filled with talc, magnetite, amphibole, sodic plagioclase, chlorite, and epidote are sporadically present throughout the core and represent smaller scale fracturing and fluid penetration under greenschist facies metamorphic conditions.

Cessation of hydrothermal fluid flow is marked by abundant late smectite, carbonate, and zeolite ± prehnite veins and iron oxyhydroxide minerals that are associated with intense alteration at 500–600 m. These minerals reflect low-temperature alteration by circulating seawater solutions, and they are most likely related to the presence of a fault at 560 mbsf. Smectite veins (Fig. 15), unlike the higher temperature vein assemblages, are often associated with alteration haloes where olivine and even pyroxene are extensively replaced by smectite. Below this interval, veins of smectite ± pyrite ± calcite, together with associated smectitic alteration of surrounding wallrock, reflect low temperature hydrothermal reactions under more reducing conditions. These effects occur throughout much of the core, but the abundant smectite veins at 600–800 m are most likely related to a second fault at 690 mbsf. This lower temperature set of veins formed in tensional fractures and is most likely related to cooling of the block during uplift of the massif to form the transverse ridge.

An anomalous feature of the Hole 735B cores is that high-temperature alteration assemblages are most abundant at the top of the section and low-temperature assemblages near the base. Greenschist assemblages, representing intermediate conditions, are relatively minor. This inversion of the normal order of things, as for example has been found for the in situ section of sheeted dikes and pillow lavas at Hole 504B (e.g., Alt, Kinoshita, Stokking, et al., 1993), is reasonably attributed to the unusual cooling history of the section. Apparently, at an early stage, conditions for the percolation of water to great depth did not exist beneath the rift valley, and alteration was largely limited to the upper portions of the gabbroic crust. Before a normal cooling profile could be established, however, the massif was unroofed and rapidly emplaced to the seafloor. The rapid cooling and relatively static conditions in the interior of the uplifted block inhibited extensive greenschist facies alteration, with only a single large epidote vein found in the entire lower two-thirds of the hole. In contrast, lower temperature alteration phases are abundant in the lower two-thirds of the core. This reflects alteration of the massive gabbro as it cooled during uplift. Further alteration occurred during subsequent circulation of seawater as the gabbros were transported away from the rift axis through a series of relatively restricted zones of fracture associated with block uplift.

GEOCHEMISTRY

To represent a systematic sampling of the major lithologies in the Leg 176 cores, 180 whole-rock samples were selected for analysis, representing about one analysis every 4.6 m of core. In principle, at least one sample representative for the main lithology was taken from each core, even when an apparently homogeneous unit spanned several cores. Seams of oxide gabbro and larger felsic veins were occasionally sampled to study the complete range of petrologic differentiation. Given the distribution of lithologies the large majority of the samples chosen for analysis were olivine gabbros and subordinate gabbro, disseminated Fe-Ti gabbro, and microgabbros. A limited number of samples were selected from the intervals strongly affected by high- and low-temperature alteration. Of the 458 igneous intervals identified in the core, about 140 are represented in the analysis suite. Analysis was done using X-ray fluorescence (XRF) for major element compositions and for the abundances of the trace elements V, Cr, Ni, Cu, Zn, Rb, Sr, Y, Zr, and Nb. Samples taken for analysis generally weighed 20 to 30 g. Larger slabs were cut from the very coarse-grained intervals, and a thin section was prepared from a billet from the same or adjacent material.

Figures 16 and 17 show the downhole variation of Mg number and TiO_2. The least evolved rocks are troctolites that occur between 500 and 520 mbsf. Throughout the entire gabbro section there are numerous thin intervals of Fe-Ti oxide gabbros and felsic rocks that are significantly to strongly differentiated. The Mg number should be used with some caution as a "differentiation index" in the case of the oxide gabbros. Mg numbers of cumulate rocks decrease as a result of the accumulation of iron-rich minerals, such that low numbers overestimate the extent of crystallization. Overall, the gabbros split into two groups: olivine gabbros and troctolites with minor oxides that have high magnesium numbers, which are crosscut by later Fe-Ti-rich oxide gabbros and felsic veins with high TiO_2 contents, low Mg number, and relatively sodic compositions that exhibit extreme variability in their composition due to the accumulation of iron oxides. Because of their crosscutting late occurrence and their extreme variability, these rock types have little value for establishing a chemical stratigraphy, which is based entirely on the chemistry of the main gabbro types and principally on the Mg number. Examining the depth profile (Fig. 16), approximately five or six major cycles can be identified of decreasing Mg number going from high Mg at depth to low Mg with increasing TiO_2

(roughly 1500–1400, 950–1400, 700–900, 525–700, 250–525, and 0–225 mbsf). Although it projects off the end of the 700–900 mbsf cycle, the overlying unit is chemically distinct. A prominent feature of the observed variation is that the lowermost three units in this cyclic repetition are more iron rich than the upper two, which is consistent with a somewhat more sodic composition and a slightly higher TiO_2 content of the rocks.

Mass chemical balance was done to calculate the bulk chemical composition of Hole 735B in 500 m sections. This was done using the average composition of each lithology in the section, the total thickness of intervals for each lithology in the section, and their average densities. This calculation demonstrates large bulk chemical differences between the sections of the hole. From the seafloor to 500 mbsf, the bulk composition has 1.4 wt% TiO_2, and a Mg number of 0.67 [Mg $\times$ 100]/[Mg + Fe^{2+}]), whereas the next 500 m has 0.7 wt% TiO_2, and a Mg number of 0.70, and the lowermost 500 m has 0.4 wt% TiO_2, and a Mg number of 0.71. Except for the most highly incompatible elements, the bulk composition of the hole is close to the composition of a primitive MORB with 0.69 wt% TiO_2, Mg number around 69.3, and 2.84 wt% Na_2O. By contrast, the upper half of the Leg 176 section contains only 0.69 wt% TiO_2, but has lower sodium (2.67%)—reflecting the depleted character of the upper olivine gabbros (2.49 vs. 2.87 wt% Na_2O in the lower olivine gabbros). Each successive interval down the hole has half as much TiO_2 as the interval above it.

This remarkable change in bulk chemistry of the hole is not due to more evolved olivine gabbros at the top of the hole. In the upper 500 m, the olivine gabbros have, in fact, significantly lower titanium and sodium and higher Mg number than the olivine gabbros lower in the hole. Rather, the difference in bulk composition is entirely due to the increasing volume of crosscutting Fe-Ti-rich oxide gabbros and gabbronorites in the upper part of the hole.

The main conclusions that can be drawn from the shipboard chemical analyses from both Legs 176 and 118 are:

1. The main rock type is a moderately fractionated olivine-bearing gabbro having between 0.2 and

1.0 wt% TiO_2. Fe-Ti oxide gabbros containing up to 7 wt% TiO_2 and up to 20 wt% Fe_2O_3 occur in centimeter- to decimeter-thick intervals throughout the core. The abundance of Fe-Ti oxide appears to decrease with depth, but this is not related to a decrease in TiO_2 of the parental liquids from which the gabbros crystallized. The development of localized concentrations of Fe-Ti-rich gabbro seems to depend on favorable conditions for formation rather than on the TiO_2 content of the starting material.

2. Gabbros with similar Mg number, MgO and Ni contents but variable TiO_2 content commonly occur together. Hence the differences in TiO_2 content cannot result from simple fractional crystallization from a common parental magma. Factors other than cotectic crystallization that affect phase proportions and compositions must have been involved. These are likely to include complex mixing of early cumulates with more differentiated liquids, assimilation-fractional crystallization processes during melt transport through the mass, and redistribution of crystal phases during solution channeling of migrating melts.

3. Within the 1000-m section drilled during Leg 176, six chemical units can be identified. With few exceptions the boundaries of these units coincide with changes in lithologic, metamorphic, and structural properties. The thickness of the separate units varies from 100 to 300 m. Most likely these chemical units represent the scale at which individual magmatic events added to the construction of oceanic Layer 3 at this ultra-slow spreading ridge.

STRUCTURAL GEOLOGY

Measurements made on the Leg 176 core by the structural team included intensity and orientation of magmatic deformation (Yoshinobu), crystal-plastic deformation (Hirth), cataclastic deformation (John), igneous and metamorphic veins (Trimby) as well as description of crosscutting relationships (Ildefonse). Additional observations on thin sections were made as a team with the aid of a video monitor. The results showed considerable variation in the structures observed throughout Hole 735B, both in style and position. Several unexpected features, notably the occurrence of significant reverse-sense shearing and a general decrease in deformation downhole, were found.

Wherever possible, observations on the Leg 176 cores were combined with results from the upper 500 m of the hole drilled during Leg 118, both through published results, and by combining the Leg 176 observations with data logs for the intensity and orientation of deformation and metamorphic veins for the 118 section provided by H. Dick (pers. comm., 1977). The team also relogged the lowermost 50 m of the Leg 118 portion of the hole to provide a basis for comparison of the Leg 176 observations to those for the upper 500 m of the hole.

The structural geologists marked all the Leg 176 cores for splitting orthogonal to the foliation. The cores were placed into the archive and working halves of split core liners in the same orientation to provide a consistent framework for description and measurement within the reference frame of the core liner. Thus the strong local concentration of poles to foliation shown in the stereo plots in Figure 18 with respect to strike (with reference to the coordinates of the core liner) are a direct artifact of the method in which they were split. They are not geographically referenced. However, shipboard paleomagnetic declinations for these cores show a similar cluster around 250˚ in the core reference frame throughout the entire cored interval. This unexpected result demonstrates that, overall, the foliations have a consistent orientation and thus can be reoriented into the geographical reference frame by making the assumption that the declination of the remnant magnetic vector dips toward the south. The resulting reorientation suggests that both the crystal-plastic and the late-magmatic foliations predominantly dip to the north, and hence toward the paleo-ridge axis.

Macroscopic Observations

A majority of the rocks from Hole 735B (78%) have coarse- to medium-grained hypidiomorphic-granular, intergranular, and subophitic textures with no preferred mineral alignment due to late magmatic deformation. The remainder contain a variably developed magmatic foliation defined by the preferred orientation of elongate plagioclase laths, and locally by pyroxene crystals with weak magmatic foliations predominating and strong fabrics developed only sporadically (Fig. 18). Magmatic foliations vary in strike and dip, with no systematic variation with depth. The majority have dips between 20˚ and 50˚.

Crystal-plastic deformation in Hole 735B, as shown in Figure 18, is highly localized, with the most intense deformation observed in the intervals 0–50 and 450–600 mbsf, with intervals of little or no crystal-plastic deformation generally increasing in number and length downhole. Overall, 77% of the rocks recovered during Leg 176 have no crystal-plastic fabric, and only 7% had more than a weak foliation, whereas 71% of the Leg 118 gabbros had no crystal-plastic fabric and 14% had more than a weak foliation. Again, there was no systematic variation of the dip of the foliation with depth, although there is with a strong concentration at about 30˚.

A striking feature of the crystal-plastic deformation fabrics from Hole 735B is the number of shear zones with reverse sense of shear concentrated within and below the 20-m-wide shear zone between 945 and 964 mbsf and also above the fault located at 690 mbsf. From the top of the core to 680 mbsf, the majority of the shear zones display normal shear. An example of a reverse shear zone is shown in Figure 19. These are as yet unexplained; however, the high temperature of their formation, and the origin of the Atlantis Bank at the inside-corner high, dictate that shear zones formed in the lower crust beneath the paleo-rift valley of the Southwest Indian Ridge.

A major feature of the Leg 176 cores is the strong positive correlation between magmatic and crystal-plastic fabrics (Fig. 18). Obviously, no magmatic fabric is preserved in regions with a very strong crystal-plastic fabric (e.g., 710–730 mbsf), but in general there is a good positive correlation between the intensities of the two fabrics, which is also reflected in a similar strike and dip. There are several interesting exceptions to this correlation, particularly in the lower portion of the hole, demonstrating that the relationship between the two may be complex in detail. The question naturally arises as to whether the "magmatic foliation" is real. This was addressed by a careful, independent assessment of 240 thin sections for the presence of crystal-plastic deformation and magmatic fabrics. Although weak magmatic fabrics are hard to see in thin section, undeformed samples with magmatic fabrics and the relative intensity of crystal-plastic fabric correlated remarkably well to the macroscopic observations of the core.

Retrograde shear zones at less than granulite facies conditions are evidenced by brittle-ductile deformation and the formation of amphibole in the plane of shear and in crosscutting veins and microcracks. Two principal retrograde shear zones are observed in Hole 735B, both of which coincide with zones of earlier late-magmatic deformation and crystal-plastic deformation. The most intense of these is in the upper 100 m of the core, where pyroxene is often entirely replaced by amphibole and true amphibolites are found. The less intense zone occurs around 500 mbsf at the bottom of the Leg 118 section and the top of the Leg 176 section.

Lower temperature cataclastic fabrics and faults are found at several levels within the Leg 176 section and at the base of the Unit IV Massive Oxide Gabbro at 274 mbsf (Dick et al., 1991a). Relatively major faults with the potential for significant displacement (e.g., hundreds of meters to kilometers) exist at 560 and at 690–700 mbsf, in addition to several minor ones at different locations. Smaller discrete planar faults with associated gouge, breccia, cataclasite, and ultracataclasite cut all rock types. These were logged at 600 locations in the core, but are concentrated in the upper half of the hole, and are virtually absent below about 1400 mbsf. The most common of these features are small-offset microfaults filled with calcite, amphibole, and/or smectite (below 1050 mbsf). Mineral assemblages associated with the brittle tectonic structures include amorphous silica, prehnite, chlorite, epidote, actinolite, and secondary plagioclase. These reflect a range of conditions for cataclastic deformation. Downhole dip shows no consistent pattern, though there is a maximum of poles to foliation near a plunge of 90˚ in stereo plots indicating a preferred subhorizontal fault orientation in the lower 1000 m of Hole 735B. Of the faults, 8.8% exhibit oblique slip, 2.8% pure dip slip, and 2.3% strike-slip.

Summary of Structural Evolution of Hole 735B

The cores from Hole 735B contain many late brittle deformation features with evidence of cataclasis. These are associated with alteration assemblages extending from the lower greenschist facies to ambient temperature. These features are almost certainly associated with block uplift and the later stages of unroofing of the massif at the inside-corner high of the Southwest Indian Ridge. This in large part reflects the bimodal metamorphic history of the massif wherein low-temperature alteration is concentrated near the bottom of the hole, whereas high temperature amphibolite facies is concentrated at the top.

Gabbroic rocks cored during Leg 176 at Hole 735B display magmatic, crystal-plastic, and brittle deformation features, together with associated overprinting relations consistent with synkinematic cooling and extension in a mid-ocean-ridge environment. The following observations provide a basis for interpreting the conditions of deformation during evolution of this block of lower oceanic crust.

1. Thick intervals of the core (up to ~150 m) are comparatively free of deformation and are either isotropic or contain local intervals with weak to moderate magmatic foliation; these intervals are most prevalent at the bottom of the hole. Magmatic foliations are often overprinted by a weak, parallel crystal-plastic fabric that may record the transition from magmatic to crystal-plastic deformation.

2. Numerous high-temperature reverse-sense shear zones occur in the interval between 900 and 1100 mbsf, including a 30-m-thick shear zone, and these are cut by lower temperature crystal-plastic or semi-brittle shear-zones (~1-10 cm thick).

3. Felsic magmatic breccias and veins are abundant throughout the upper 1100 m, and decrease in abundance toward the bottom of the hole.

4. The transition from crystal-plastic to lower temperature brittle deformation is associated with hydrothermal alteration at amphibolite to transitional greenschist-facies conditions.

5. Intense cataclasis is extremely localized downhole into zones of variable thickness up to centimeters thick.

6. Metamorphic veins show a wide variation in abundance and a general decrease in dip downhole; steeply dipping amphibole veins are common to 800 mbsf; moderately dipping, smectite veins dominate between 800 and 1500 mbsf.

7. There is a strong correlation between regions rich in Fe-Ti oxides and regions with strong crystal-plastic deformation. The relationship between crystal-plastic deformation and the concentration of oxide-rich zones, however, is not unique. Macro- and microstructural observations indicate (a) oxide-rich zones occur as late-crystallizing interstitial material,(b) oxide-rich zones are frequently spatially associated with faults and crystal-plastic shear zones, (c) lower temperature crystal-plastic and cataclastic deformation locally overprints some oxide zones, (d) oxides locally cut high-temperature crystal-plastic fabrics along shear zones, and (e) many oxide-bearing shear zones cut through oxide-poor undeformed gabbros.

8. Based on thickness and fracture intensity of recovered cataclastic rocks, there are two major zones (560 and 690–700 mbsf) and several minor zones of cataclasis (including 490, 1076, and 1100–1120 mbsf). The sense and magnitude of displacement on these faults is unknown; however, they likely are associated with uplift of this block.

These observations indicate that the processes that control crustal accretion at slow-spreading ridges are strongly influenced by localized deformation at conditions ranging from magmatic to low-temperature cataclastic. The correlation between structural domains and igneous intervals suggests that this segment of the Southwest Indian Ridge is not supplied by a steady-state magma source. Rather, intrusion and deformation are episodic phenomena that may occur separately or synchronously but at different rates. In many cases, zones of localized deformation remain active over a wide range of conditions, for example, cataclastic overprint of oxide-rich crystal-plastic shear zones that were initially active under partially molten conditions.

PALEOMAGNETICS

Paleomagnetic intensities, inclinations, and declinations were measured separately on all the archive halves of the Leg 176 cores and on a large number of minicores drilled from the working halves. The average natural remanent magnetization (NRM) intensity of the Leg 176 minicores is 2.5 A/m, the same as the estimated value of 2.5 A/m for the upper 500 m of Hole 735B once the drilling induced component is removed (Pariso and Johnson, 1993). There appears to be no general decrease in magnetization downhole; however, magnetic susceptibilities vary from 8.12×10^{-4} to 0.123 SI, with mean values smaller than for gabbros from the upper 500 m of the hole, with less scatter and a slight decrease with depth (Fig. 20). Magnetic “hardness” increases with decreasing size and compensates for the strong decrease in abundance of relatively coarse-grained oxide gabbros downhole. Olivine gabbro, the major constituent in the lower 1000 m of Hole 735B, though nearly oxide-free in the upper 500 m (Natland et al., 1991), has significantly more relatively fine-grained Fe-Ti oxides in the lower 1000 m of Hole 735B. Overall, the Hole 735B gabbros have a very stable remanent magnetization with a high and often very sharp blocking temperature suggesting relatively rapid acquisition of thermoremanence during cooling of the gabbros.

The vertical structure of the sources of lineated marine magnetic anomalies has remained poorly known ever since the recognition, more than 30 years ago, that the oceanic crust records reversals of the Earth’s geomagnetic field. Several authors have suggested that some or most of the stable source might reside in the gabbroic crust based on the magnetization of dredged gabbros (Fox and Opdyke, 1973; Kent et al., 1978). However, the surficial samples have been subjected to varying degrees of hydrothermal alteration and weathering during faulting and emplacement to the seafloor that would likely significantly affect their magnetic properties. During the site survey for Leg 118 (Dick et al., 1991b), well-defined magnetic anomalies were mapped over large regions of the rift mountains of the Southwest Indian Ridge adjacent to the transform fault. Extensive dredging of these regions, including Atlantis Bank, recovered largely gabbro and peridotite, suggesting that these lithologies must be responsible for the anomalies (Dick et al., 1991b). The magnetic properties of the Leg 118 cores from Hole 735B were found to be consistent with a gabbroic source layer for the anomaly over the site (Kikawa and Ozawa, 1992; Pariso and Johnson, 1993). The Leg 176 cores, however, are not only consistent with these interpretations, but together with the Leg 118 cores demonstrate that the 1.5-km Hole 735B section is the source of the lineated magnetic anomaly over the site, to the extent that this section is representative of the crust in three dimensions.

This conclusion presents the possibility that gabbroic crust may potentially contribute to, and even dominate over, the contribution of pillow basalts and sheeted dikes to marine magnetic anomalies elsewhere. However, the rapid acquisition of thermal remanence of the Hole 735B gabbros is consistent with rapid cooling due to unroofing and uplift to sea level at the ridge-transform intersection. This may not be the case for normal Southwest Indian Ridge crust away from transforms, which would cool under a 2-km carapace of pillow basalts and sheeted dikes, and acquire its thermal remanence more slowly.

Thermal and alternating field demagnetization studies of discrete samples from Leg 176 reveal two magnetization components: a low-stability component apparently related to drilling, and more stable components with steeper inclinations. The mean characteristic inclination (Inc) for Leg 176 discrete samples is reversed, with Inc = 71.4˚ (+0.3˚/ –3.1˚), uncorrected for any hole deviation from vertical (Fig. 20). This is statistically identical to that found in the upper 500 m (71.3˚, +0.4˚/ –11.0˚) when the latter are recalculated using the method of McFadden and Reid (1982). Since Antarctica has been relatively fixed in the plate reference frame over the last 11 Ma, the present latitude of Hole 735B is likely close to that of the paleo-ridge axis at the time of remanence acquisition. Thus, the observed inclination is steeper than the expected 52˚ for the site, and requires a tectonic rotation of the section of approximately 19˚ ±5˚ (depending on the deviation of the hole from vertical).

Overall, the tight cluster of stable magnetic inclinations downhole is significant to the interpretation of the igneous petrology and structure of Hole 735B, as the inclinations indicate that there has been little tectonic disruption of the section since it cooled below the Curie point at about 580˚C. Moreover, there is an unexpected strong preferred orientation of declinations at around 260˚ in the reference frame of the core liner. This is explained by the fact that the structural geologists systematically oriented each section of core for splitting so that they were cut orthogonal to the foliation, with each half placed in the working and archive halves so that the foliation dipped consistently in one direction.

Thus, the consistent declinations demonstrate that these foliations are not random, and suggest that gross reorientation of structural features in the core may be possible. Assuming a south-pointing characteristic remanence declination, the mean declination of 260˚ would be restored to 180˚ by a counterclockwise rotation of approximately 80˚. Structural planar features that preferentially dip toward 090˚ in the core reference frame would thus dip toward the axial rift to the north.

PHYSICAL PROPERTIES AND DOWNHOLE MEASUREMENTS

Physical properties were measured using the multisensor track (MST) on all the whole core (natural gamma ray, gamma-ray densiometry, magnetic susceptibility). Also measured were index properties including density, porosity, compressional wave velocity, and thermal conductivity on archived half core pieces and on minicores from the working half. Only the magnetic susceptibility measurements made on the MST proved to have geologic value.

Thermal conductivity measurements were made at 219 intervals through the borehole section. Over the section the thermal conductivity is 2.276 ± 0.214 W/(m·K). The thermal conductivity varied considerably in the region of felsic veins. These values lie within the range measured for the upper 500 m of Hole 735B and for gabbroic rocks in general (Clark, 1966).

Magnetic Susceptibility

The MST track system measured in excess of 22,000 magnetic susceptibility points. These are shown in Figure 21 and exhibit two characteristic features. The first is an overall decrease in susceptibility downhole defined largely by a gradual decrease in the baseline value with depth. The second is the occurrence of more than 600 extreme spikes of high susceptibility that can be individually correlated to the location of intervals of oxide-rich gabbros and gabbronorites enclosed within oxide-poor olivine gabbro and crosscutting felsic veins in the Hole 735B cores. The MST spikes indicate that the typical interval is no more than 10 to 15 cm thick, and at times significantly smaller. These intervals should be most abundant in the upper 500 m of the core, where susceptibility measurements on individual samples define the highest overall unit susceptibility. The proportion and frequency of these oxide-rich intervals decrease systematically downhole from 274 m at the base of the Unit 4 massive oxide olivine gabbro, but were not measured by MST during Leg 118. The occurrence of oxide gabbros correlates remarkably well with both the intensity of deformation and average oxide percent in the gabbros.

Density

Mass and volumetric measurements were made on 218 minicores with a mean porosity of 0.649 ± 2.884% (the population being heavily skewed by the large number of minimal porosities and the small number of porosities significantly greater than 1%). The mean bulk density was 2.979 ± 0.10 g/cm^3, and a mean grain density was 2.991 ± 0.107 g/cm^3, close to the density of the typical olivine gabbro (2.96 g/cm^3). Density varied with mineral content and was highest in oxide gabbros (3.21 g/cm^3) due to the presence of substantial ilmenite and magnetite (4.7–5.2 g/cm^3), and lowest in troctolitic gabbros and olivine gabbros, where the proportion of plagioclase (2.7 g/cm^3) was greatest. Density shows variations consistent with the lithologic variations downhole, with the greatest scatter in the upper 500 m where oxide gabbros are most abundant (between 2.8 and 3.3 g/cm^3). Density also shows increasing scatter below 925 mbsf (2.8 and 2.9 g/cm^3). A slight decrease in mean density in samples from the bottom of the hole reflects an increasing proportion of plagioclase-rich olivine gabbro and troctolite.

Vertical Incidence Seismic Profile Reflectors

The physical properties measurements provide considerable insight into the origin of the vertical incidence seismic profile reflectors identified from the Leg 118 VSP (Swift et al., 1991). The compressional velocities of 217 minicores were measured; they averaged 6777 ± 292 m/s, and are show together with the data from Leg 118 in Figure 22. No significant variation in minicore compressional velocities occurs for the Leg 176 cores downhole, which could correspond to either the VSP reflector at 560 m, or that between 760 and 825 m. Higher in the hole, however, there is a clear dip in velocities for the massive oxide gabbro Unit IV that corresponds to a striking increase in the density of minicores and the vertical-incidence seismic profile reflector at 225-250 mbsf (Iturrino et al., 1991; Dick et al., 1991a). A sharp increase in seismic velocity of the Leg 118 cores near the top of the hole occurs in the vicinity of another reflector at 50 m. The latter corresponds to a zone of amphibolites with intense shear and crystal-plastic deformation that has produced a strong crystal fabric orientation. Iturrino et al. (1991) demonstrated that these are elastically anisotropic, with strong directional variations in *Vp* related to foliation. The reflector is located at a break in the deformed interval where highly deformed amphibolites are juxtaposed against relatively undeformed ones.

The absence of either a break in density or compressional *P*-wave velocity corresponding to the two lower VSP reflectors at 560 m and 760–825 m, then, demonstrates that these are not due to the intrinsic physical properties of the gabbros themselves, either the development of a strong preferred mineral fabric, or variations in density. Rather, they must correspond to another variable such as the presence of faults and fractures. This is confirmed by examination of the recovery record from Hole 735B (Fig. 22). Recovery in both massive fine- and coarse-grained, foliated and unfoliated gabbros was high, generally close to 100% in Hole 735B. Drilling rates, however, varied considerably in these lithologies, dropping dramatically for fine-grained intervals. Where the rocks were believed to be highly fractured, drilling rates increased dramatically, and recovery dropped to as low as 31%. The precise coincidence of the two lower VSP reflectors with intervals of dramatically reduced recovery, therefore, apparently confirms the hypothesis that these are highly fractured zones corresponding to some form of faulting associated with the late uplift of the platform.

The downhole measurements performed at the end of the leg confirmed that the fault centered at 560 mbsf is about 4 m thick, that it has reduced formation velocities, densities, and resistivities, and elevated porosities. Additional information from the logs, including an attempted, but regrettably degraded, formation microscanner (FMS) log, and a reasonably successful VSP experiment, await shore-based processing.

In summary, the sequence of rocks observed in Hole 735B is unlike that found in well-studied ophiolites. A full on-land counterpart to these rocks has yet to be found. Nor does this sequence of rocks resemble a layered igneous intrusion. Hole 735B provides a first example of synkinematic igneous differentiation in which the upper levels of the gabbroic crust were enriched in the late differentiated melts through tectonic processes, rather than simple gravitationally driven crystallization differentiation.

CONCLUSIONS

All of the scientific objectives of Leg 176 were dependent on deepening Hole 735B. The ultimate success of the leg will be measured by the results published by the science party and other interested investigators in the years to come. The primary objective of Leg 176 was recovering a representative section of gabbroic Layer 3 to determine its stratigraphic variation with depth. This objective was achieved beyond our expectations, manifested in deepening Hole 735B to more than 1.5 km with an overall recovery of more than 86% in an environment (ultra-slow spreading ridges) where the lower crust is believed to be only about 2 km thick. The supplementary scientific objectives of Leg 176, testing whether or not the Moho is coincident with the crust-mantle boundary and deepening Hole 735B well below the crust-mantle boundary were not achieved due to operational time limitations and drill string failure. Toward these objectives, however, Leg 176 successfully demonstrated that the *JOIDES Resolution*, with her present technology, has the capacity for deep drilling and high recovery at this location and that the success of Leg 118 was not an anomalous circumstance. We await future drilling programs at this location to fully realize all the science objectives proposed for Leg 176, which include some of the highest order priorities of the Long Range Plan of the Ocean Drilling Program.

REFERENCES

Alt, J.C., Kinoshita, H., Stokking, L.B., et al., 1993. *Proc. ODP, Init. Repts.*, Leg 148: College Station, TX (Ocean Drilling Program).

Aumento, F., and Loubat, H., 1971. The Mid-Atlantic Ridge Near 45˚N. XVI. Serpentinized Ultramafic Intrusions. *Can. J. Earth Sci.*, 8:631-663.

Bloomer, S.H., and Meyer, P.S. 1992. Mid-ocean ridges; slimline magma chambers; discussion. *Nature* (London), 357:117-118.

Bloomer, S.H., Natland, J.H., Meyer, P.S., and Dick, H.J.B., 1991. Textural and mineralogical variations in gabbroic rocks from Hole 735B. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 21-40.

Bonatti, E., and Honnorez, J., 1976. Sections of the Earth’s crust in the Equatorial Atlantic. *J. Geophys. Res.*, 81:4087-4103.

Bowen, N.L., 1920. Differentiation by deformation. *Proc. Nat. Acad. Sci.*, 6:159-162.

Bown, J.W., and White, R.S., 1994. Variation with spreading rate of oceanic crustal thickness and geochemistry. *Earth Planet. Sci. Lett.*, 121:435-439.

Cande, S.C., and Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.*, 100:6093-6095.

Cann, J.R., 1974. A model for oceanic crustal structure developed. *Geophys. J.R. Astr. Soc.*, 39:169-187.

Cannat, M., 1991. Plastic deformation at an oceanic spreading ridge: a microstructural study of the Site 735 gabbros (Southwest Indian Ocean): *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 399-408.

Cannat, M., 1993. Emplacement of mantle rocks in the seafloor at mid-ocean ridges. *J. Geophys. Res.*, 98:4163-4172.

Cannat, M., Karson, J.A., Miller, D.J., et. al., 1995. *Proc. ODP Init. Repts.*, 153: College Station, TX (Ocean Drilling Program).

Cannat, M., Mével, C., and Stakes, D., 1991. Normal ductile shear zones at an oceanic spreading ridge: tectonic evolution of Site 735 gabbros (Southwest Indian Ocean). *In* Von Herzen, R.P. Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 415-430.

Carbotte, S., and Macdonald, K., 1992. East Pacific Rise 8°–10°30′N: Evolution of ridge segments and discontinuities from SeaMARC II and three-dimensional magnetic studies. *J. Geophys. Res.*, 97:6959-6982.

Christensen, N.I., 1972. The abundance of serpentinites in the oceanic crust. *J. Geol.*, 80:709-719.

Christensen, N.I., and Salisbury, M.H., 1975. Structure and constitution of the lower oceanic crust. *Rev. Geophys. Space Phys.*, 13:57-86.

Clark, S.P. (Ed.), 1966. *Handbook of Physical Constants*. Mem. Geol. Soc. Am. 97.

Coleman, R.G., 1977. *Ophiolites: Ancient Oceanic Lithosphere*. Springer Verlag (New York).

Coleman, R.G., and Irwin, W.P., 1974. Ophiolites and ancient continental margins. *In* Burk, C.A., and Drake, C.L. (Eds.), *The Geology of Continental Margins*: Springer-Verlag (New York), 921-931.

Detrick, R.S., Mutter, J.C., Buhl, P., and Kim, I.I., 1990. No evidence from multichannel reflection data for a crustal magma chamber in the MARK area on the Mid-Atlantic Ridge. *Nature*, 347:61-64.

Dick, H.J B., 1989. Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism. *In* Saunders, A.D., and Norry, M.J. (Eds.), *Magmatism in the Ocean Basins*, Geol. Soc. Spec. Pub., 42:71-105.

Dick, H.J.B., 1996. Hess versus Penrose: What is the composition of the lower ocean crust? *Eos, Trans. Am. Geophys. Union*, 77:S275.

Dick, H.J.B., Bryan, W.B., and Thompson, G., 1981. Low-angle faulting and steady-state emplacement of plutonic rocks at ridge/transform intersections. *Eos, Trans. Am. Geophys. Union*, 62:406.

Dick, H.J.B., Meyer, P.S., Bloomer, S., Kirby, S., Stakes, D., and Mawer, C., 1991a. Lithostratigraphic evolution of an in-situ section of oceanic layer 3. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 439-540.

Dick, H.J.B., Robinson, P.T., and Meyer, P.S., 1992. The plutonic foundation of a slow-spreading ridge. *In* Duncan, R.A., Rea, D.K., Weissel, J.K., Von Rad, V. and Kidd, R.B. (Eds.), *The Indian Ocean: a synthesis of results*. Am. Geophys. Union, Geophys. Monogr. 70:1-39.

Dick, H.J.B., Schouten, H., Meyer, P.S., Gallo, D.G., Berg, H., Tyce, R., Patriat, P., Johnson, K., Snow, J., and Fisher, A., 1991b. Tectonic evolution of the Atlantis II Fracture Zone. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results,* 118: College Station, TX (Ocean Drilling Program), 359-398.

Dick, H.J.B., Schouten, H., Meyer, P.S., Gallo, D.G., Berg, H., Tyce, R., Patriat, P., Johnson, K., Snow, J., and Fisher, A., 1991c. Bathymetric map of the Atlantis II Fracture Zone, Southwest Indian Ridge. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program).

Engel, C.G., and Fisher, R.L., 1975. Granitic to ultramafic rock complexes of the Indian Ocean ridge system, western Indian Ocean. *Geol. Soc. Am. Bull.*, 86:1553-1578.

Fisher, R.L., Dick, H.J.B., Natland, J.H., and Meyer, P.S., 1986. Mafic/ultramafic suites of the slowly spreading southwest Indian Ridge: Protea exploration of the Antarctic Plate Boundary, 24˚E-47˚E. *Ophioliti*, 11:147-178.

Fisher, R.L., and Sclater, J.G., 1983. Tectonic evolution of the Southwest Indian Ocean since the Mid-Cretaceous: plate motions and stability of the pole of Antarctica/Africa for at least 80 Myr. *Geophys. J.R. Astr. Soc.*, 73:553-576.

Fox, P.J., and Opdyke, N., 1973. Geology of the oceanic crust: magnetic properties of oceanic rocks. *J. Geophys. Res.*, 78:5139-5154.

Harper, G.D., 1985. Tectonics of slow spreading mid-ocean ridges and consequences of a variable depth to the brittle/ductile transition. *Tectonics*, 4:395-409.

Hess, H.H., 1962. The history of the ocean basins. *Geol. Soc. Am. Buddington Vol.*, 599-620.

Hill, M.N., 1957. Recent geophysical exploration of the ocean floor. *Phys. Chem. Earth*, 2:129-163.

Hopkinson, L., and Roberts, S., 1995. Ridge axis deformation and coeval melt migration within layer 3 gabbros: evidence from the Lizard Complex. *U.K. Contrib. Mineral. Petrol.*, 121:126-138.

Iturrino, G.J., Christensen, N.I., Kirby, S., and Salisbury, M.H., 1991. Seismic velocities and elastic properties of oceanic gabbroic rocks from Hole 735B. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP*, *Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 227-244.

Jackson, H.R., Reid, I., and Falconer, R.K.H., 1982. Crustal structure near the Arctic mid-ocean ridge. *J. Geophys. Res.*, 87:1773-1783.

Karson, J.A., 1990. Seafloor spreading on the Mid-Atlantic Ridge: Implications for the structure of ophiolites and oceanic lithosphere produced in slow-spreading environments. *In* Malpas, J., Moores, E.M., Panyiotou, A., and Xenophontos, C. (Eds.), *Ophiolites: Oceanic Crustal Analogues*. Proc. Symp. "Troodos 1987": Nicosia, Cyprus (Minist. Agric. Nat. Resour.), 547-555.

Karson, J. A., 1991. Accommodation zones and transfer faults: Integral components of Mid-Atlantic Ridge extensional systems. *In* Peters, T., Nicolas, A., and Coleman, R.J. (Eds.), *Ophiolite Genesis and Evolution of the Oceanic Lithosphere:* Oman, Ministry of Petroleum and Minerals, Sultanate of Oman, Kluwer Academic Publishers (Netherlands), 21-37.

Karson, J.A., and Dick, H.J.B., 1983. Tectonics of ridge/transform intersections at the Kane Fracture Zone. *Mar. Geophys. Res.*, 6:51-98.

Karson, J.A., Thompson, G., Humphris, S.E., Edmond, J.M., Bryan, W.B., Brown, J.R., Winters, A.T., Pockalny, R.A., Casey, J.F., Campbell, A.C., Klinkhammer, G., Palmer, M.R, Kinzler, R.J., and Sulanowska, M.M., 1987. Along-axis variations in seafloor spreading in the MARK area. *Nature*, 328:681-685.

Kent, D.V., Honnorez, B.M., Opdyke, N.D., and Fox, P.J., 1978. Magnetic properties of dredged oceanic gabbros and the source of marine magnetic anomalies. *Geophys. J. R. Astr. Soc.*, 55:513-537.

Kikawa, E., and Ozawa, K., 1992. Contribution of oceanic gabbros to sea-floor spreading magnetic anomalies. *Science*, 258:796-799.

Kikawa, E., and Pariso, J. E., 1991. Magnetic properties of gabbros from Hole 735B, Southwest Indian Ridge. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 285-307.

MacLeod, C.J., Boudier, F., Yaouancq, G., and Richter, C., 1996. Gabbro fabrics from Site 894, Hess Deep: implications for magma chamber processes at the East Pacific Rise. *In* Mével, C., Gillis, K.M., Allan, J.F., and Meyer, P.S., (Eds.), *Proc. ODP, Sci. Results*, 147: College Station, TX (Ocean Drilling Program), 317-328.

Magde, L.S., Dick, H.J.B., and Hart, S.R., 1995. Tectonics, alteration and the fractal distribution of hydrothermal veins in the lower ocean crust. *Earth Planet. Sci. Lett.*, 129:103-119.

McCarthy, J., Mutter, J.C., Morton, J.L., Sleep, N.H., and Thompson, G.T., 1988. Relic magma chamber structures preserved within the Mesozoic North Atlantic crust? *Geol. Soc. Am. Bull.*, 100:1423-1436.

McFadden, P.L., and Reid., A.B., 1982. Analysis of paleomagnetic inclination data. *Geophys. J. Royal Astron. Soc.*, 69:307-319.

Melson, W.G., and Thompson, G., 1970. Layered basic complex in oceanic crust, Romanche fracture, equatorial Atlantic Ocean. *Science*, 168:817-820.

Mével, C., and Cannat, M., 1991. Lithospheric stretching and hydrothermal processes in oceanic gabbros from slow-spreading ridges. *In* Peters, T., Nicolas, A., and Coleman, R.J. (Eds.), *Ophiolite Genesis and Evolution of the Oceanic Lithosphere:* Oman, Ministry of Petroleum and Minerals, Kluwer Academic Publishers (Netherlands), 293-312.

Mével, C.C., Cannat, M., Gente, P. Marion, E., Auzende, J.-M., and Karson, J.A., 1991. Emplacement of deep crustal and mantle rocks on the west wall of the MARK area (Mid-Atlantic Ridge, 23˚N). *Tectonophysics*, 190:31-53.

Minshull, T.A., and White, R.S., 1996. Thin crust on the flanks of the slow-spreading Southwest Indian Ridge. *Geophys. J. Int.*, 125:139-148.

Muller, M.R., Robinson, C.J., Minshull, R.S., and Bickle, M.J., 1997. Thin crust beneath ocean drilling program borehole 735B at the Southwest Indian Ridge? *Earth Planet. Sci. Lett.*, 148:93-108.

Mutter, J.C. and North Atlantic Transect (NAT) Study Group, 1985. Multichannel seismic images of the oceanic crust's internal structure: evidence for a magma chamber beneath the Mesozoic Mid- Atlantic Ridge. *Geology*, 13 629-632.

Mutter, J.C., and Detrick, R.S., 1984. Multichannel seismic evidence for anomalously thin crust at Blake Spur fracture zone. *Geology*, 12:534-537.

Natland, J.H., and Dick, H.J.B., 1996. Melt migration through high-level gabbroic cumulates of the East Pacific Rise at Hess Deep: the origin of magma lenses and the deep crustal structure of fast- spreading ridges. *In* Mével, C., Gillis, K.M., Allan, J.F., and Meyer, P.S., (Eds.), *Proc. ODP, Sci. Results*, 147: College Station, TX (Ocean Drilling Program), 21-58.

Natland, J.H., Meyer, P.S., Dick, H.J.B., and Bloomer, S.H., 1991. Magmatic oxides and sulfides in gabbroic rocks from ODP Hole 735B and the later development of the liquid line of descent. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 75-112.

Nicolas, A., Boudier, F., and Ildefonse, B., 1996. Variable crustal thickness in the Oman ophiolite: Implication for oceanic crust. *J. Geophys. Res.*, 101:17941-17950.

Norton, I.O., and Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. *J. Geophys. Res.*, 84:6803-6830.

Ozawa, K., Meyer, P.S., and Bloomer, S.H., 1991. Mineralogy and textures of iron-titanium oxide gabbros and associated olivine gabbros from Hole 735B. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 41-73.

Pariso, J. E., and Johnson, P.H., 1993. Do lower crustal rocks record reversals of the Earth's magnetic field? Magnetic petrology of oceanic gabbros from ocean drilling program Hole 735B. *J. Geophys. Res.*, 98:16013-16032.

Pariso, J E., Scott, J.H., Kikawa, E., and Johnson, H.P., 1991. A magnetic logging study of Hole 735B gabbros at the Southwest Indian Ridge. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 309-323.

Raitt, R.W., 1963. The crustal rock. *In* Hill, M. N. (Ed.), *The Sea*, Wiley Interscience (New York), 85-102.

Reid, I., and Jackson, H.R., 1981. Oceanic spreading rate and crustal thickness. *Mar. Geophys. Res.*, 5:165-172.

Robinson, P.T., Dick, H.J.B., Von Herzen, R.P., 1991. Metamorphism and alteration in oceanic layer 3: Hole 735B. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 541-552.

Robinson, P.T., Von Herzen, R., et al., 1989. *Proc. ODP, Init. Repts.* 118: College Station, TX (Ocean Drilling Program).

Sclater, J.G., Fisher, R.L., Patriat, P., Tapscott, C., and Parsons, B., 1981. Eocene to Recent development of the Southwest Indian Ridge, a consequence of the evolution of the Indian Ocean Triple Junction. *Geophys. J. R. Astr. Soc.*, 64:587-604.

Sinton, J.M., and Detrick, R.S., 1992. Mid-ocean ridge magma chambers. *J. Geophys. Res.*, 7:197-216.

Stakes, D.S., 1991. Oxygen and hydrogen isotope compositions of oceanic plutonic rocks: High-temperature deformation and metamorphism of oceanic layer 3. *In* Taylor, H.P., Jr., O'Neil, J.R., and Kaplan, I.R. (Eds.), Stable Isotope Geochemistry: A Tribute to Samuel Epstein, *Geochem. Soc.*, Spec. Pub. 3:77-90.

Stakes, D., Mével, C., Cannat, M., and Chaput, T., 1991. Metamorphic stratigraphy of Hole 735B. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 153-180.

Swift, S. A., Hoskins, H., and Stephen, R. A., 1991. Seismic stratigraphy in a transverse ridge, Atlantis II Fracture Zone. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 219-226.

Tapscott, C.R., Patriat, P., Fisher, R.L., Sclater, J.G., Hoskins, H., and Parsons, B., 1980. The Indian Ocean triple junction. *J. Geophys. Res.*, 85:4723-4739.

Thompson, G., and Melson, W.G., 1972. The petrology of oceanic crust across fracture zones in the Atlantic Ocean: Evidence of a new kind of sea-floor spreading. *J. Geology*, 80:526-538.

Tucholke, B. E., and Lin, J., 1994. A geological model for the structure of ridge segments in slow spreading ocean crust. *J. Geophys. Res.*, 99:11937-11958.

Vanko, D.A., and Stakes, D.S., 1991. Fluids in oceanic Layer 3: evidence from veined rocks, Hole 735B, Southwest Indian Ridge. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 181-215.

Whitehead, J.A., Jr., Dick, H.J.B., and Schouten, H., 1984. A mechanism for magmatic accretion under spreading centres. *Nature*, 312:146-148.

FIGURE CAPTIONS

Figure 1. Location of the Atlantis II Fracture Zone. Position of the Southwest Indian Ridge based on recent satellite gravity maps of the southern oceans and available bathymetric data.

Figure 2. Bathymetric map of the Atlantis II Fracture Zone modified from Dick et al. (1991c). Locations of Hole 735B and the conjugate site 735B' (SWIR 6) are shown. SWIR 6 is located on the counter lithospheric flow-line on crust of the same age and position relative to the paleo-transform as Hole 735B. Active southern and northern rift valleys are at 33˚40'S and 31˚350'S, respectively.

Figure 3. A. Hand-contoured 100-m-contour bathymetric map of Site 735 showing the location of Hole 735B modified from Dick et al. (1991b). SeaBeam tracks hand-shifted by eye to eliminate conflicts in the data. Solid lines indicate actual data, whereas hatched lines show inferred contours. Contour interval is 250 m. Small solid dots and arrows indicate the starting point and approximate track of dredge hauls. Large solid dots show the location of Sites 735 and 732 (just north of the contoured area on the crest of the median tectonic ridge). Filled circles indicate the approximate proportions of rock types recovered in each dredge: + = gabbro; white = basalt and diabase, light stipples = greenstone, and heavy stipples = serpentinized peridotite. **B.** Hand-contoured bathymetric map of the eastern rift mountains north of the Southwest Indian Ridge axis showing crust of the same age as that at Site 735 and the conjugate position of Hole 735B (735B') on the counter-lithospheric flow line, based on magnetic anomalies and plate reconstruction. This conjugate site is the location of Southwest Indian Ridge 6, the final backup site for Leg 176, where the volcanic carapace originally overlying Hole 735B is preserved intact.

Figure 4. Magnetic anomalies over Site 735 based on the survey of Dick et al. (1991b). Bathymetry contoured at 200-m intervals. Crustal magnetization is shown shaded, with normal polarity crustal magnetization shown as gray and reverse polarity shown as white. Dark gray areas have crustal magnetization greater than 1 A/m. Polarity identifications and numbering modified from Dick et al. (1991b) by M. Tivey (pers. comm., 1997) based on the time scale of Cande and Kent (1995).

Figure 5. Outcrop map in vicinity of Hole 735B constructed from Leg 118 video survey. Swath field of view is ~8 m. The ratio of outcrop to sediment is proportional to the distribution of patterns along the swath. Time stamp and depths from video image and voice-over are noted along swath pattern. Textured sediment refers to a coating of sediment so thin that the texture of the outcrop underneath is discernable. Locations of Holes 735A and 735B along survey lines are also indicated.

Figure 6. Temporal cross sections across the Southwest Indian Ridge rift valley drawn parallel to the spreading direction (not across the fracture zone, but parallel to it), showing the postulated tectonic evolution of the transverse ridge and Hole 735B (Dick et al., 1991b). The sequential sections are drawn at about 18 km from the transform fault. Crust spreading to the right passes into the transverse ridge and spreads parallel to the transform valley. Crust spreading to the left spreads into the rift mountains of the Southwest Indian Ridge parallel to the inactive extension of the Atlantis II Fracture Zone. **A.** Initial symmetric spreading, possibly at the end of a magmatic pulse. Late magmatic brittle-ductile deformation occurs because of lithospheric necking above (and in the vicinity of whatever passes for a magma chamber at these spreading rates). Hydrothermal alteration at high temperatures accompanies necking and ductile flow in subsolidus regions. **B.** At some point, the shallow crust is welded to the old, cold lithosphere to which the ridge axis abuts, causing formation of a detachment fault, and nodal basin, initiation of low-angle faulting, continued brittle-ductile faulting, and amphibolite-facies alteration of rocks drilled at Hole 735B. **C, D.** Block uplift of the rift mountains at the ridge-transform corner forms a transverse ridge enhanced by regional isostatic compensation of the local negative mass anomaly at the nodal basin. Initiation of the block uplift terminates the extension driving cracking, and drastically reduces permeability in the Hole 735B rocks, effectively terminating most circulation of seawater and alteration. Greenschist-facies retrograde alteration continues along the faults on which the block is uplifted to account for the greenschist-facies alteration that predominates in dredged gabbros.

Figure 7. Seismic velocity structure from Muller et al. (1997). **A.** *P*-wave seismic velocity model on the north–south seismic Line CAM101 of Muller et al. (1997). The velocity contour interval is 0.3 km/s. Numbered OBH positions are shown on the seafloor. The position of ODP Hole 735B has been projected from 1 km west of the line. The Moho is indicated as a thicker line where its depth is constrained by wide-angle reflections. **B.** Resolution contours for the seismic model. The resolution of each velocity node is given by the diagonal of the inversion resolution matrix a number between 0.0 and 1.0, affected by the ray coverage sampling each node. Values of greater than 0.5 are considered well resolved and reliable.

Figure 8. Lithostratigraphic column showing the change in proportions of igneous intervals through Hole 735B from the seafloor to 1508 mbsf and the locations of pegmatitic gabbros, microgabbros, and igneous layering.

Figure 9. Representative core close-up photographs. **A.** Typical coarse-grained olivine gabbro (interval 176-735B-171R-2, 32–44 cm). **B.** Olivine microgabbro crosscutting olivine gabbro (interval 176-735B-189R-3, 90–120 cm. **C.** Oxide olivine gabbro vein (interval 176-735B-171R-2, 2–19 cm). **D.** Foliated gabbro (interval 176-735B-93R-3, 76–93 cm). **E.** Pegmatoidal olivine gabbro (pieces from Sections 176-735B-177R-3 and 177R-4). **F.** Varitextured olivine gabbro (interval 176-735B-196R-5, 23–97 cm).

Figure 10. Representative layered sections of the Leg 176 core. **A.** Size-graded and modal layering (interval 176-735B-171R-4, 35–90 cm). **B.** Troctolitic layer in olivine gabbro (interval 176-735B-186R-4, 35–55 cm). **C.** Mafic layers in olivine gabbro (interval 176-735B-190R-2, 0–95 cm).

Figure 11. Downhole distribution of secondary phases in Hole 735B, related to the variation in total rock alteration with depth. Data are from thin section observations.

Figure 12. A. Distribution of total veins by percentage of core in gabbroic rocks recovered during Legs 118 and 176. **B.** Distribution of felsic, plagioclase, and amphibole + plagioclase veins by percentage of core. Below 1250 mbsf, felsic veins are rare. **C.** Distribution of plagioclase +

diopside and diopside veins by percentage of core. Below 750 mbsf, diopside and plagioclase + diopside veins do not occur. **D.** Distribution of amphibole veins by percentage of core. Below 600 mbsf, amphibole veins are rare. **E.** Distribution of carbonate and smectite veins downsection. **F.** Distribution of chlorite and zeolite veins downsection.

Figure 13. Plagioclase and diopside veins, and combinations thereof, on splays from an apparently igneous felsic vein (interval 176-735B-110R-4, 0–38 cm).

Figure 14. Subvertical amphibole vein crosscutting foliated olivine gabbro (interval 176-735B-92R- 1, 10–15 cm).

Figure 15. Vein of pale-green smectite in Sample 176-735B-133R-7 (Piece 1, 126–137 cm). Olivine, plagioclase, and clinopyroxene are highly altered to smectite in the alteration halo. Altered plagioclase appears pale-green, olivine dark, and altered clinopyroxene brown or brilliant at greater distance to the vein (incipient alteration).

Figure 16. Mg number (calculated as $Mg^{2+}/Fe^{2+} + Mg^{2+}$; $Fe^{2+} = 0.85 \times Fe^{3+}$) vs. depth for Hole 735B. Samples are subdivided mainly on the basis of TiO_2. Filled diamonds = troctolite and olivine gabbro having less than 0.4 wt% TiO_2; half-filled diamonds = gabbro, gabbonorite, and disseminated-oxide gabbro having between 0.4 and 1.0 wt% TiO_2; open diamonds = Fe-Ti oxide gabbro with more than 1.0 wt% TiO_2; half-filled squares = felsic samples or hybrid samples with a significant felsic component. Filled triangle is a sample from a basaltic dike.

Figure 17. Weight percent TiO_2 vs. depth in Hole 735B. Symbols as in Figure 16.

Figure 18. A. Late magmatic and crystal-plastic foliation intensities plotted with total vein intensities downhole for Hole 735B. No data exist for the upper 500 m of Hole 735B for magmatic foliation. **B.** Stereoplots for structures in Hole 735B cores. Poles to foliation are plotted in the reference frame of the core liner, with the strong azimuthal orientation reflecting careful

cutting of cores orthogonal to foliation and consistent placement in the core liners for description with respect to foliation dip. **C.** Representative photomicrographs of magmatic foliation, high-temperature (granulite grade) crystal-plastic foliation, and low-temperature cataclastic deformation.

Figure 19. Close-up photograph of reverse fault (interval 176-735B-149R-3, 48–94 cm).

Figure 20. Stable thermal remanent magnetism, magnetic susceptibility, and inclination for Hole 735B after demagnetization of minicores.

Figure 21. Multisensor track log of magnetic susceptibility for all cores from the Leg 176 section of Hole 735B. Measurements are filtered to eliminate empty section of core liner, leaving in excess of 22,000 measurement points. Inset shows correlations between individual peaks and lithologies in a section of core from 1072 to 1084 mbsf.

Figure 22. Comparison of discrete sample bulk density and velocity with percent recovery downhole.

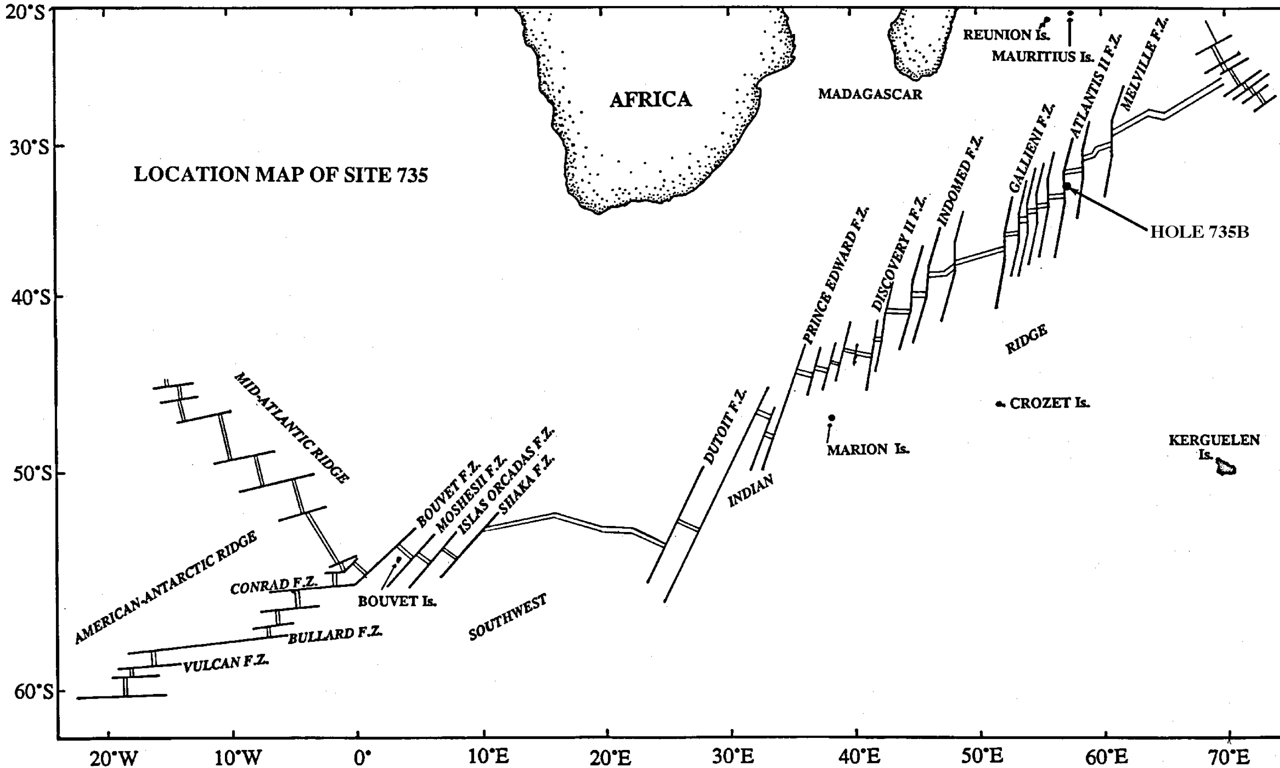

LOCATION MAP OF SITE 735
AFRICA
MADAGASCAR
REUNION Is.
MAURITIUS Is.
MELVILLE F.Z.
ATLANTIS II F.Z.
GALLIENI F.Z.
INDOMED F.Z.
DISCOVERY II F.Z.
PRINCE EDWARD F.Z.
HOLE 735B
RIDGE
CROZET Is.
MARION Is.
KERGUELEN Is.
DUTOIT F.Z.
INDIAN
MID-ATLANTIC RIDGE
BOUVET F.Z.
MOSHESII F.Z.
ISLAS ORCADAS F.Z.
SHAKA F.Z.
AMERICAN-ANTARCTIC RIDGE
CONRAD F.Z.
BOUVET Is.
SOUTHWEST
BULLARD F.Z.
VULCAN F.Z.
20°S
30°S
40°S
50°S
60°S
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
60°E
70°E

Figure 1

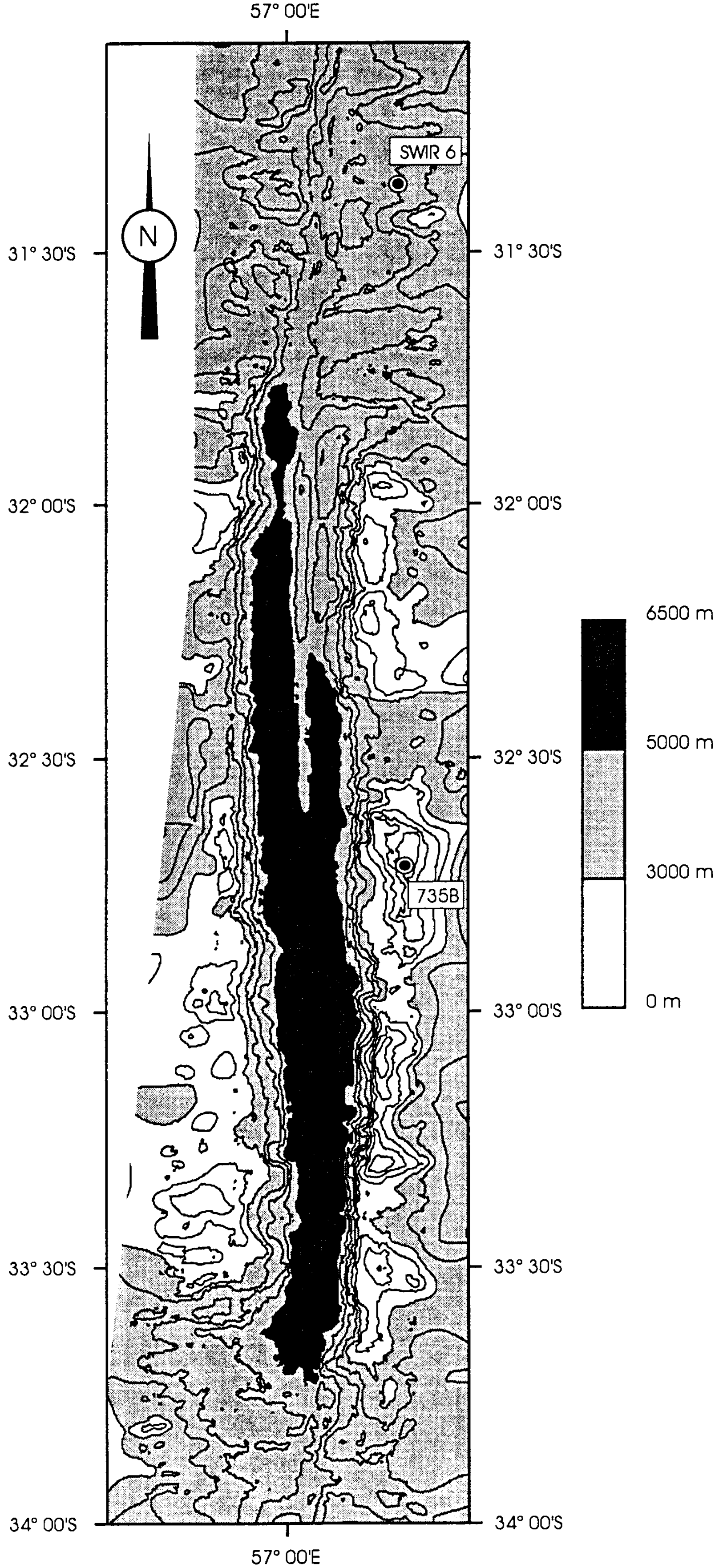
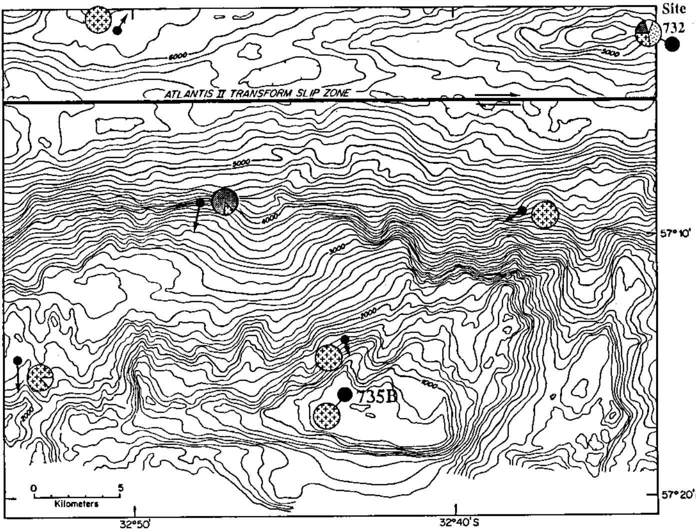

57° 00'E
SWIR 6
N
31° 30'S
32° 00'S
32° 30'S
735B
33° 00'S
33° 30'S
34° 00'S
6500 m
5000 m
3000 m
0 m

Figure 2

A


Site
732
6000
5000
ATLANTIS II TRANSFORM SLIP ZONE
3000
4000
3000
2000
1000
735B
2000
0
5
Kilometers
57°10'
57°20'E
32°50'
32°40'S

B

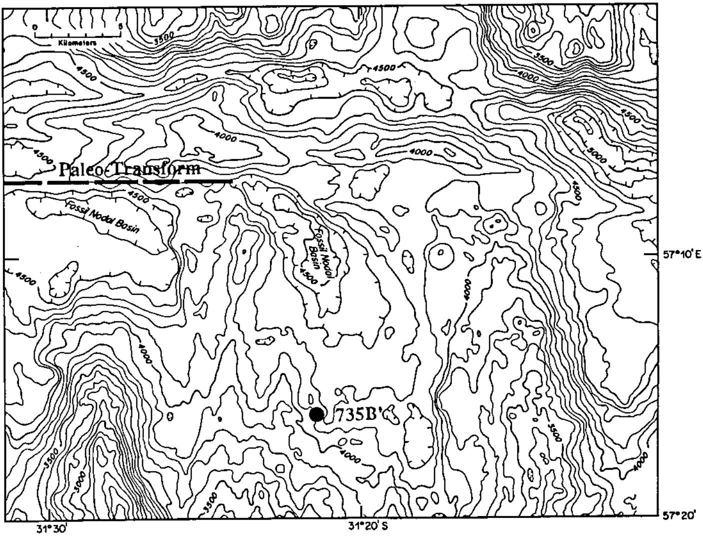

0
5
Kilometers
3500
4500
4000
Paleo-Transform
Fossil Nodal Basin
Fossil Nodal Basin
735B'
3000
57°10'E
57°20'
31°30'
31°20'S

Figure 3

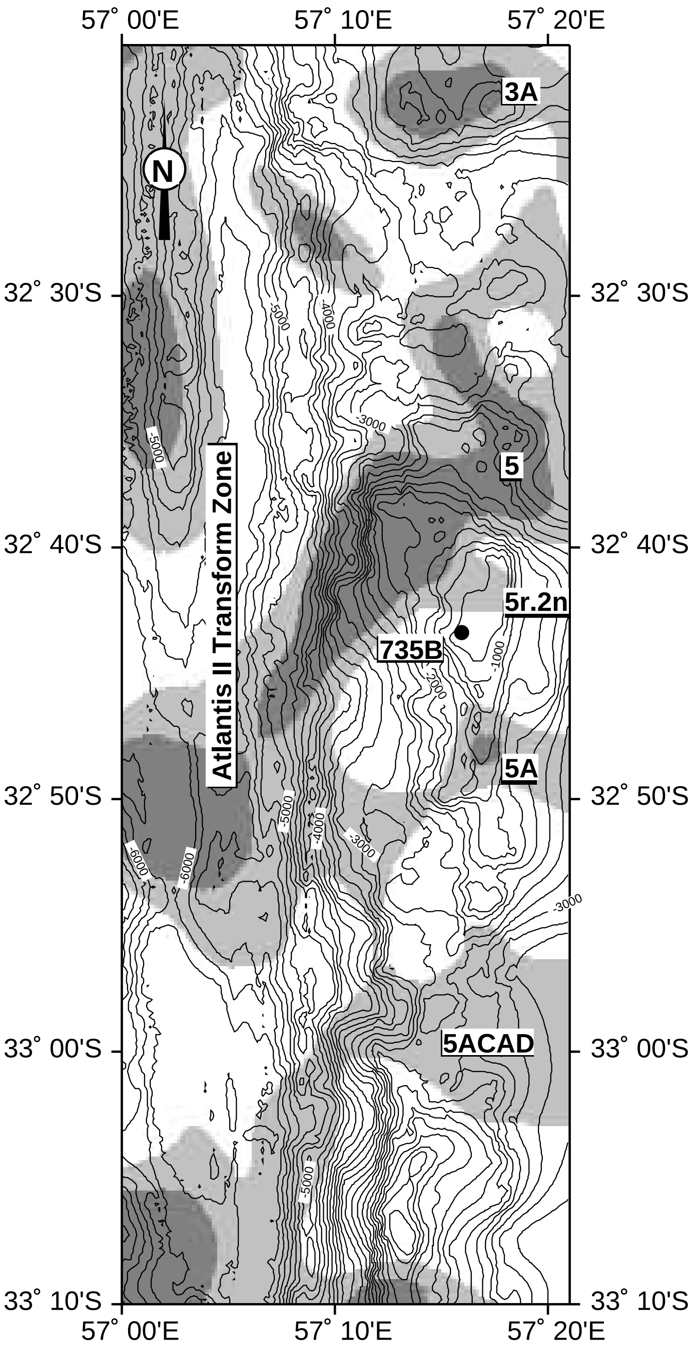
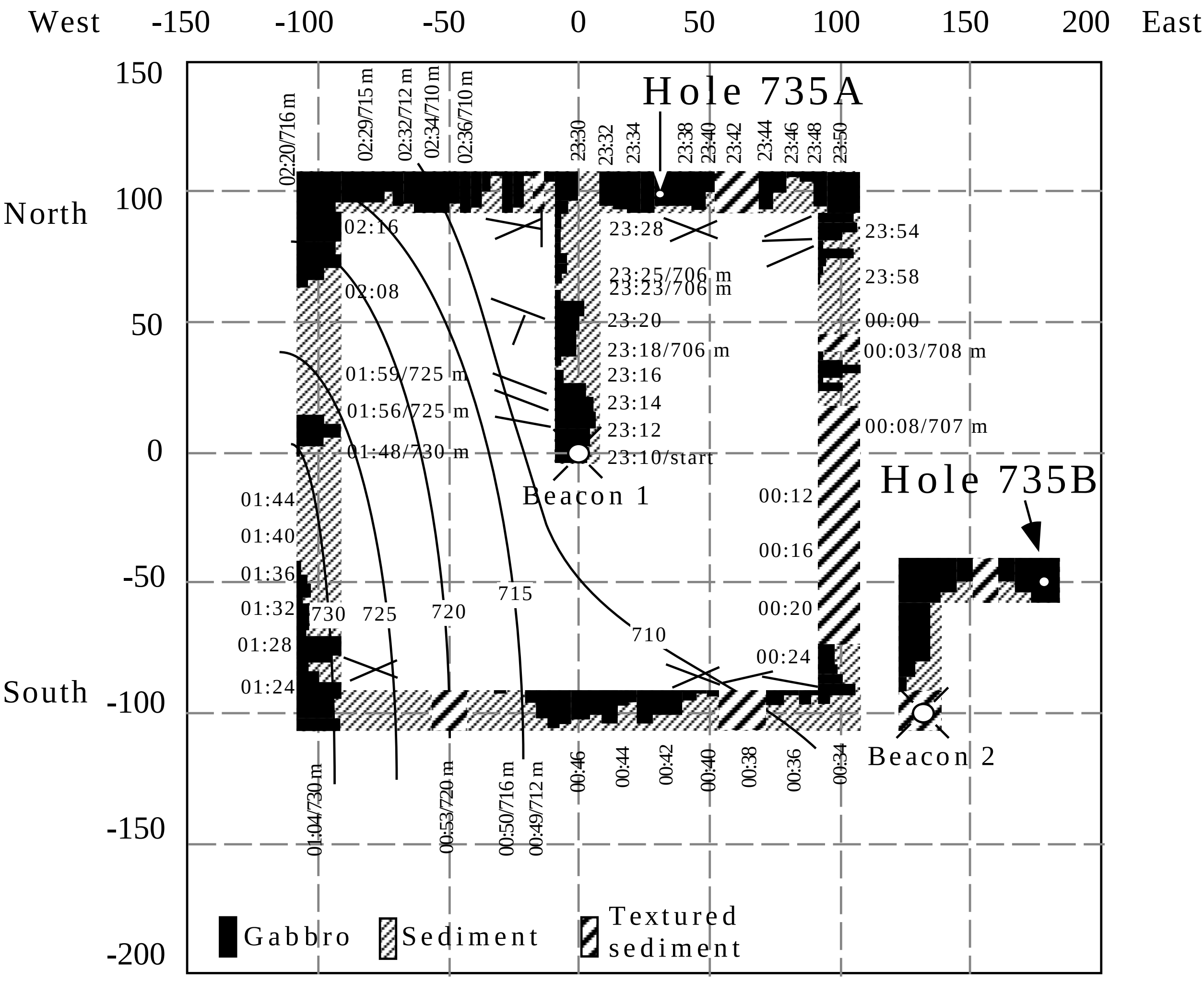

57° 00'E
57° 10'E
57° 20'E
32° 30'S
32° 40'S
32° 50'S
33° 00'S
33° 10'S
N
3A
5
5r.2n
735B
5A
5ACAD
Atlantis II Transform Zone
-5000
-4000
-3000
-2000
-1000
-6000

Figure 4



West
-150
-100
-50
0
50
100
150
200
East
150
100
50
0
-50
-100
-150
-200
North
South
Hole 735A
Hole 735B
02:20/716 m
02:29/715 m
02:32/712 m
02:34/710 m
02:36/710 m
23:30
23:32
23:34
23:38
23:40
23:42
23:44
23:46
23:48
23:50
02:16
02:08
01:59/725 m
01:56/725 m
01:48/730 m
23:28
23:25/706 m
23:23/706 m
23:20
23:18/706 m
23:16
23:14
23:12
23:10/start
23:54
23:58
00:00
00:03/708 m
00:08/707 m
00:12
00:16
00:20
00:24
Beacon 1
Beacon 2
01:44
01:40
01:36
01:32
01:28
01:24
730
725
720
715
710
01:04/730 m
00:53/720 m
00:50/716 m
00:49/712 m
00:46
00:44
00:42
00:40
00:38
00:36
00:34
Gabbro
Sediment
Textured sediment

Figure 5

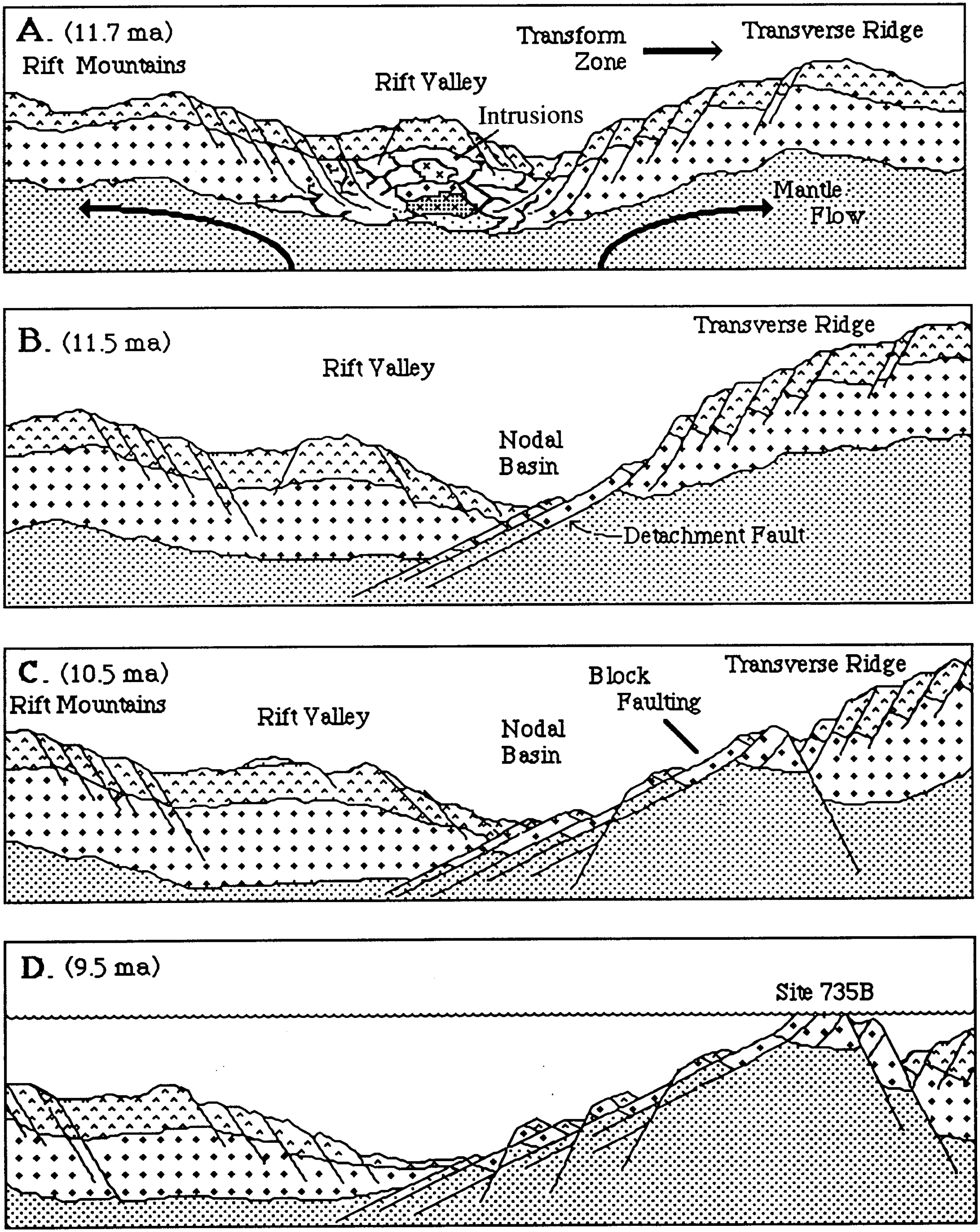
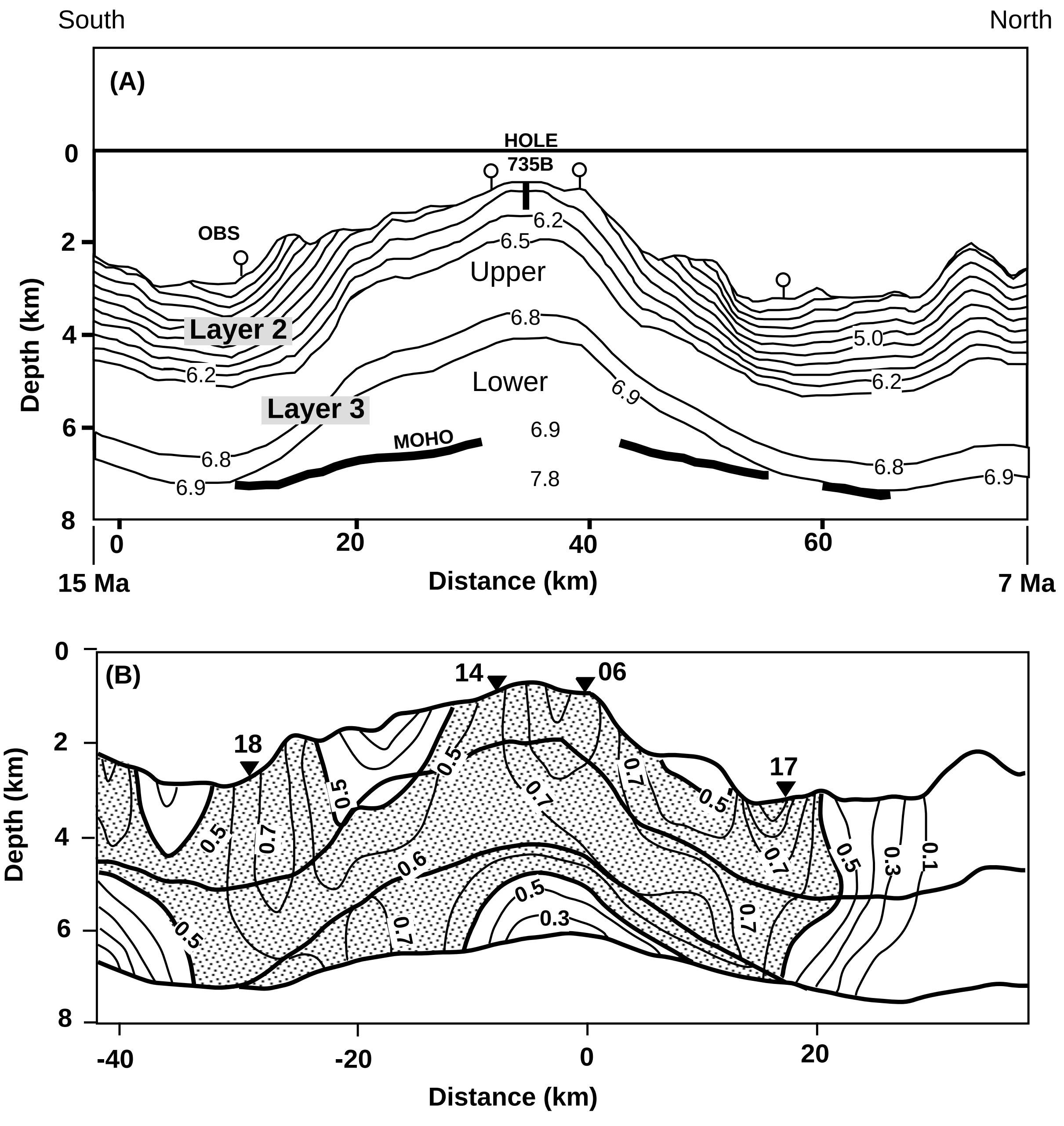
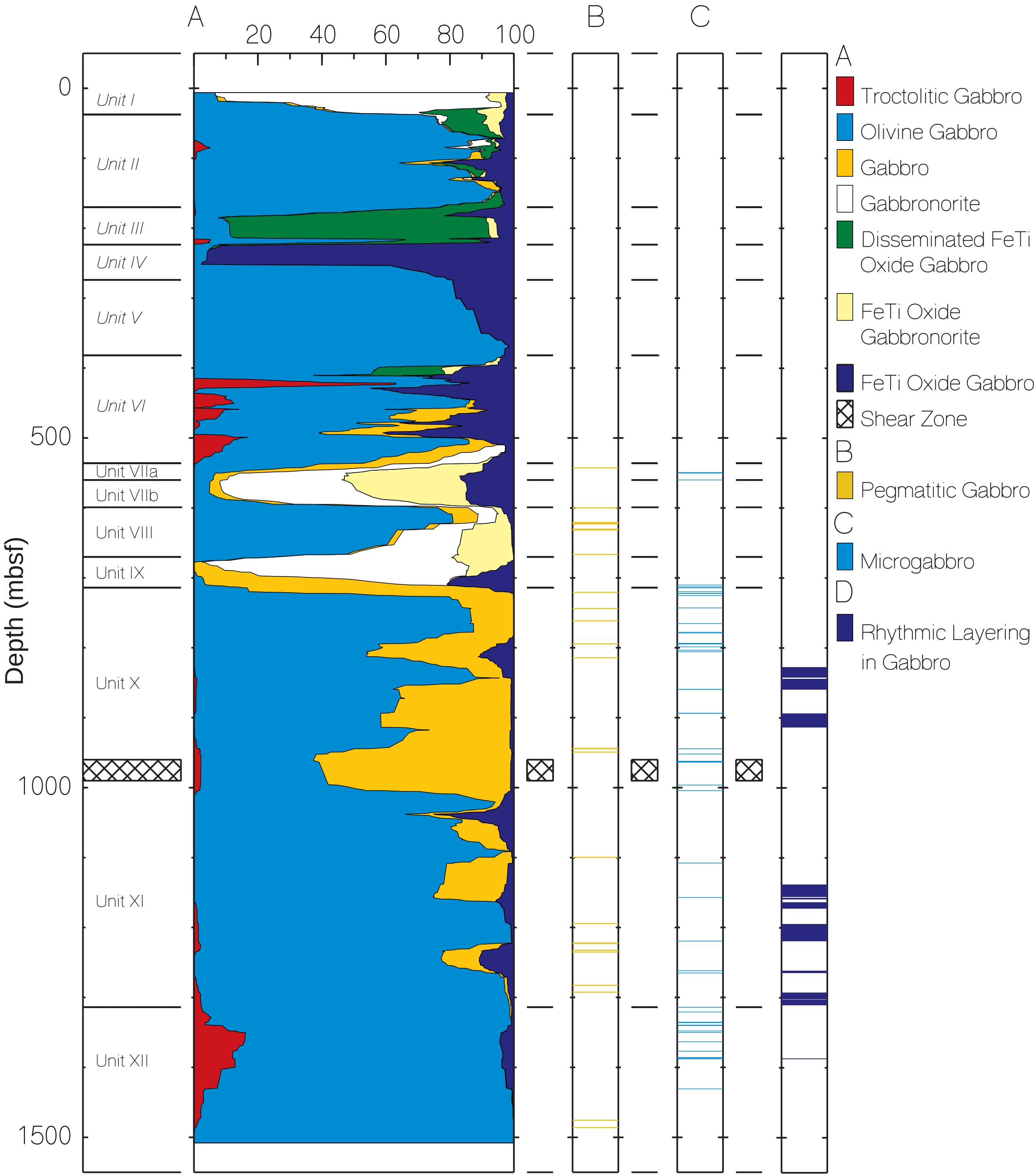

A. (11.7 ma)
Rift Mountains
Rift Valley
Intrusions
Transform Zone
Transverse Ridge
Mantle Flow
B. (11.5 ma)
Rift Valley
Transverse Ridge
Nodal Basin
Detachment Fault
C. (10.5 ma)
Rift Mountains
Rift Valley
Nodal Basin
Block Faulting
Transverse Ridge
D. (9.5 ma)
Site 735B

Figure 6



South
North
(A)
HOLE
735B
OBS
6.2
6.5
Upper
Layer 2
6.8
5.0
6.2
Lower
6.9
Layer 3
MOHO
6.9
6.8
6.9
7.8
6.8
6.9
Depth (km)
Distance (km)
15 Ma
7 Ma
(B)
14
06
18
17
0.5
0.7
0.6
0.3
0.1
Depth (km)
Distance (km)

Figure 7



A
20
40
60
80
100
B
C
Depth (mbsf)
0
500
1000
1500
Unit I
Unit II
Unit III
Unit IV
Unit V
Unit VI
Unit VIIa
Unit VIIb
Unit VIII
Unit IX
Unit X
Unit XI
Unit XII
A
Troctolitic Gabbro
Olivine Gabbro
Gabbro
Gabbronorite
Disseminated FeTi Oxide Gabbro
FeTi Oxide Gabbronorite
FeTi Oxide Gabbro
Shear Zone
B
Pegmatitic Gabbro
C
Microgabbro
D
Rhythmic Layering in Gabbro

Figure 8

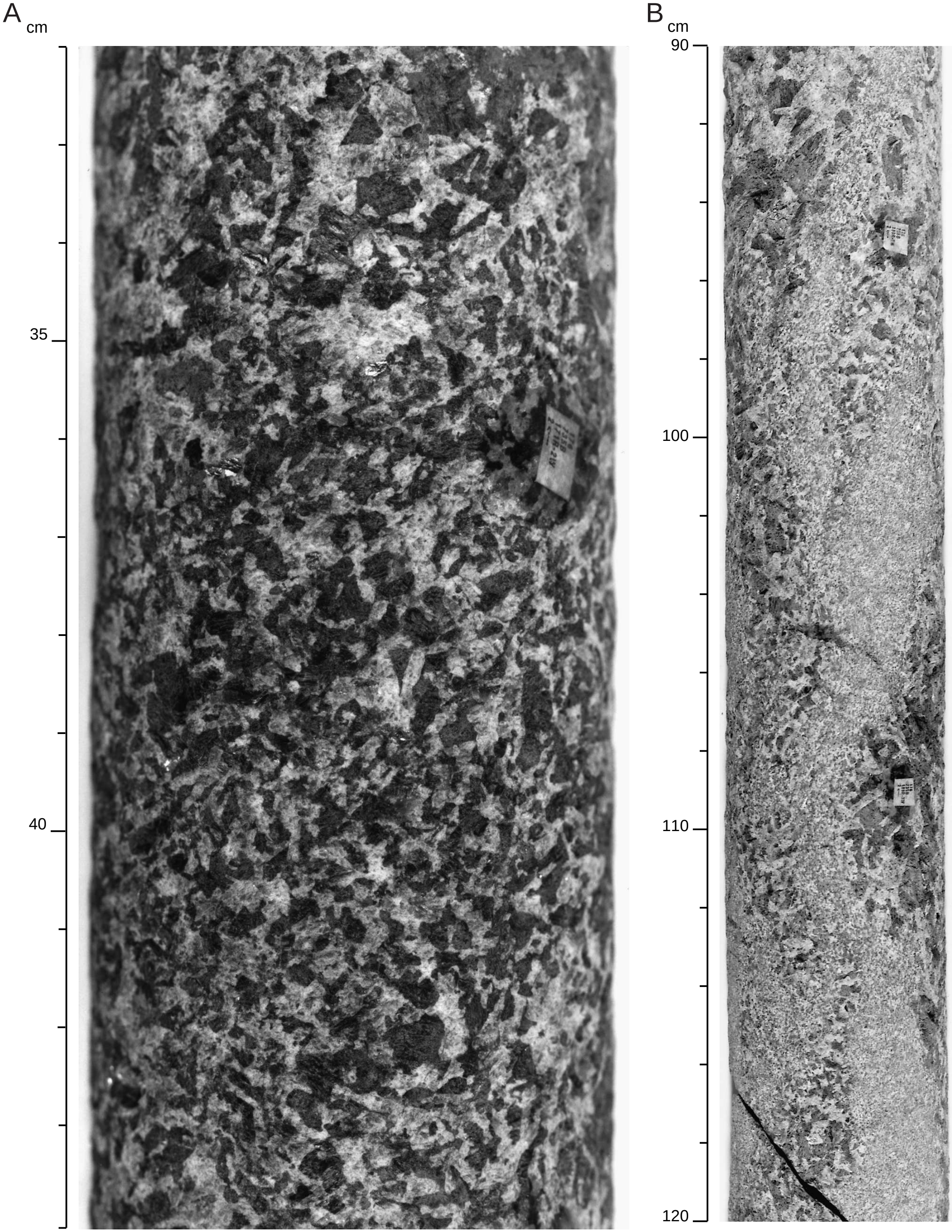


Figure 9A

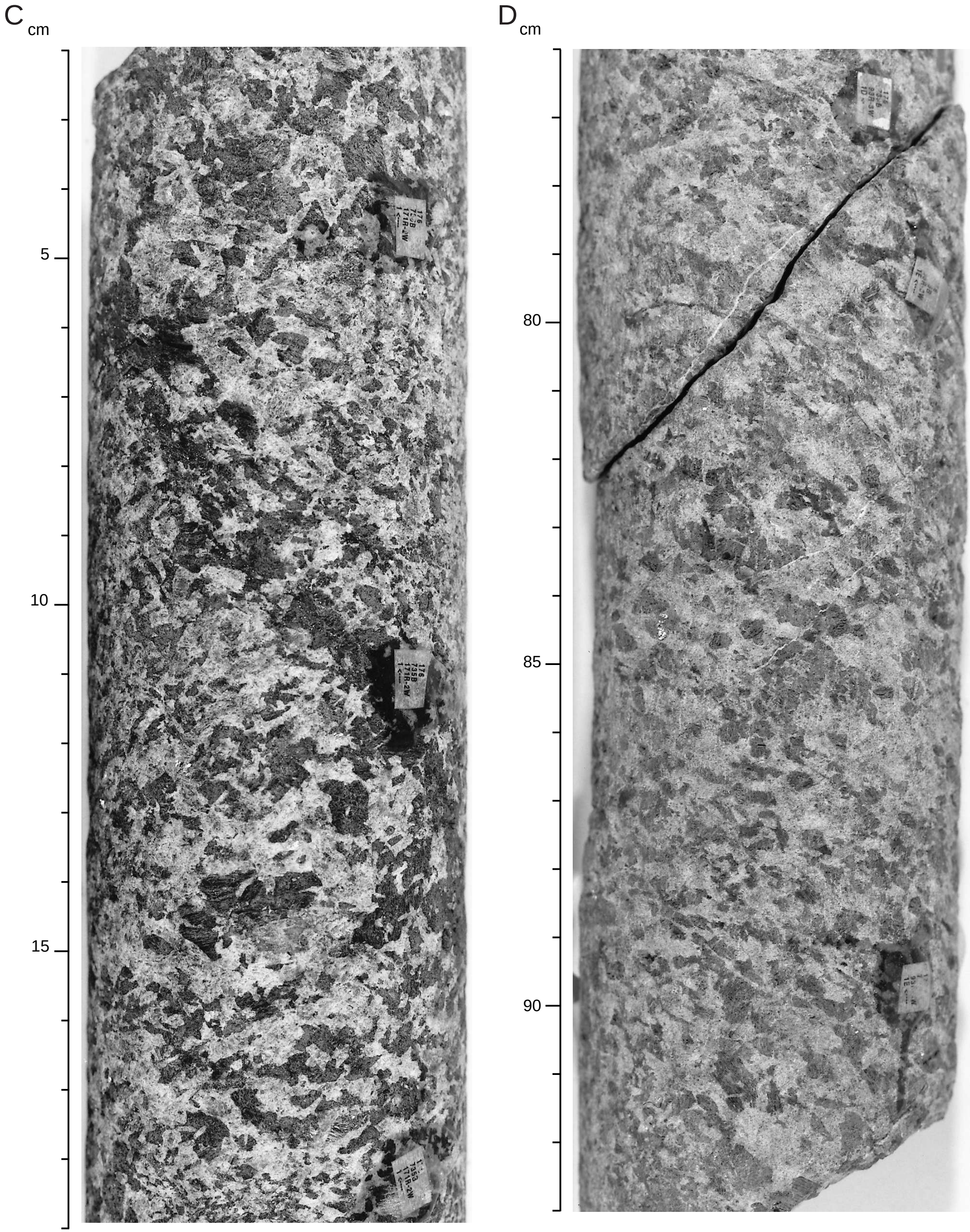


Figure 9B

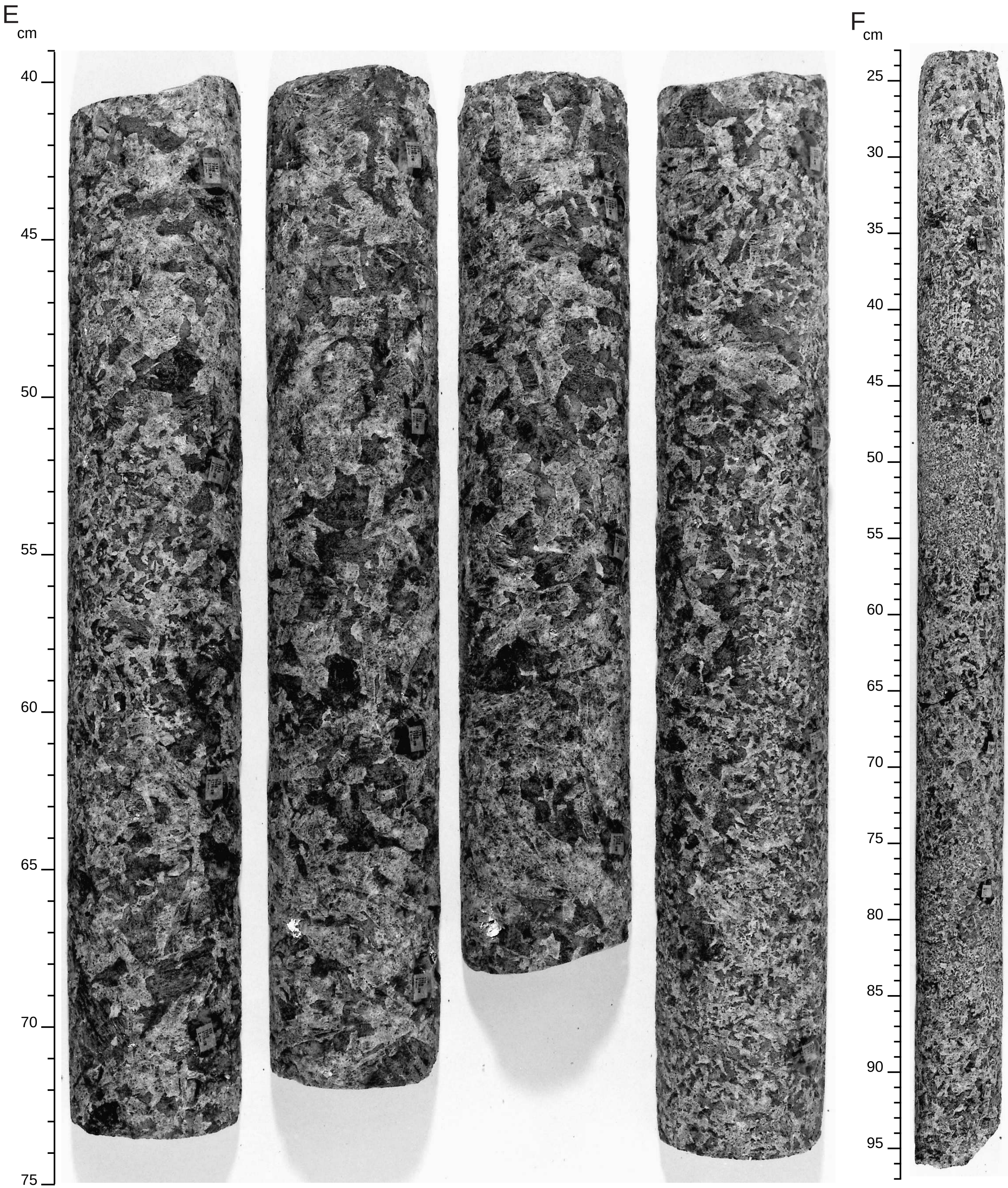
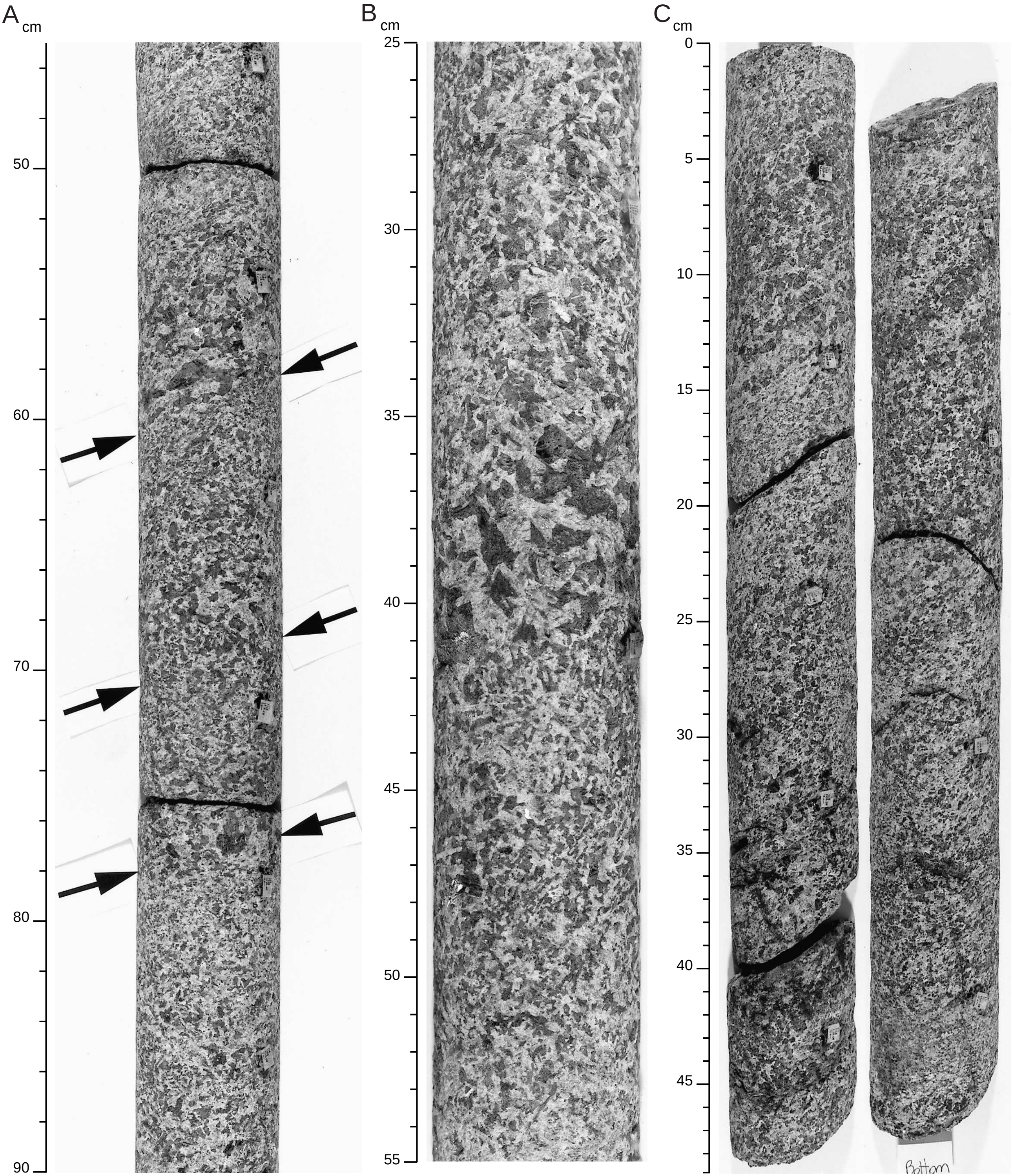

E
cm
40
45
50
55
60
65
70
75
F
cm
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

Figure 9C



A cm
50
60
70
80
90
B cm
25
30
35
40
45
50
55
C cm
0
5
10
15
20
25
30
35
40
45
Bottom

Figure 10

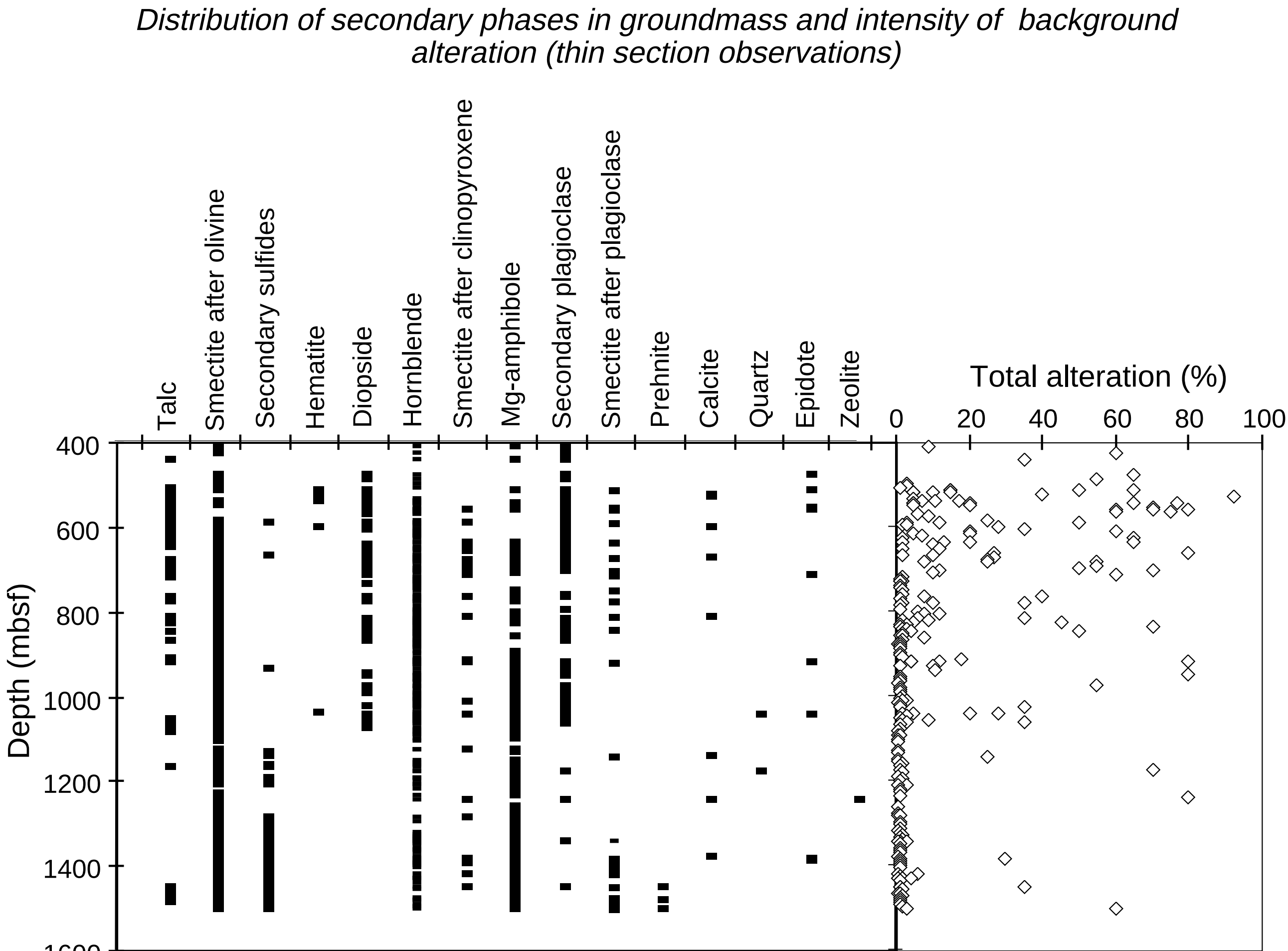

Distribution of secondary phases in groundmass and intensity of background alteration (thin section observations)
Talc
Smectite after olivine
Secondary sulfides
Hematite
Diopside
Hornblende
Smectite after clinopyroxene
Mg-amphibole
Secondary plagioclase
Smectite after plagioclase
Prehnite
Calcite
Quartz
Epidote
Zeolite
Total alteration (%)
0
20
40
60
80
100
400
600
800
1000
1200
1400
1600
Depth (mbsf)

Figure 11

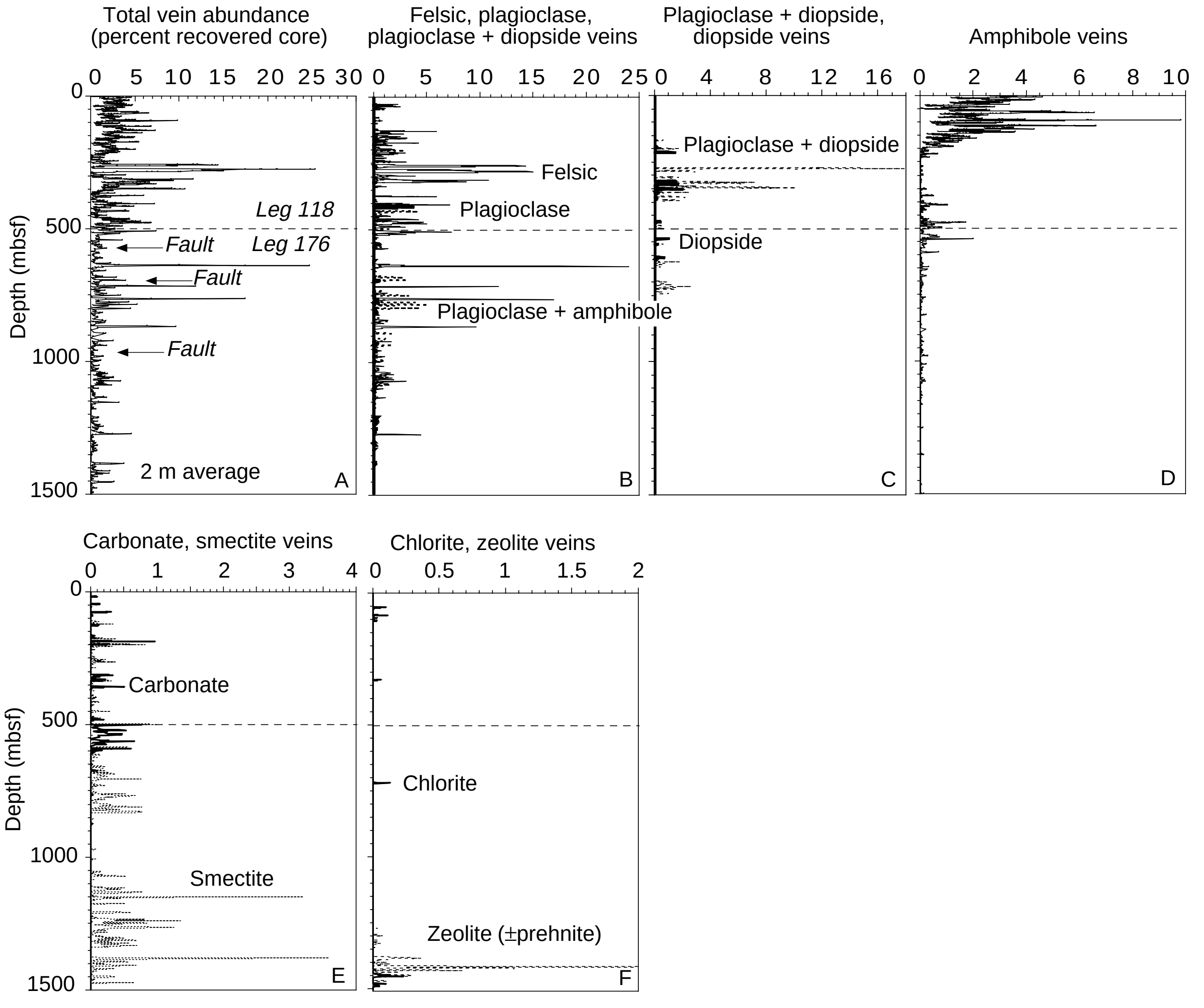

Total vein abundance (percent recovered core)
0 5 10 15 20 25 30
Depth (mbsf)
0
500
1000
1500
Leg 118
Leg 176
Fault
Fault
Fault
2 m average
A
Felsic, plagioclase, plagioclase + diopside veins
0 5 10 15 20 25
Felsic
Plagioclase
Plagioclase + amphibole
B
Plagioclase + diopside, diopside veins
0 4 8 12 16
Plagioclase + diopside
Diopside
C
Amphibole veins
0 2 4 6 8 10
D
Carbonate, smectite veins
0 1 2 3 4
Carbonate
Smectite
E
Chlorite, zeolite veins
0 0.5 1 1.5 2
Chlorite
Zeolite (±prehnite)
F

Figure 12

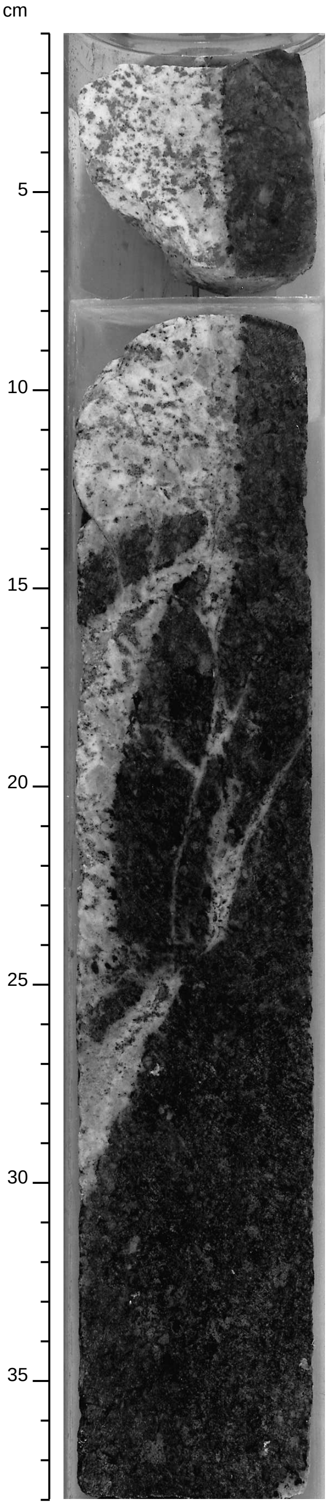


Figure 13

Figure 14

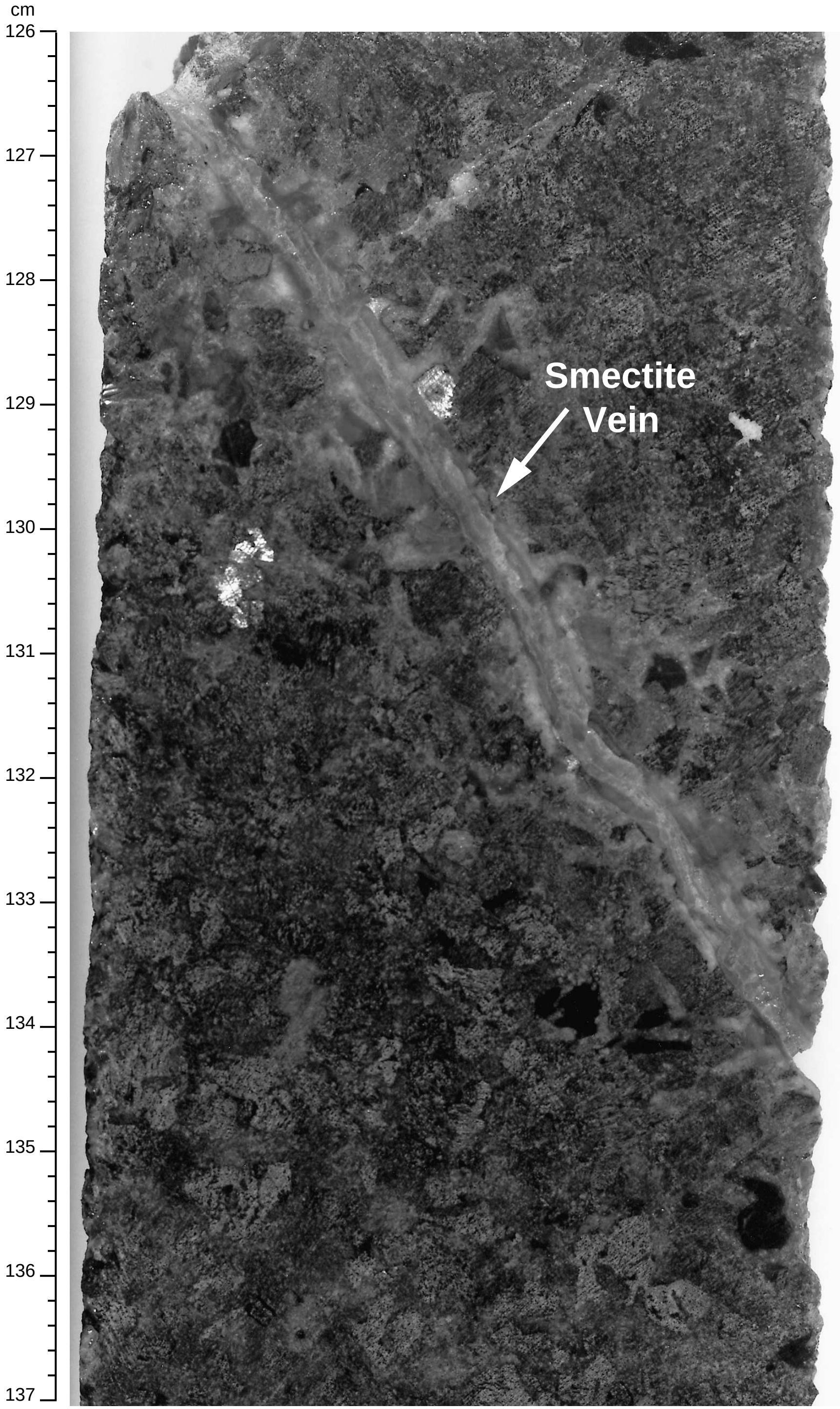

cm
126
127
128
129
130
131
132
133
134
135
136
137
Smectite Vein

Figure 15

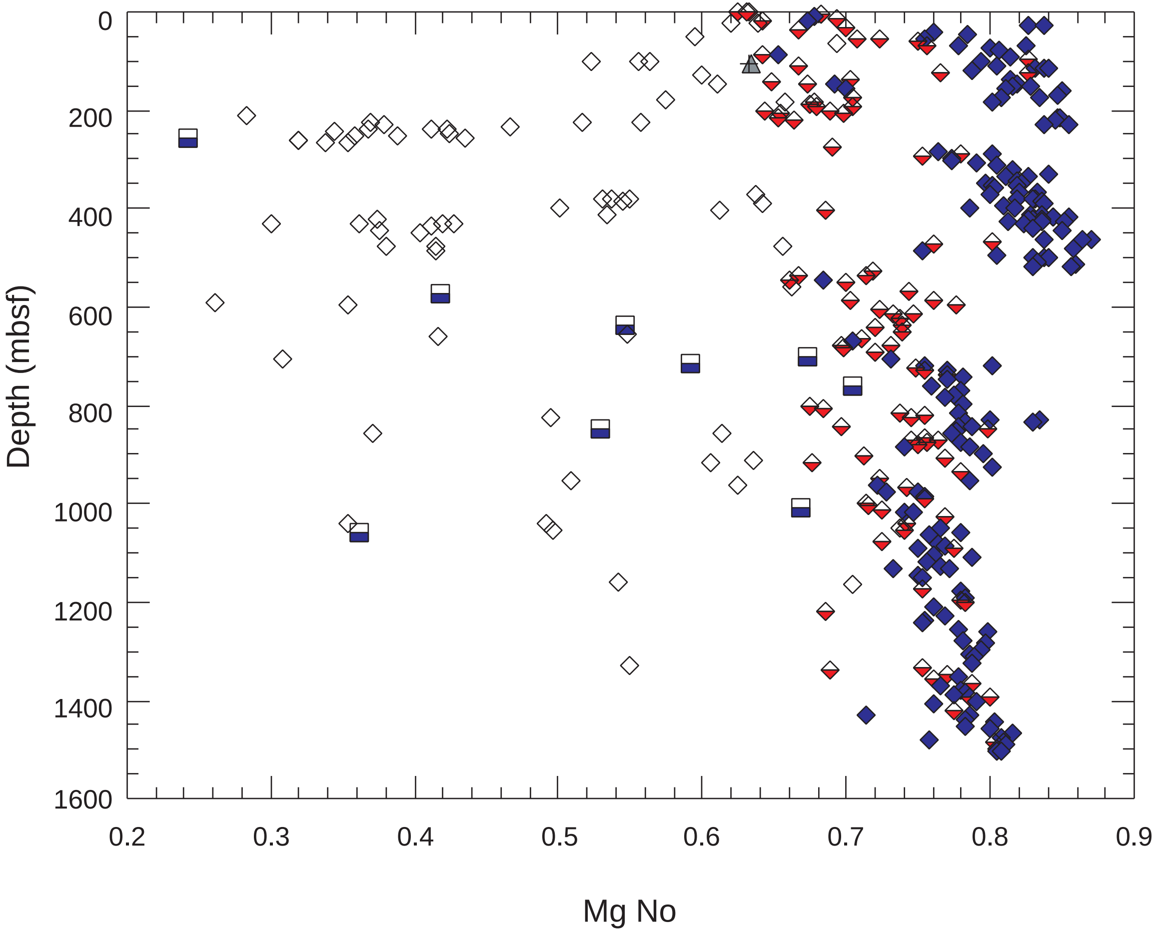

Depth (mbsf)
0
200
400
600
800
1000
1200
1400
1600
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Mg No

Figure 16

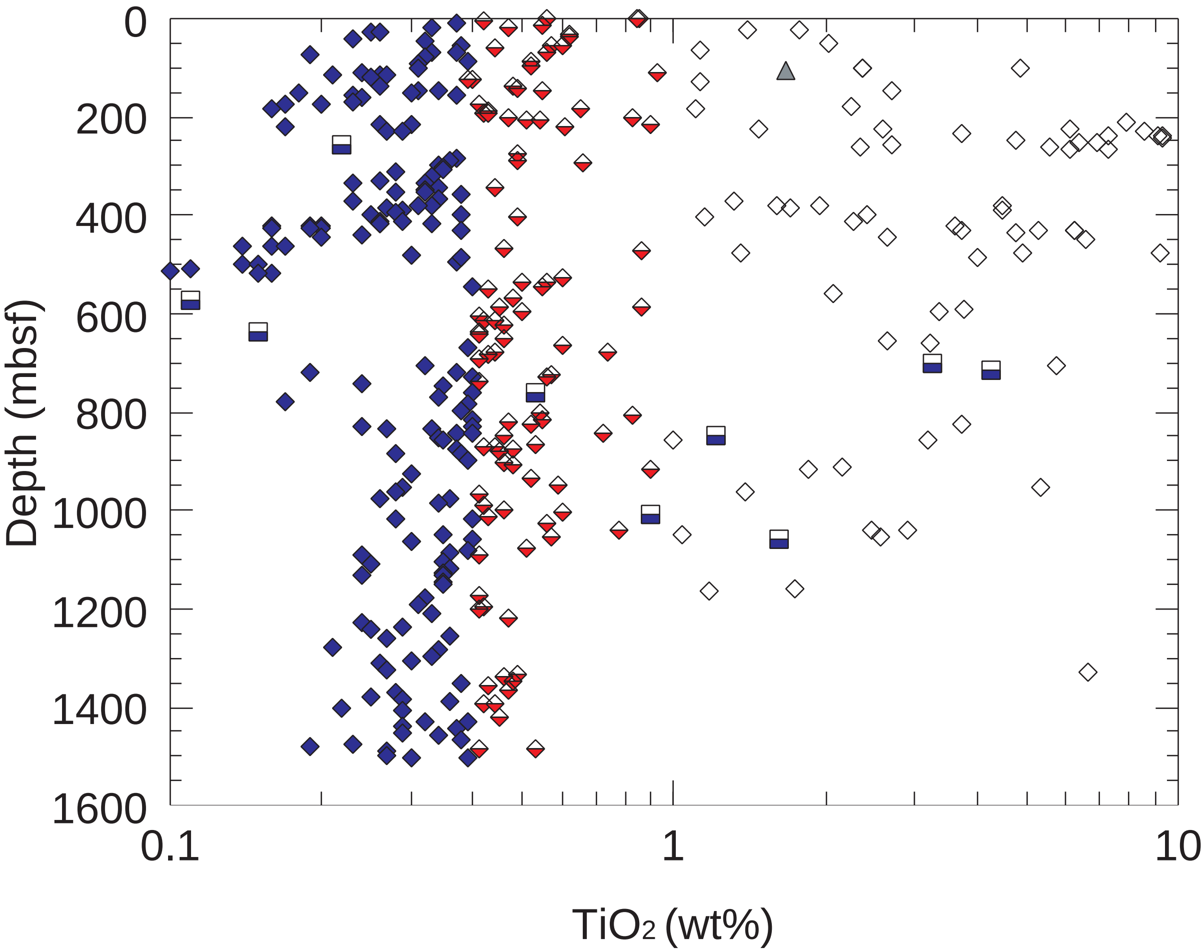
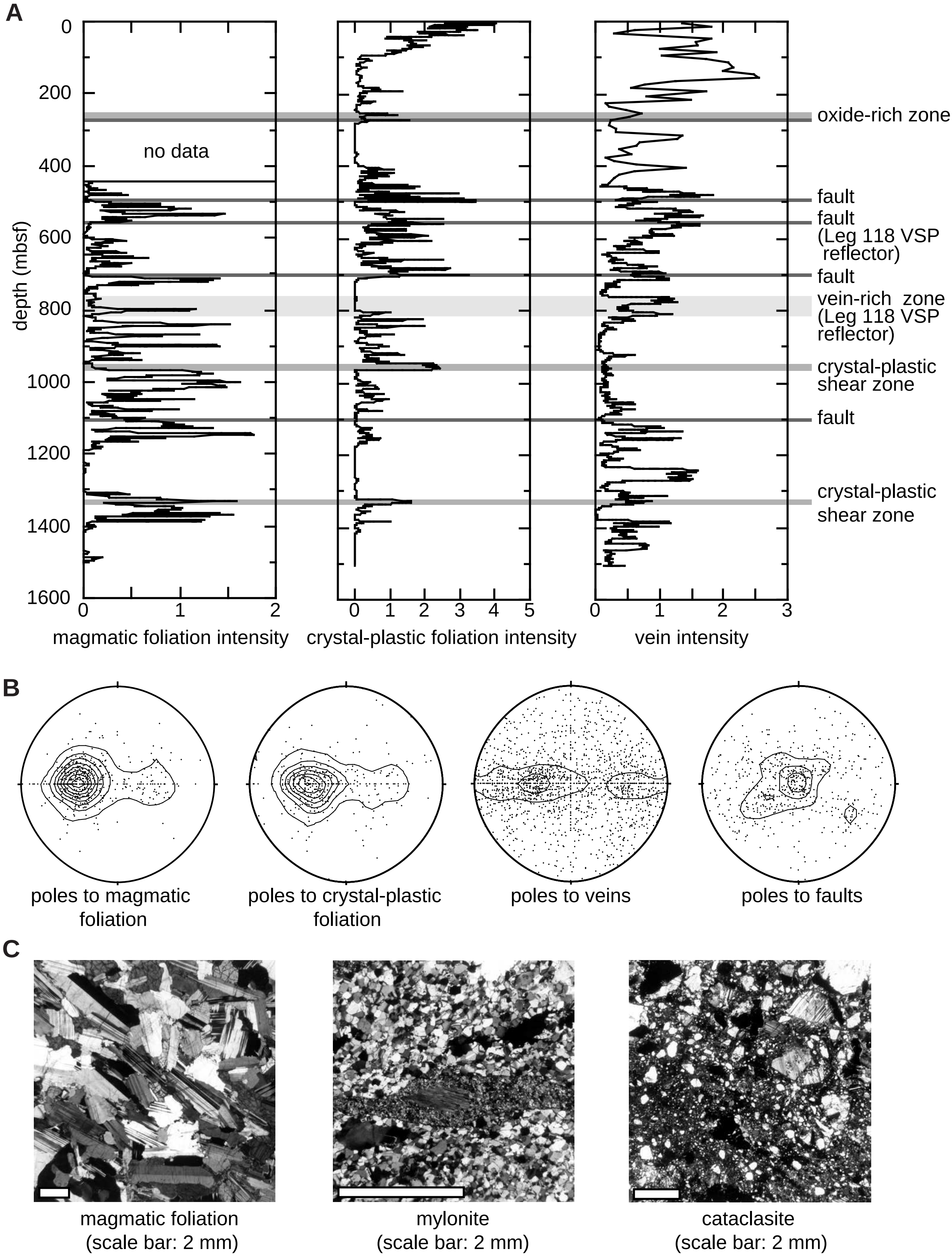


Figure 17



A
no data
depth (mbsf)
0
200
400
600
800
1000
1200
1400
1600
magmatic foliation intensity
crystal-plastic foliation intensity
vein intensity
oxide-rich zone
fault
fault
(Leg 118 VSP
reflector)
fault
vein-rich zone
(Leg 118 VSP
reflector)
crystal-plastic
shear zone
fault
crystal-plastic
shear zone
B
poles to magmatic
foliation
poles to crystal-plastic
foliation
poles to veins
poles to faults
C
magmatic foliation
(scale bar: 2 mm)
mylonite
(scale bar: 2 mm)
cataclasite
(scale bar: 2 mm)

Figure 18

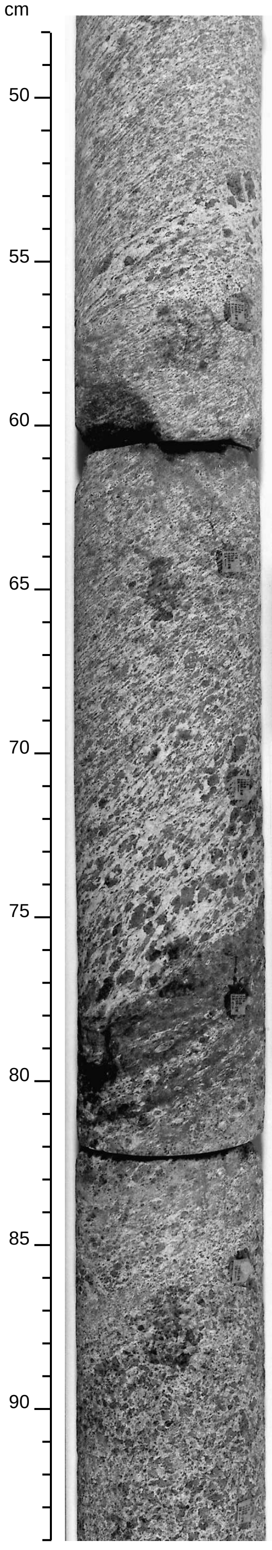


Figure 19

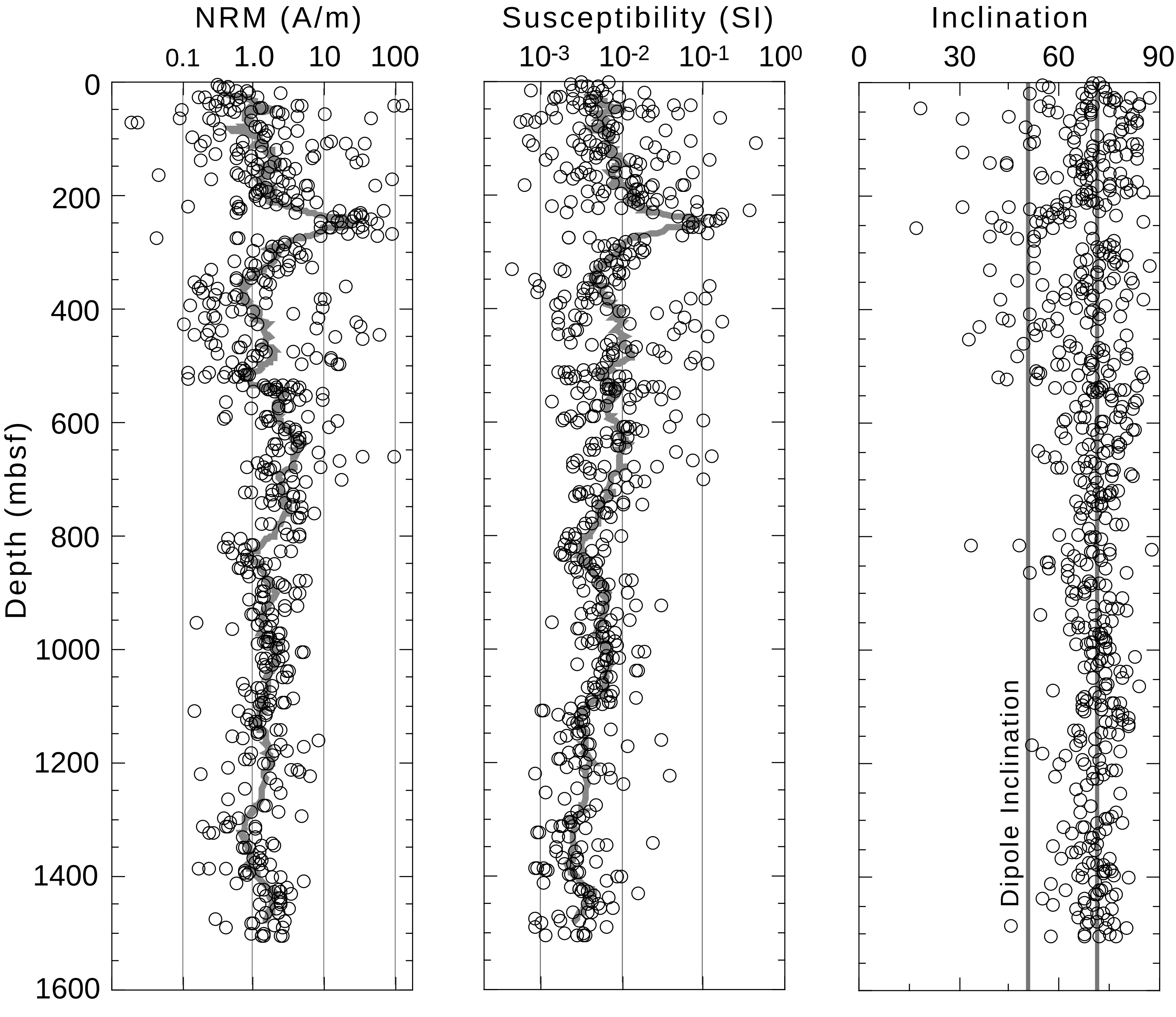
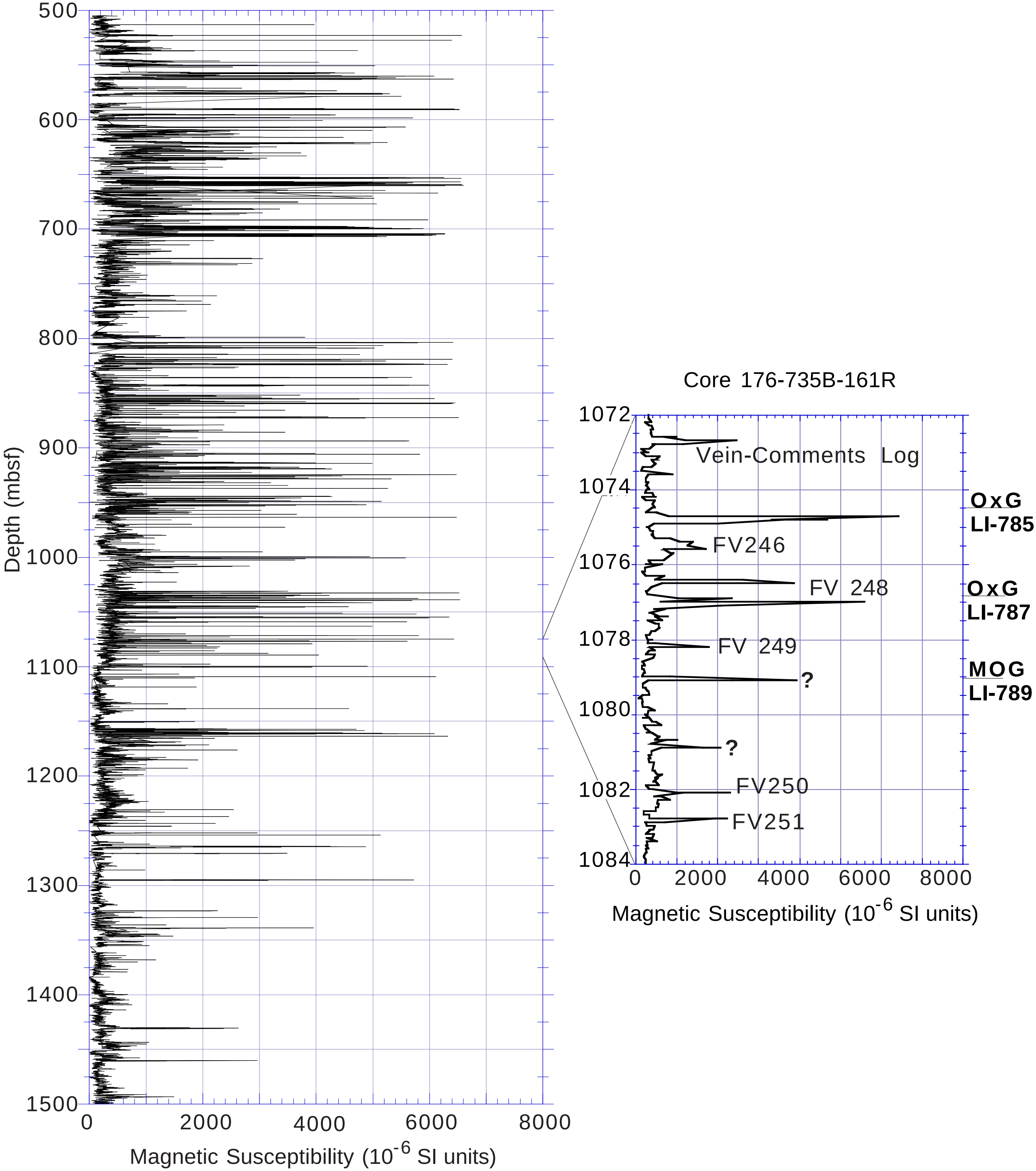
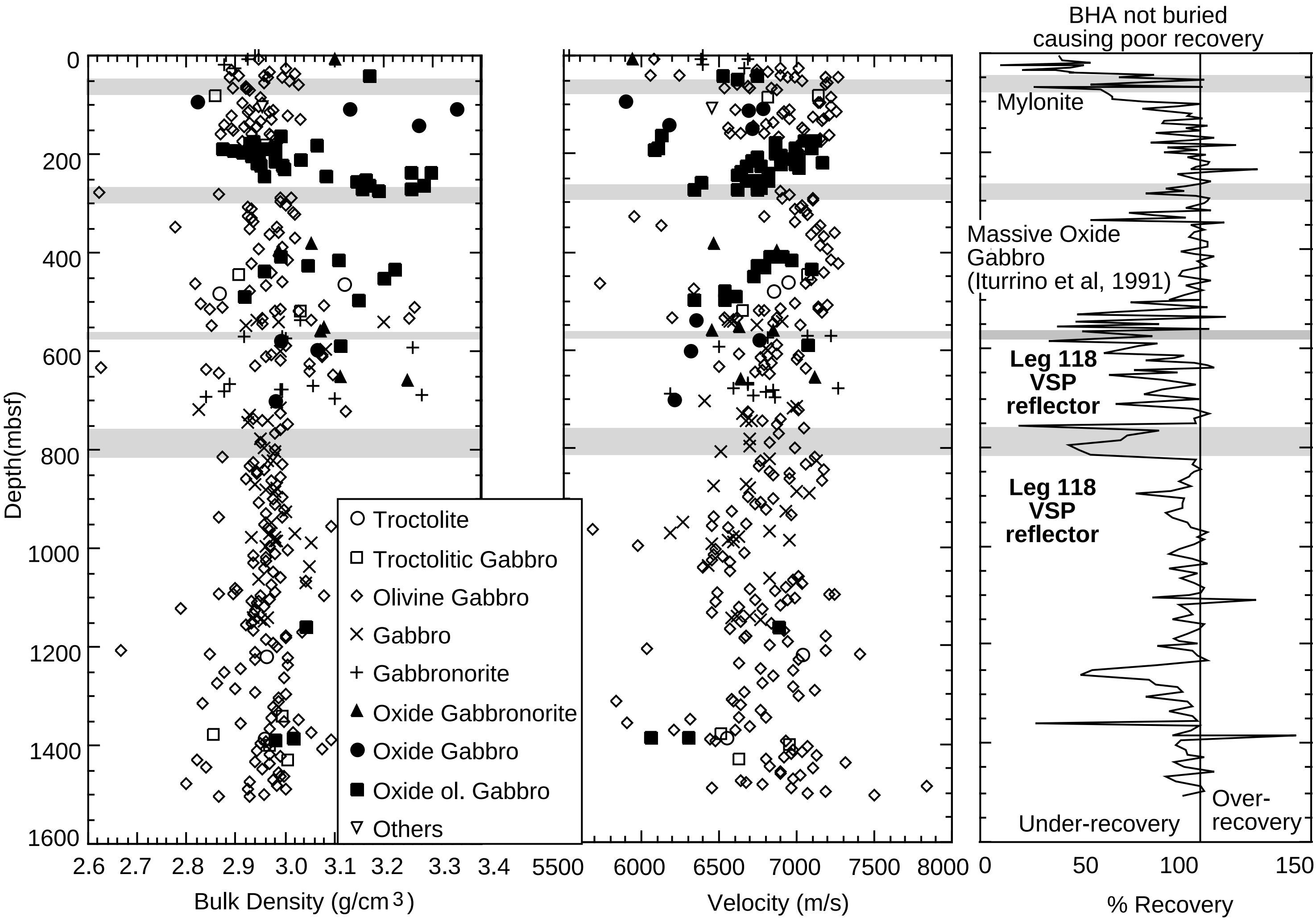

NRM (A/m)
0.1
1.0
10
100
Susceptibility (SI)
10^{-3}
10^{-2}
10^{-1}
10^{0}
Inclination
0
30
60
90
Depth (mbsf)
0
200
400
600
800
1000
1200
1400
1600
Dipole Inclination

Figure 20



Depth (mbsf)
500
600
700
800
900
1000
1100
1200
1300
1400
1500
0
2000
4000
6000
8000
Magnetic Susceptibility (10-6 SI units)
Core 176-735B-161R
1072
1074
1076
1078
1080
1082
1084
Vein-Comments Log
FV246
FV 248
FV 249
?
?
FV250
FV251
OxG
LI-785
OxG
LI-787
MOG
LI-789
0
2000
4000
6000
8000
Magnetic Susceptibility (10-6 SI units)

Figure 21



BHA not buried
causing poor recovery
Mylonite
Massive Oxide
Gabbro
(Iturrino et al, 1991)
Leg 118
VSP
reflector
Leg 118
VSP
reflector
Under-recovery
Over-
recovery
Troctolite
Troctolitic Gabbro
Olivine Gabbro
Gabbro
Gabbronorite
Oxide Gabbronorite
Oxide Gabbro
Oxide ol. Gabbro
Others
Depth(mbsf)
Bulk Density (g/cm3)
Velocity (m/s)
% Recovery

Figure 22

OPERATIONS SYNOPSIS

The ODP Operations and engineering personnel aboard *JOIDES Resolution* for Leg 176 were

Operations Manager:	Michael Storms
Schlumberger Engineer:	Michael O'Connell

OVERVIEW AND SIGNIFICANT ACCOMPLISHMENTS

Leg 176 began two days earlier than scheduled in Cape Town, South Africa, with the first line ashore at 1000 hr on 8 October 1997 and ended at 1130 hr 9 December 1997 with the first line ashore, again in Cape Town, South Africa.

Leg 176 drilling operations were quite different from most ODP legs. We conducted all drilling operations at a single site in a single hole. Hole 735B was first established during Leg 118. On that leg, a hard rock base (HRB) was set in 731 m of water and a 9-7/8" hole was cored to a depth of 500 meters below seafloor (mbsf). Another 0.7 m of penetration was made on that leg using the 3-3/4" Navidril core barrel (NCB), establishing a "cored" total depth of 500.7 mbsf. During Leg 176, we set out to reoccupy Hole 735B and deepen it to 1500 mbsf or as deep as possible.

By the end of the leg, Hole 735B was deepened from 1235.8 meters below rig floor (mbrf) or 504.8 mbsf to a total depth (TD) of 2239.0 mbrf or 1508.0 mbsf. We have not established why the Leg 176 tag depth was 4.8 m deeper than the total depth documented at the end of Leg 118.

The rotary core barrel (RCB) wireline coring system was used exclusively during the leg. A total of 10 RCB C-7 core bits resulted in the recovery of 122 cores. We cored a total of 1003.2 m of new hole recovering 865.99 m of core or 86.3% of the section. Penetration rates varied from 1.3 to 6.1 m/hr in the gabbro and olivine gabbro formations. Coring was faster in coarse-grained rocks and highly fractured intervals. The slower rates were experienced in the more massive, finer grained, foliated rocks. The average rate of penetration (ROP) for the leg was 2.7 m/hr. We took drift measurements at eight stations between 500 and 1400 mbsf. Hole deviation based on the Tensor electronic multishot data was moderate, varying between 4.3° and 4.8°. A total of 31 reentries were made into Hole 735B during the course of the leg at an average of 0.3 hr per reentry.

Our progress in the hole ended when a 5" drill pipe connection failed leaving 43-2/3 stands of 5" drill pipe and a coring bottom-hole assembly (BHA) in the hole (1403 m). The failure occurred when the pipe was 97 m off bottom during a routine wiper trip to replace wear-knotted drill pipe with standard 5-1/2" drill pipe. We engaged the fish on our first attempt with a 9-1/2" overshot dressed with a 6-7/8" basket grapple and mill control. It was being lifted to its total weight of 130,000 lb when the fish parted in the tube of the fished 5" drill pipe. The failure point coincided with the point at which the pipe had buckled upon impact with the bottom of the hole. We ultimately recovered 497 m of 5" drill pipe. The fish remaining in the hole (906 m) consists of 26 stands of 5" drill pipe (734 m) plus the coring BHA (172 m). We made seven unsuccessful fishing attempts over a period of 7.4 days, before abandoning attempts to clear the hole. Allowing for the junk in the hole, the current TD is 1337 mbrf or 606 mbsf.

The drill string was not the only thing broken during Leg 176. Several historical records were broken as well. Leg 176 recovered more hard rock (866 m) than any other hole in the history of ODP or the predecessor Deep Sea Drilling Project (DSDP), nearly doubling the previous Leg 118 record of 434 m. We also cored more than twice the hard rock (1003 m) of any other single leg, shattering the previous Leg 118 record of 501 m. Hole 735B is now the fifth deepest hole in ODP history. In addition, Hole 735B now qualifies as the third longest single-hole continuously cored interval (mud or rock) in ODP history.

We conducted logging operations in two phases. The first phase (to 492 mbsf) was done after the initial reentry into the hole before commencing coring operations. It included the triple-combo (natural gamma sonde [NGS], accelerator porosity sonde [APS], hostile environment lithodensity sonde [HLDS], and the dual laterolog [DLL]) plus temperature log. The second string included the NGS, the dipole shear sonic imager (DSI), and the formation microscanner (FMS). We aborted this logging run, however, due to data acquisition difficulties.

We conducted the second phase of logging plus VSP experiments after abandoning attempts to fish the hole. The first tool string consisted of the HLDS, caliper, APS, and the hostile environment spectral natural gamma sonde (HNGS). The second logging run consisted of the natural gamma tool (NGT), DSI, general purpose inclinometry tool (GPIT), and the FMS. The third tool string was composed of the NGT, GPIT, and DLL probes.

During the first logging run, we obtained good density, porosity, and gamma-ray measurements from 49 mbsf to 595 mbsf or 11 m above the hole obstruction at 606 mbsf. The second logging run (DSI-FMS) resulted in good data recorded by the DSI. Cross-dipole and *P* and *S* wave mode data were recorded during the first pass and cross-dipole, upper dipole, and Stoneley modes during the second pass. The FMS, however, did not fare as well. After spending some time testing different gain options to improve the data quality from the FMS, we opted to recover the tool and repeat the logging run with a replacement FMS. Unfortunately, the results from the second tool run were similar to those recorded with the first tool. A possible explanation for the poor response is that the tools could not respond quickly enough to the extreme resistivity contrasts between the Fe-Ti oxide gabbros and the olivine gabbros. The deployment of the third tool string resulted in very good resistivity data with the DLL.

The fourth and final logging run consisted of the Schlumberger Seismos Prakla VSP tool (borehole geometry kit tool [BGKT]). The objectives of the VSP were to acquire data over the section of hole not covered by the Leg 118 VSP and to acquire better VSP data using the new tool. We hoped that better quality data would perhaps resolve sub-bottom reflectors below 1500 mbsf and perhaps give better observations of the seismic attenuation at the site. The VSP operation took about 16 hr from rig floor to rig floor. We shot both air gun and water gun sources to the sonde clamped at 23 depths in the hole. The tool did not give appreciably better data than was acquired on Leg 118, but we did fill in the coverage between 500 and 600 mbsf.

After concluding the wireline logging and VSP exercises, we round tripped the drill string one last time for a final fishing attempt. The fish was contacted ~2 m deeper than before at 1339 mbrf or 608 mbsf. During subsequent working of the pipe we contacted the fish at the shallower depth; however, all attempts at engagement proved futile. We abandoned our last fishing attempt at 1400 hr 1 December 1997 and began preparations to get under way for Cape Town, South Africa. We departed Hole 735B at 1900 hr 1 December 1997.

PORT CALL - CAPE TOWN I

The pacing item of the port call was the installation of a new Global Maritime Distress Safety System (GMDSS) radio. Manufactured in Denmark, this system is mandated for installation on all ocean-going vessels by February 1999. The installation for the *JOIDES Resolution* was accelerated so the new system would be operational for the forthcoming high-latitude legs. The many benefits of the GMDSS include expanded coverage; continual reception of weather forecasting, navigation, and safety broadcasts; and quick/easy distress signal broadcasting of Global Positioning System (GPS) location coordinates.

Off-loaded goods included four 40' refrigerated containers containing core samples and four "scrap" core liner boxes. Because the off-going freight volume was low, the TAMU surface freight was consolidated with that of Ocean Drilling, Ltd. (ODL) in a single 40' container. Radioactive sources, lithium batteries, and a frozen shipment of samples were also off loaded for shipment to their respective destinations.

Hardware and equipment taken aboard during the port call included two boxes of core liners, two 40' containers of routine hardware and supplies, two reconditioned positioning beacons (S.N. 2025 and S.N. 2030), and three tilt beacons (S.N. 1039, S.N. 1040, and S.N. 1137) for use with the HRB, and two flats of ancillary HRB hardware. Bulk products loaded included 18 metric tons (MT) of Bentonite gel (delivered in P-trucks) and 78 MT of Sepiolite in 1.0 MT bags. Another 27 MT were stored in Cape Town for loading prior to Leg 177. In addition, the fuel tanks were topped off with 1800 MT of marine gas oil.

We conducted private VIP tours of the vessel on the first day of port call, followed by a reception for various dignitaries at the Capetonian Hotel. Public tours were conducted on the second day.

TRANSIT TO SITE 735

At 1300 hr Wednesday 15 October 1997, we passed the last line ashore and headed out of Table Bay, Cape Town harbor. At 1346 hr, we discharged the pilot and got under way at full speed for Site 735.

Rough seas rounding the Cape of Good Hope, strong headwinds, and the effects of the Agulhas Current slowed our transit; however, we ultimately accomplished the 2003 nmi transit to Site 735 in 9.0 days at an average speed of 9.3 kt. Propulsion motor P-17A was taken off line during the transit due to armature damage when a field coil failed. The engineers rebuilt the unit while on site, and it was placed back on line prior to our departure for Cape Town. We were also forced to reduce speed for approximately 1 hr using manual steering and magnetic compass for heading when an emergency generator test caused a malfunction of the Automatic Station Keeping (ASK) system. This system is linked to the ship’s gyro compass. The problem was ultimately traced to a dead cell in the ASK backup battery bank. Subsequent system testing was successful once the bad battery was replaced. Besides routine Preventative Maintenance System (PMS) tasks, the installation of a rig-floor waste collection system was completed during the transit and efforts continued on the installation/testing of a new waste burning incinerator system required for the forthcoming Antarctic expeditions.

We arrived on location Friday, 24 October 1997, and at 1345 hr, the first positioning beacon was dropped using the 10-yr-old Satellite Navigation (SatNav) coordinates (32°43.395'S Latitude, 57°15.959'E Longitude) for Hole 735B.

SITE 735

Locating Hole 735B

We immediately went to work making up an outer core barrel assembly and four stands of 8-1/4" drill collars. Three stands were racked back in the derrick because our first pipe trip used only a single stand of drill collars in the bottom-hole assembly (BHA) for logging the existing 500-m-deep hole. After tripping the drill string to the seafloor, we deployed the vibration-isolated television (VIT) camera and began searching for Hole 735B. Because this hole was being reoccupied and the seafloor depth was known to be 731.0 m, we did not require a Precision Depth Recorder (PDR) reading. In less than 1 hr, using an expanding-box search pattern, we located the guidebase deployed on Leg 118. Final GPS location coordinates for Hole 735B were ultimately determined to be 32°43.3928'S and 57°15.9606'E or ~5 m away from the original coordinates of 10 yr ago.

Initial Logging of Hole 735B

At 2000 hr on 24 October 97, we reentered Hole 735B; however, we encountered resistance almost immediately at a depth of 736 m (5 mbsf). We pulled clear of the seafloor, picked up the top drive, and using slow rotation reentered for the second time at 2130 hr. This time the end of the drill string was placed at a logging depth of 780 m (49 mbsf) without incident.

We initiated logging operations with the triple-combo consisting of the NGS, APS, HLDS, and the DLL probes. We also obtained temperature data using the Lamont-Doherty Earth Observatory (LDEO) temperature tool. The first logging run advanced to 492 mbsf or just 8 m short of the total depth of 500.0 mbsf. Our second logging run included the NGS, DSI, and the FMS. We had to abort this run because of data acquisition difficulties. We completed the first phase of logging operations by 1700 hr 25 October 1997.

Following a pipe trip to change over to a coring BHA, we again reentered Hole 735B and ran to bottom. The top drive was used at several points in the hole; however, minimal resistance was encountered on the trip because the last core recovered on Leg 118 was taken with the motor-driven core barrel (MDCB), we expected the lowermost 0.7 m of the hole to be under gauge for RCB operations. The bit tagged bottom at 504.8 mbsf, or 4.8 m below the depth that RCB coring ended on Leg 118, and 4.1 m below the depth of MDCB drilling. This discrepancy between the depth to the bottom of the hole recorded at the end of Leg 118 and the depth at which Leg 176 coring operations began remains unexplained.

Core Bit Number 1

We began continuous coring operations with Core 176-735B-89R at a total depth of 1235.8 m or 504.8 mbsf. The coring BHA consisted of a 9.875" x 2.313" C-7 tungsten carbide insert roller cone bit with 4 x 16 jets, an RCB outer core barrel assembly, eight each 8-1/4" drill collars, one set of mechanical drilling jars, two 8-1/4" drill collars, a tapered drill collar, and two stands of 5-1/2" drill pipe. We used a 20-ft drilling knobby and wear-knotted drill pipe at the top of the string through the upper/lower guide horn.

Our first cored interval advanced only 3.0 m to reach the proper place on the drilling kelly for a pipe connection. We followed this with two full length (9.6 m) cores. Partial cores (ranging in length from 3.7 to 8.0 m) were taken beginning with Core 176-735B-92R because of the extremely slow ROP. Core jammed inside the acetate butyrate core liners for three cores in a row, so beginning with Core 176-735B-96R, we deployed the core barrels without liners and continued this procedure for the remainder of the leg. We used Bentonite gel mud exclusively, circulating the mud in 20-30 bbl sweeps every core or every second core as required to enhance hole cleaning. This mud program was typical for the leg. No fill was noted when making connections, and no hole problems were identified. Upon recovering Core 176-735B-96R, we observed that the core catchers and cored material were missing. The threaded connection between the core catcher sub and the 11-1/8" inner barrel sub unscrewed, leaving the core barrel components and core material inside the pipe just above the bit. Either the connection had not been made up tightly enough or the 6.2 hr rotating time had vibrated the connection loose. We decided that attempting to fish the items out of the pipe would be futile, so the bit run was ended at a depth of 556.3 mbsf. We tripped the pipe back to the surface. The bit cleared the rig floor at 2145 hr and Core 176-735B-96R was recovered from the pipe. We found the core bit to be in good condition except for the inner (nose) row of carbide buttons. One of these was worn back nearly to the matrix material. The remaining cutting structure was in excellent condition as were the bearings. With the first core bit, we cored 51.5 m and recovered 34.32 m (66.6%) in 25.9 bit-rotating hours. The average ROP was 2.0 m/hr.

Core Bit Number 2

Using the same BHA configuration and a new C-7 core bit, we function tested the mechanical drilling jars and ran in the hole (RIH). We deployed the subsea television camera and reentered the HRB in less than 15 min of ship maneuvering. These quick (15 min) reentries proved to be the rule for the remainder of the leg. In this case, the driller again could not induce the bit into the hole, and another reentry had to be made with the top drive picked up. On the second attempt, we reentered the HRB at 0300 hr 28 October 1997 and using slow top drive rotation we "walked" the bit into the off-center hole without incident. Coring began with Core 176-735B-97R from 556.3 mbsf. Coring on this bit run was impacted by large long-period swells, which translated into rig floor heaves of 2.0 to 3.0 m, making it difficult for the driller to maintain optimum weight-on-bit (WOB). The seas moderated on the third day, but by then it was time to pull the bit for replacement. Our original goal was to obtain a minimum of 40 rotating hours on this bit, but because of the large load fluctuations experienced, we decided to be conservative and terminate coring operations slightly earlier than planned. In addition, the pump pressure was elevated for the final three cores and we suspected that two of the bit jets may have become plugged. We suspended coring after cutting Core 176-735B-111R to a depth of 642.7 mbsf. The pipe was tripped back to the surface and the bit cleared the rig floor at 0930 hr on 30 October 1997. The core bit was again found to be in good condition except for the inner (nose) row of carbide buttons. These were worn back nearly to the matrix material. Two jets were plugged in the bit with a combination of cuttings and Teflon bit seal material. In addition, we identified a 5" crack extending longitudinally outward from the base of the pocket in the drilling jar body. With the second bit, we cored 86.4 m and recovered 64.05 m (74.1%) in 36.0 rotating hours. The average ROP was 2.4 m/hr.

Core Bit Number 3

We ran in the hole with a new C-7 core bit and a new set of mechanical drilling jars making another 15-min reentry at 1350 hr 30 October 1997. We ran to bottom and found 8 m of loose fill at total depth (TD). We initiated coring with Core 176-735B-112R at 642.7 mbsf. Our goal on this run was to replace the bit after completing Core 176-735B-124R; however, observations of core tapering and some suspicious markings in Core 176-735B-123R halted operations after only 3.4 m of advance on Core 176-735B-124R. With the hole depth at 752.1 mbsf, we tripped the pipe back to the surface, clearing the rig floor at 0530 hr on 2 November 1997. Surprisingly, we again found the bit to be in good condition with effective bearing seals and no sign of imminent catastrophic failure. The internal cutter wear was more advanced than seen on the two earlier bits. The inner (nose) row of carbide buttons was completely worn back into the matrix material, and one of the two opposite cutters with three carbide inserts also was worn back to the matrix material. In addition, some wear was evident at the tip of the core guide, indicating that ROP would have begun to suffer soon. With the third bit, we cored 109.4 m and recovered 96.43 m (88.1%) in 43.8 bit rotating hours. The average ROP was 2.5 m/hr.

Core Bit Number 4

As a precaution, because of the earlier cracking incident, we again laid out the drilling jars for nondestructive testing (NDT) inspection and pressure testing prior to running them back in the hole with the fourth core bit. During the NDT inspection, we identified small crack indications initiating from the two corners at the base of each pocket in the jar body. We set these jars aside and because the remaining set of drilling jars had not yet passed pressure testing, this BHA was made up without jars. At 0845 hr 2 November 1997, we reentered the hole and ran to 742.0 mbsf or ~10 m off bottom. Using the Tensor electronic multishot tool we conducted a wireline drift survey from 742.0 mbsf to 500.0 mbsf. Six measurements were made at 50-m increments, and a hole deviation of 4.5°+ 0.3° was measured. Upon completing the survey, we began coring Core 176-735B-125R from 752.1 mbsf. While cutting Core 176-735B-136R, we noted a drop in circulating pressure of 100 psi and assumed that the RCB bit seal had failed. Although the bit continued to recover gauge core and advanced at a respectable penetration rate, we decided to again be conservative and pull the bit after 46.8 hr. We halted coring after recovering Core 176-735B-

140R to 889.3 mbsf. The bit arrived at the rig floor by 0500 hr 5 November 1997. Just as on earlier bit runs, we found the bit to be in good condition with no sign of eminent catastrophic failure. As expected the internal cutter wear was slightly more advanced than on previous bits, with the inner (nose) row of carbide buttons completely worn back into the matrix material and both of the two opposite cutters with three carbide inserts each also found worn back to the matrix material. Slight wear was evident at the tip of the core guide. Bearing seals were considered effective and bearing condition was actually slightly better (tighter) than that of the previous bit. With the fourth bit, we cored 137.2 m and recovered 106.15 m (77.4%) in 46.8 bit rotating hours. The average ROP was 2.9 m/hr.

Core Bit Number 5-First Deployment

During the previous bit run, we rebuilt the final remaining set of drilling jars and added packing to the seal chamber. The jars passed a pressure test of 1500 psi for 10 min and were judged acceptable for use. A new C-7 core bit was made up and after 15 min we made yet another routine reentry at 0800 hr 5 November 1997. We were tripping the bit to bottom when it encountered a hard bridge at a depth of 123 mbsf. After picking up the top drive, we again encountered an obstruction, this time at 117.0 mbsf. We spent close to 1-1/2 hr attempting to clear the bridge with the C-7 core bit to no avail. The top drive repeatedly stalled out with little or no WOB each time it contacted the obstruction. After deliberation, we decided that we would be more successful using a more massive tricone drill bit, so the drill string was recovered back to the rig floor by 1545 hr that same day.

Tricone Drill Bit Deployment Number 1

Leaving the BHA configuration unchanged, we exchanged the Rock Bit Industries (RBI) C-7 style core bit for a Smith F57 tricone drill bit. We reentered the hole at 1915 hr 5 November 1997 (15 min reentry), and the pipe was RIH tagging the obstruction at the same depth as before (117.0 mbsf). Top drive stalling continued to be a problem during our attempts to clear the bridge. This was aggravated by significant heave resulting from long period swells generated by a significant low pressure cell some 80 km to the south of the drilling location. Ultimately, by using high revolutions per minute (RPM; 100-130) coupled with low WOB and some skillful drilling by the

ODL Drilling Superintendent, a foothold was attained in the bridge. All total, in less than an hour, we had cleared the hole once again. Top drive stalling torques of 750 amps and overpulls of up to 60K lb were experienced during the episode. We theorized that an angular piece of material must have sloughed off of the side of the hole leaving a high-angle bridge that caused both core and drill bits to wedge immediately upon contact. We subsequently washed/reamed the hole to bottom to ensure that any other bridges or hard fill on bottom would be broken up by the more rugged tricone drill bit before resuming coring operations. No other bridges were identified, however, and only 2.0 m of soft fill was encountered on bottom. We circulated this out in short order and pumped a 50 bbl Bentonite gel mud sweep. We then tripped the pipe back to return the BHA to a coring configuration. The tricone drill bit cleared the rig floor at 0630 hr 6 November 1997.

Core Bit Number 5-Second Deployment

The same C-7 core bit was made up that was run initially when the hole obstruction was first encountered. The bit was undamaged and showed no wear from its first deployment. The drilling jars failed a routine pressure test, and because they were the only remaining set of jars, rig time was taken to add packing and retest. We then made up the jars with the remaining BHA and tripped the drill string to bottom, reentering the hole at 1230 hr on 6 November 1997. We encountered no problems passing the previously bridged area, and the pipe went straight to bottom without incident. No fill was detected at TD, and we began coring Core 176-735B-141R from 889.3 mbsf. While we were cutting the second core of this bit run, the drilling torque escalated to 600 amps and we experienced 60K lb overpull picking up off bottom. High torque, top drive stalling, and overpull of 40-60K lb continued through Core 176-735B-145R. Although we encountered no problems after Core 176-735B-146R, we pumped three 30 bbl bentonite gel sweeps after Cores 176-735B-147R, 148R, and 150R. Beginning with Core 176-735B-150R, we restored the original mud program of 30 bbl gel mud sweeps every other core. We stopped coring while cutting Core 176-735B-151R at a depth of 987.5 mbsf when drilling torque escalated to more than 50 amps above normal and ROP dropped off to 1.6 m/hr. The bit cleared the seafloor at 0250 hr and was at the rig floor by 0415 hr 9 November 1997. As before, the bit was in good condition with no sign of imminent catastrophic failure. The internal cutters were severely worn with the inner (nose) row of carbide buttons completely worn back into the matrix material. Both of the two opposite cutters with three carbide inserts were also worn back to the matrix material. Bearing seals were effective and bearing condition was good. With the fifth bit, we cored a total of 98.2 m and recovered 91.28 m (93.0%) in 47.3 bit rotating hours. The average ROP was 2.1 m/hr.

Core Bit Number 6

We made up yet another new C-7 core bit with the BHA; however, drilling jars were not included this time because during the NDT inspection the final remaining set was also identified as having crack indications. The last set of jars was set aside and the remaining BHA was run in the hole. Reentry was made at 0700 hr 9 November 1997, and the drill string was run to the bottom without incident. Only 0.5 m of fill was present on bottom. We initiated coring with Core 176-735B-152R at a depth of 987.5 mbsf and continued coring through Core 176-735B-163R to a depth of 1099.4 mbsf. The customary 20-30 bbl gel mud sweeps were increased at this point to every core rather than every other core. We terminated coring early while cutting Core 176-735B-163R, because the drilling torque abruptly increased more than 50 amps and the ROP dropped to 2.5 m/hr from earlier, higher rates. The bit reached the rig floor by 2330 hr 11 November 1997 and proved to be in good condition with no sign of imminent catastrophic failure. The internal cutter wear was severe, however, and the inner (nose) row of carbide buttons was completely worn back into the matrix material as were both of the two opposite cutters with three carbide inserts. One insert had fallen out of the core gauge row and another had broken off. Bearing seals were effective and bearing condition was as good or better than any of the previous bits. The sixth bit cored 111.9 m and recovered 106.35 m (95.0%) in 45.9 bit rotating hours. The average ROP was 2.4 m/hr.

Core Bit Number 7

We made up the seventh new C-7 core bit and weld repaired a crack in the latch sleeve prior to running in the hole. The BHA was run as before without drilling jars. We reentered at 0245 hr 12 November 1997 and ran the drill string to bottom where we tagged ~2.0 m of fill. This was easily circulated out. We initiated coring with Core 176-735B-164R at a depth of 1099.4 mbsf and continued to a depth of 1191.1 mbsf. As before, we pumped 20 bbl Bentonite mud sweeps after every core and again ran without liners. No fill was identified after any of the connections; however, while cutting Core 176-735B-174R, the drilling torque increased dramatically from the normal 360-400 amps to 500-600 amps. The torque dropped back to normal when the bit was picked up off bottom. We had only 33.3 rotating hours on the bit, but it was impossible to rule out the possibility of a potential bit problem. We therefore decided to err on the side of conservatism, and the final core was recovered after advancing only 3.0 m. Upon clearing the rig floor at 0430 hrs 14 November 1997, we found the bit to be in excellent condition, similar to the second core bit run of 36.0 hr. We noticed a high degree of wear and burnishing on the crossover sub between the 5" and 5-1/2" drill pipe during the pipe trip. This may have been the source of the excessive drilling torque. A check of the pipe tally placed the crossover at or near seafloor in the vicinity of the HRB. The seventh bit cored a total of 91.7 m and recovered 86.81 m (94.7%) in 33.3 bit rotating hours. The average ROP was 2.8 m/hr.

Core Bit Number 8

We ran the eighth new C-7 core bit in the hole and replaced the 5-1/2" to 5" crossover sub. In addition, we added 10 more stands of 5" drill pipe to the string to remove the crossover from the area of the HRB. We made another routine 15-min reentry (0700 hr 14 November 1997), and the bit was run to bottom. There was no indication of fill on bottom, and drilling torque was normal. We began coring Core 176-735B-175R at a depth of 1191.1 mbsf and continued to a depth of 1360.6 mbsf. We terminated coring after advancing 5.6 m on Core 176-735B-193R when the drilling torque increased by 100 amps. The bit had 53.8 rotating hours at that time so we took the conservative approach and pulled the bit. The bit reached the rig floor at 1530 hr 17 November 1997, and we found it to be in good condition. One cover plate from the grease reservoir was missing, however, and this may have contributed to the increased torque downhole. The eighth bit cored 169.5 m and recovered 140.80 m (83.1%) in 53.8 bit rotating hours. The average ROP was 3.1 m/hr. The increased ROP and decreased recovery rate was indicative of the more fractured nature of the formation through much of this interval.

Core Bit Number 9

We ran the ninth new C-7 core bit in the hole with an additional five stands of 5" drill pipe to keep the 5" x 5-1/2" crossover sub well above the HRB. After slipping and cutting the drill line for the first time during this leg, we reentered the hole at 2045 hr 17 November 1997. We ran to a depth of 1295.0 mbsf, where the bit met an obstruction and was unable to pass. We picked up the top drive and were able to ream the remaining 65.6 m without difficulty. We found no indication of any fill on bottom, and the drilling torque was normal. We initiated coring with Core 176-735B-194R at a depth of 1360.6 mbsf and continued to a depth of 1386.4 mbsf. Coring was terminated at 3.1 m on Core 176-735B-197R because of deterioration in the weather. Aside from the heave compensator beginning to exceed operating limits, we experienced several 3% (5 ea) and 5% (2 ea) positioning alarms. We stopped coring after only 8.8 rotating hours on the bit and began to pull out of the hole. After pulling the pipe to a depth of 739.0 m (8.0 mbsf), the drill string was hung off on the elevators while the driller laid out the previously pulled stand of drill pipe. At that time the bit contacted a ledge in the hole, causing the drill string to jump upward in the landing elevators. Using the still made up stand in the string above the rotary, the string was lifted off the elevators approximately 2.0 m where the bit was free from contacting the ledge. Two attempts were required before the drill string could be lowered past the ledge to the next tool joint. At that point, we laid out a double of drill pipe, and a full stand of pipe was then pulled allowing the bit to clear the HRB. The bit cleared the seafloor at 2115 hr 18 November 1997 under marginal weather and sea conditions. Winds were ranging from 33 to 41 kt gusting to 51 kt and swells were running 8-18 ft at 8-9 s periods. The vessel was heaving 10-18 ft. Because of extremely rough seas at the time, we decided to hang off the BHA/transition pipe below the keel and wait for the weather to abate. At 2215 hr 18 November 1997, the string was hung off on the elevators, and we commenced waiting on weather (WOW). By 0245 hr the following morning, conditions moderated enough to recover and nondestructive test (NDT) the BHA. We found no crack indications during the "magnaflux" inspection; however, two drill collars (#2 and #3) were bent. This was obviously the result of the incident that occurred at the seafloor and described above. The recovered bit was in excellent condition although (nose) cutter wear was much higher (50% of the carbide inserts worn away) than expected of a bit with less than 9 rotating hours. The ninth bit cored only 25.8 m but recovered an impressive 25.44 m (98.6%) in 8.8 bit rotating hours. The average ROP was 2.9 m/hr.

Core Bit Number 10

By 1500 hr 19 November 1997, our sea conditions had begun to moderate, and the captain felt confident that the storm system was both weakening and moving off location. We made up another new C-7 core bit and reentered at 1945 hr 19 November 1997. When the bit reached a depth of 1295.0 mbsf, it was again unable to pass, just as in bit run Number 8. As before, we picked up the top drive and reamed to bottom without incident. There was no indication of any fill on bottom. We proceeded to core beginning with Core 176-735B-198R at a depth of 1386.4 mbsf and continuing to a depth of 1508.0 mbsf. We took drift measurements at 1100 mbsf and 1400 mbsf determining hole deviation at those points to be 4.6° and 4.8°, respectively. We pumped 20 bbl bentonite mud sweeps after each of the first four cores, then increased the sweeps to 30 bbl per core because of the fairly rapid ROP. No fill was identified after any of the connections. We terminated coring after Core 176-735B-210R to short trip five stands of wear-knotted drill pipe out of the hole and replace it with standard 5-1/2" drill pipe. We could have proceeded coring using knobby drilling joints but the cores would have been shorter (9.2 m vs. 9.6/9.7) and it would have been more time consuming to handle the knobbies, whereas the wear-knotted pipe could be handled using the automated pipe racker. After pulling all but four joints of the wear-knotted pipe from the hole, we suffered a drill string failure. The pipe was landed in the elevators while the driller placed a double of drill pipe into the mousehole with the top drive. During this operation the drill string twice came into contact with a ledge in the hole when the vessel moved down because of heave, causing the drill string to rise approximately 0.5 m above the landing elevators. The driller made back up to the drill string as quickly as possible with the top drive, and the string was lifted off of the landing elevators. By that point, the damage had already been done, however, and the weight indicator showed a loss of 130K lb of string weight. Our calculations indicated that the string parted in the 5" drill pipe at or near the seafloor. We deployed the subsea camera to inspect the drill string/HRB to confirm that the failed pipe was not above the seafloor and then recovered the drill string. At 0600 22 November 1997, we identified the point of failure as the last engaged thread of a 5" drill pipe pin connection located at 739 m (8 mbsf). The fish we left in the hole was 1403 m in length and consisted of a 172-m-long BHA plus 43-2/3 stands of 5" drill pipe (1231 m).

Fishing Attempt Number 1

For our first fishing attempt, we made up a 9-1/2" overshot dressed with a 6-7/8" basket grapple and mill control. This was deployed on a fishing BHA consisting of five 8-1/4" drill collars, one tapered drill collar, and two stands of 5-1/2" heavy wall drill pipe. We reentered the hole at 1030 hr 22 November 1997. While lowering the pipe to 12.0 mbsf, the overshot started hanging up on a ledge, preventing the drill string from being hung off on the elevators for the next connection. We pulled the pipe clear of the seafloor and added a 10-ft pup joint to space the string out lower and, we hoped, past the bad spot. We reentered the HRB at 1130 hr and lowered the overshot to the top of the fish at 838 m (107 mbsf). The fish was engaged in short order, and we were proceeding to lift it to its total weight of 130K lb when it parted leaving only 35K lb of weight suspended below the overshot. We pulled the fishing string to the surface, where we recovered a total of 497 m of 5" drill pipe by 1930 hr 22 November 1997. The fish parted in the 5" drill pipe tube two feet below the box tool joint. This was at a point where the tube had buckled when the string impacted the bottom of the hole after the initial failure. The portion of fish remaining in the hole (906 m) consisted of 26 stands (734 m) of 5" drill pipe plus the coring BHA of 172 m.

Fishing Attempt Number 2

For our second fishing attempt, we assembled an 8-7/8" overshot dressed with a 5" basket grapple and mill control. We used the same fishing BHA with the addition of a 10-ft drill collar pup joint. After a brief trip to the seafloor, we reentered the hole at 0000 hr 23 November 1997. We contacted the fish at 0630 hr that same day at a depth of 1337 m (606 mbsf). After nearly 3 hr, however, no engagement was accomplished, and we elected to pull the drill string out of the hole. The fishing tools cleared the rig floor by 1200 hr and significant damage was observed on the lip guide of the overshot, including a large chunk of missing material. We could find no indication that the fish had ever contacted the mill control or basket grapple.

Milling Attempt Number 1

Based on the recovered piece of failed drill pipe tube, we suspected that the top of the fish was bent over and elongated at the top. Therefore, we made up a 9-5/8" flat-bottomed junk mill and ran to the seafloor. We reentered the hole at 1545 hr 23 November 1997, and by 2030 hr the fish was contacted at the same depth of 1337 m (606 mbsf) as before. Milling continued until 0330 hr 24 November 1997 when a depth of 1339 m (608 mbsf) was reached. It was difficult to tell if the mill was on top of the fish or just sidetracking down the side of the pipe; however, we hoped for the former. When the tools were pulled out of the hole and cleared the rig floor (0600 hr), we could find no evidence that the bottom of the mill had ever contacted the top of the fish. The sides of the mill, however, were worn back ~2" where obvious metal-on-metal contact had occurred.

Milling Attempt Number 2

We then made a second milling attempt with a concave junk mill. This mill had more carbide cutting structure on the sides as well as the bottom. We elected to run an additional stand of 8-1/4" drill collars this time because of the anticipated heavy swell and attendant large heave. We reentered the hole at 0900 hr 24 November 1997, and by 1245 hr the fish was contacted at approximately the same depth (1338 m or 607 mbsf). As before, milling continued until 1530 hr 24 November 1997 when we reached a depth of 1340 m (609 mbsf). The tools were pulled out of the hole and cleared the rig floor at 1830 hr. This time we did find some evidence that the bottom of the mill had contacted the top of the fish, although there was also significant side wear.

Fishing Attempt Number 3

For fishing attempt Number 3, we reentered the hole at 2230 hr 24 November 1997 with an 8-7/8" overshot dressed with a 5" basket grapple and mill control. By 0330 hr 25 November 1997, we had contacted the fish at a depth of 1340 m (609 mbsf). By this time, there were large long-period swells generating 3 m heave at times, aggravating our attempts to engage the fish. Nothing worthwhile was accomplished, and the drill string was recovered to the rig floor by 0445 hr that same day. This time we found the lip guide bent over to such a degree that it would not have gone over the fish. The damage was likely the result of the high heave experienced during the fishing period. As before, there was no indication that we had ever contacted the fish with the mill control or basket grapple.

Milling Attempt Number 3

We made a third attempt at milling with a fresh concave junk mill, because we assumed that the top of the fish was likely severely damaged. The same BHA was made up, except we added a string stabilizer just above the first full drill collar. We hoped that the stabilizer would stiffen up the BHA and aid in keeping the mill straight in the hole, reducing its propensity to sidetrack. We reentered the hole at 0930 hr 25 November 1997, and it became immediately apparent that our BHA configuration would not work. With the bit at 19 mbsf, the torque was so severe that we decided the stabilizer would have to be removed from the string or we would risk sticking the BHA downhole. The drill string was recovered, and we laid out the stabilizer by 1230 hr. We reentered the hole without the stabilizer at 1515 hr and by 1915 hr we contacted the fish at a depth of 1340 m (609 mbsf). This time the milling parameters were excellent with all indications that the mill was grinding away on the top of the fish. We suspended milling at 2145 hr 25 November 1997 after reaching a depth of 1342 m (611 mbsf). The milling BHA was pulled out of the hole, clearing the rig floor at 0045 hr 26 November 1997. The wear pattern on the bottom of the mill appeared to be circular with a ±5" diameter, giving us new hope that the fish may be recoverable.

Fishing Attempt Number 4

On the fourth fishing attempt we again ran the 8-7/8" overshot, this time with an extension to allow more of the fish to be swallowed. It was again dressed with a 5" basket grapple and mill control. We reentered the hole with this assembly at 0345 hr 26 November 1997. For the first time since initiating fishing operations, we observed back flow from the pipe during connections. At 0715 hr, we contacted the fish at a depth of 1342 m (611 mbsf). This time conditions were different. Each time we contacted the fish with the overshot, the pipe would torque up and stall the top drive instantaneously. Overpulls of 40K lb were required to pull the tool free. At no time did we see any pump pressure indication that the fishing tool had swallowed the fish. Our efforts to engage the fish continued, using no RPM, slow RPM, high RPM, light weight, heavy weight, etc.—all to no avail. We finally abandoned further attempts at 0815 hr and recovered the fishing assembly by 1200 hr 26 November 1997. After inspection, it was obvious that the fish had not entered the throat of the overshot.

Fishing Attempt Number 5

We suspected that because of its length, diameter, and rigidity, the overshot assembly may not have made it all the way down to the fish. We also theorized that the hole was possibly being sidetracked with the lost drill pipe acting as a whipstock; however, this was inconsistent with the junk mill data. We decided to try a shortened overshot assembly to see if it would work any better. We reentered the hole at 1600 hr 26 November 1997 and by 2000 hr 26 November 1997 we contacted the fish at a depth of 1342 m (611 mbsf). All of our attempts to engage the fish were unsuccessful, and the tools were once again retrieved to the rig floor arriving at 0045 hr 27 November 1997.

Tricone Drill Bit Deployment Number 2

All indications at this point were that the mill/fishing tools were sidetracking the fish rather than setting down on top of it. To verify this, we decided to run the same 9-7/8" Smith F57 tricone drill bit that was used earlier to clear the obstruction in the hole. We reentered the hole at 0330 hr 27 November 1997, and at 0645 hr the fish was contacted at a depth of 1337 m (606 mbsf) or the original depth prior to the milling operations. The bit was torquing as if it were either on top of the fish or possibly attempting to ream out the undergauged hole made by the sidetracking mills. Our suspicions confirmed, we recovered the drilling assembly, clearing the rig floor by 1000 hr 27 November 1997.

Fishing Attempt Number 6

The challenge at this point was to capture the fish without going down the sidetracked hole. To attempt straightening out the pipe in the hole, we fabricated a wall hook out of an 8-7/8" extension sub and a 9-1/2" extension sub. The larger extension sub would be less likely to follow the sidetrack hole. The smaller sub provided the threads necessary to make up to the 8-7/8" overshot body. The 8-7/8" was needed because there were no 5" basket grapples or mill controls aboard for the 9-1/2" body. With the new fishing tool, we reentered the hole at 1915 hr 27 November 1997, and by 2300 hr the fish was again contacted at a depth of 1337 m (606 mbsf). Engaging the fish was unsuccessful again. Each time we set down on the fish, the torque would jump up and the top drive unit would stall. We worked the tool for 2-1/4 hr before abandoning the effort and retrieving the tool. The fishing tool was back on the rig floor by 0345 hr 28 November 1997; however, the lower 0.5 m of the wall hook was left in the hole.

Milling Run Number 4

With the additional junk in the hole, another milling run was required. We ran in with a 9-1/2" flat bottomed junk mill, reentering the hole at 0645 hr 28 November 1997. By 1030 hr, we again contacted the fish, this time slightly higher at a depth of 1336.6 m (605.6 mbsf). Milling on the junk went surprisingly well with constant torque and very slow ROP. After 2-1/2 hr, we halted the milling and recovered the tools to the surface. By 1615 hr 28 November 1997, the mill was back at the rig floor showing definite signs of being on top of the drill pipe fish. A very discernable concentric wear pattern ~5.0" in diameter was identifiable on the mill face. This gave everyone encouragement that the top of the fish had centralized in the hole before the wall hook had failed.

Fishing Attempt Number 7

Once again we ran in with an 8-7/8" overshot assembly, reentering the hole at 1900 hr 28 November 1997. Our seventh fishing attempt began at 2300 hr 28 November 1997 at a depth of 1337 m (606 mbsf). Enthusiasm soon turned to frustration as our latest fishing attempt was characterized almost exactly as the previous one. Immediate stall torque was experienced upon contact with the fish. We worked the overshot for 2 hr; however, at no time was there any indication of increased pump pressure or overpull that might suggest engagement with the fish. At this point, we decided to stop fishing and complete the wireline logging and VSP experiments, as this would give us a little contingency time in the schedule should there be unforeseen problems with the logging program or deterioration in the weather, thus necessitating an earlier than scheduled departure from the drill site. We recovered the fishing tools, clearing the rig floor by 0515 hr that same day. All drill collars were laid down except those required for logging.

Wireline Logging and VSP Experiment

We used a shortened BHA for logging, consisting of a reentry cleanout bit, five each 8-1/4" drill collars, one each tapered drill collar, and two stands of 5-1/2" transition drill pipe. We installed a landing saver sub with a "special" landing ring two drill collars up from the bit to provide a landing point for the Kinley Crimper/Cutter assembly should it be required. The landing ring inside diameter (ID) had to be opened up to 3.918" to accommodate the oversized Schlumberger VSP tool. Details of this modification are included later in the report under "Downhole Logging and VSP." We reentered the hole at 0745 hr 29 November 1997, and the pipe was placed at 780 m or 49 mbsf with a 30-ft drilling knobby through the guide horn. At 0915 hr, we began to rig up the Schlumberger logging sheaves and wireline compensator.

The first tool string consisted of HLDT, caliper, APS, and HNGS probes. The second logging run consisted of NGT, DSI, GPIT, and FMS probes. The third tool string was composed of NGT, GPIT, and DLL probes. We rigged down the VSP tools and logging sheaves by 0415 hr 1 December 1997 and proceeded to pull the drill string, clearing the seafloor at 0430 hr and reaching the rig floor by 0530 hr.

Fishing Attempt Number 8

While the logging/VSP efforts were under way, we fabricated another fishing assembly. An 8-7/8" overshot assembly was shortened as much as possible, bringing the mill control and basket grapple closer to the open end of the overshot. In addition, "Cutrite" hard facing was applied to the lip guide, creating a "milling capable" overshot assembly. We hoped that the combination of the shorter fishing assembly and the limited milling ability would allow the basket grapple to engage the drill pipe fish.

After making the BHA up with the new fishing tool, we round-tripped the drill string one last time for a final fishing attempt. The fish was contacted ~2 m deeper than before at 1339 mbrf or 608 mbsf. During subsequent working of the pipe, we contacted the fish at the shallower (607 mbsf) depth; however, all attempts to engage the fish proved futile. We abandoned our final fishing attempt at 1400 hr 1 December 1997 and began preparations to get under way for Cape Town, South Africa. Upon recovery of the fishing tool, the overshot showed obvious indications that a fish (drill pipe, wall hook, ???) had at some time been inside the overshot as far up as the mill control assembly.

TRANSIT TO CAPE TOWN, SOUTH AFRICA

We began the return voyage to Cape Town, South Africa, at 1900 hr on 1 December 1997. During the transit, the rig crews worked on the usual clean-up, painting, report writing, and PMS activities. In addition, we held a meeting with rig personnel, the Leg 176 Co-Chief Scientists, and the Leg 176 Staff Scientist to discuss approaches and operational options for a possible future deep hole (2500^+ mbsf) in the Site 735 Southwest Indian Ridge operating area.

Good weather and favorable seas allowed the return trip to Cape Town to be accomplished in good time, and we arrived at the pilot station at 1030 hr, a 1998 nmi voyage averaging 10.9 kt. The first line was ashore at 1130 hr on 9 December 1997, officially ending Leg 176.

HOLE 735B CORING BITS

We used RBI, C-7 style, tungsten carbide insert, roller cone core bits exclusively for coring during the leg. Ten core bits were deployed. Meters of penetration and rotating hours achieved on the various bit runs ranged from 25.8 m penetrated in 8.8 hr to 169.5 m penetrated in 53.8 hr. Penetration rates tended to be a function of grain size, the degree of foliation, and fracturing in the rocks. In the massive, more fine-grained "foliated" rocks the penetration rates ranged from 1.3 to 2.3 m/hr. In the coarser grained gabbros and more highly fractured zones, the penetration rates were from 2.5 to 6.1 m/hr. The average ROP for the leg was 2.7 m/hr.

We felt that the C-7 core bit was optimum for this leg and formation. A C-57 might have performed better than the C-7 in some lithologies (in the coarse-grained gabbros) but would have been more vulnerable to cutter damage in the finer grained, foliated rocks. The bearings performed well and never exhibited any potential for catastrophic failure. Bit life on all runs was determined by wear on the ID nose cutters. These carbide buttons wore significantly even on the bit with only 8^+ rotating hours. Eventually, the buttons were completely worn back into the matrix material.

Interestingly enough, the bits continued to drill ahead at reasonable penetration rates and recovered gauge core with the nose buttons completely gone. For future drilling at this site, consideration should be given to applying a diamond coating to the carbide buttons to see if cutter life could be extended. In general, bit performance was excellent.

CORING SYSTEM PERFORMANCE

We used the RCB wireline coring system exclusively during this leg. Performance was excellent. Recovery for the leg averaged 86.3%, which is impressive for hard-rock coring. Bit seal failure was evident on most bit runs, and it was clear that the bit seals will not outlast bit life in this type of formation. We could identify nothing catastrophic as a result of the bit seal failures because the ~100 psi pump pressure increase had no negative impact on the coring process. On one occasion, however, Teflon material from the bit seal did become lodged in one of the bit jets. Given the experience gained on Leg 176, the RCB bit seal does need to be redesigned for normal coring operations where severe core erosion is often experienced while drilling deep holes in sedimentary formations where bit life is even longer.
About midway through the leg, we began to use the sleeveless core catchers designed for use with the extended core barrel (XCB) flow control system. The hard-rock coring was taking a toll on the standard core catchers. The core catcher dogs became so tightly pressed into the sleeves that we could not remove the core catchers from the core catcher subs without using an air chisel. This, of course, destroyed many of the core catcher components, primarily the outer sleeves. Also, early on in the coring process, we experienced a lot of core jamming inside the butyrate core liners. Beginning with Core 176-735B-99R, we deployed the core barrels without core liners and the problem was not repeated.

Two RCB coring system failures occurred during the leg. On the first occasion, a core catcher sub backed off from the inner barrel sub after 6^+ hr of downhole rotating time. We had to make a pipe trip to get the cored material and coring components back. Subsequent to this, we coated all core barrel connections with liquid Teflon and made them up with a 48" wrench and a cheater pipe. The incident was not repeated after that. The second failure occurred when a pin thread failed between inner barrel connections during unloading of core at the rig floor. This was attributed to threads/barrels that had been in service for quite a while and could not stand up to the rigors of high-recovery hard-rock coring. The barrels were replaced and no further failures occurred. An Incident Report was sent in documenting the details surrounding each of the failures.

TUBULARS AND BHA COMPONENTS

Operating in relatively shallow water (731 m) while drilling relatively deeply into hard rock poses some unique problems for drilling operations. In the case of Hole 735B, these problems became even more challenging because of the fairly constant long-period southerly swells and periodic low pressure cells that occasionally generated gale force (8/9) winds and seas. For most of the leg, our vessel heave ranged from 1 to 2 m. On a few instances, the heave exceeded 3 m. On one of these occasions, operations had to be suspended because the operating limitations of the passive heave compensator were exceeded and the ASK system was having difficulty staying on site without frequent triggering of the 3% (22 m)/5% (37 m) yellow/red alarms. These statements are made in preface to the following Leg 176 incidents regarding tubulars and BHA components.

On one occasion, two each 8-1/4" drill collars were bent ~2 m from their respective pin/box ends. While pulling out of the hole after core bit run #9, the drill bit hung up on a ledge during a down heave putting the BHA into compression. The resultant buckling of one connection caused the box end of collar #2 and the pin end of collar #3 to be bent. Due to deteriorating weather conditions, we were tripping the drill string back to the surface. We had just pulled a stand of 5" drill pipe placing the bit at a depth of 739.0 m or 8.0 mbsf. The string was landed in the elevators, but still attached to the top drive, when the bit came in contact with a ledge in the hole. This caused the full weight of the drill string to be applied to the bit, and the drill string jumped upward in the landing elevators. The string was lifted off of the elevators ~2.0 m where the bit was free from contacting the ledge. After two attempts, we finally were able to lower the string past the ledge to the next tool joint. A double of drill pipe was laid out of the string, and we then pulled a full stand of pipe allowing the bit to clear the seafloor/HRB.

At the surface, two 8 1/4" drill collars # 2 and #3 (1st and 2nd DCs above the outer core barrel assembly) were found to be slightly bent at their respective box/pin ends, indicating that this connection had been placed in compression and buckling had occurred. The two bent drill collars were replaced, and the entire BHA was inspected with no crack indications found. To avoid the potential for a reoccurrence of the incident, both drill crews were instructed to space out in a similar manner during all reentry operations and when pulling the bit clear of the seafloor. This avoided placing the bit in the suspect portion of the hole while making or breaking connections at the rig floor. In this case, the problem was aggravated by significant heave during the drill string retrieval. At the time, the wind was blowing 33-41 kt and gusting to 51 kt. Swells were running 8'-18' at 8-9 s periods and vessel heave was 10-18 ft. An Incident Report was submitted and the two drill collars were returned to shore to be used for sub stock.

On another occasion, a pin thread on a joint of 5" drill pipe failed while short tripping wear-knotted drill pipe from the hole. Subsequently, the pipe being fished failed again, this time in the 5" tube body. The drill string was being pulled with the top drive during a routine wiper trip to change out five stands of 5-1/2" wear-knotted drill pipe. The drill string was landed in the elevators while a double of drill pipe was being put into the mousehole with the top drive. During this operation, the drill string twice came into contact with a ledge in the hole when the vessel heaved down. This caused the string to rise ~18" above the landing elevators. The top drive was made back up to the drill string as quickly as possible, and the string was lifted off of the landing elevators. At this point, the weight indicator showed a loss of 130K lb of string weight. Initial calculations indicated that the string parted in the 5" drill pipe at or near the seafloor. We deployed the subsea camera to inspect the drill string/HRB and ensure that the failed pipe was not above the seafloor.

When the drill string was recovered, we found the point of failure to be at a pin connection in the 5" drill pipe when it was located at 739 m or 8 mbsf. The fish left in the hole was 1403 m in length and consisted of the BHA (172 m) plus 43-2/3 stands of 5" drill pipe (1231 m). A 9-1/2" overshot dressed with a 6-7/8" basket grapple with mill control was used to engage the fish at a depth of 838 m (107 mbsf). As we lifted the fish to its total weight of 130K lb, it failed again leaving only 35K lb of weight suspended below the overshot. The fishing string was pulled to the surface where a total of 497 m of 5" drill pipe was recovered below the overshot. The fish parted in the tube of the 5" drill pipe two feet below the box tool joint at a point where the tube had buckled when the string impacted the bottom of the hole. The portion of fish remaining in the hole (906 m) consisted of 26 stands of 5" drill pipe (734 m) and the coring BHA (172 m). Subsequent milling/fishing operations were unsuccessful in engaging or removing the remaining junk from the hole. Weather conditions at the time of failure were not particularly bad, although vessel heave was in excess of 2 m. The wind was blowing at 24-30 kt, seas/swells were running 11-12 ft at 7-9 s periods, the average roll was 3° (maximum 6°), and the average pitch was 2° (maximum 5°). Vessel heave was approximately 8 ft. The remaining 51 joints of 5" drill pipe recovered from the hole were identified with a double yellow band. The 21 joints of 5" pipe that were above the failure point were identified with a single yellow band. All of this 5" pipe was stored in the previously empty starboard 5" pipe racker. Additional 5-1/2" pipe to be inspected during the post Leg 176 Cape Town port call was not marked but included the top 21 stands (63 joints). Of this pipe, four stands (12 joints) had aluminum wear knots installed.

FISHING TOOLS AND MILLS

We made a total of four milling runs and eight fishing attempts to try to remove the failed drill pipe and BHA from the hole. Each deployment is documented in the body of this report. We used both 8-7/8" and 9-1/2" overshots in our fishing attempts. We used a 6-7/8" basket grapple and mill control to engage the upset connection on the 5" drill pipe tool joint (7" OD) on the first attempt and ultimately recovered 497 m of 5" drill pipe. For all subsequent fishing operations, we used a 5" basket grapple and mill control to try to engage the tube body of the failed 5" drill pipe. These attempts were all unsuccessful. We considered using a taper tap fishing tool to attempt engagement of the inside diameter of the fish, but this was ruled out for several reasons. First, the failed end of the tube was crushed where the pipe buckled upon impact with the seafloor. Unless the milling attempts were successful we would not have been able to engage the fish internally. Second, the taper tap had no way to circulate to the bottom of the fish, which was likely firmly stuck in the hole at that point. If the fish was engaged with the tap, and was indeed stuck in the hole, we had no jars in the string and no way to disengage the tap. To prevent sidetracking the fish, we fabricated a wall hook from a 9-1/2" extension sub and an 8-7/8" extension sub. This would not have been a problem if the 5" basket grapples and mill controls for the 9-1/2" overshot had been available, but they were only available for the 8-7/8" size overshot. In addition, we had some incompatibility associated with the 8-7/8" overshot hardware that limited our tool make-up. We had one top sub with a 6-5/8" box and another with an old Hycalog box thread dating back to the *Glomar Challenger* days. We really did not want to run the Hycalog thread because the fish weight was nearly 100K w/o overpull, and the thread possibly could see some bending loads for which it was not designed. The bottom threads on the top subs were different, so we ended up with only one overshot bowl that would screw onto the stronger top sub and two that would only fit the weaker top sub. In addition, the extension subs we had would not make up to the stronger top sub. After the first run the Hycalog box thread was damaged (egged and shoulder damage) and was very hard to make up on later runs. It was the only option, however, when we wanted to run an extension sub to try to swallow the fish deeper.

We returned all of the 8-7/8" overshot parts to shore. We felt that this was the most practical way to solve the thread incompatibility problems and get things back in shape for future potential fishing jobs.

The following 9-1/2" overshot parts were used on Leg 176 and were either damaged or lost: One each OF2020 lip guides, one each OF0132 mill control, one each OF0035 basket grapple, one each OF0140 inner seal, one each OF0630 9-1/2" Extension Sub, and one each OF2023 flat bottom guide.

The following list of overshot parts would help out future fishing operations:

1. 2 each 9-1/2" OD lip guides for the 8-7/8" overshot
2. 2 each mill controls for the 9-1/2" overshot assembly
3. 2 each basket grapples for the 9-1/2" overshot assembly
4. 1 each 9-m -long 8-7/8" extension sub
   This would allow fishing the next tool joint instead of trying to fish a damaged tube. It would have to have heavy duty thread protectors on it because it would be stored in the riser hold. Also a short crossover would be good to allow running a 9-1/2" overshot with the long extension sub.
5. Beef up our inventory of lip guides for both the 8-7/8" and 9-1/2" overshots.
6. Do away with the Hycalog top subs altogether. This is a really poor connection for fishing operations. It also requires running a long bit sub as a crossover, which is also weak because it is bored out for the float and bearing. We also have the same connection for one of the 9-1/2" overshot assemblies that needs to be replaced.
7. Sort out the thread compatibility problems with the 8-7/8" overshot top sub to bowl.
8. Provide a junk mill with an extreme concave face to center a drill pipe tube better and not allow it to fall so easily off the fish you are attempting to dress.

DOWNHOLE LOGGING AND VSP

Because the Schlumberger VSP tool was oversized (3.85"+ OD) it would not fit through a standard landing ring (3.81" ID) placed in the landing saver sub. The landing shoulder is required for landing the Kinley crimper/cutter tool should a logging tool become stuck in the hole. To solve this problem, a standard landing ring was opened up to 3.918" ID. The landing shoulder on the Kinley tool is 4.000" and that left ~41 thousandths on a side to land on.

The modified ring was painted and marked both with a paint marker and a wire bound tag to indicate its current internal diameter size. We have stored this modified replaceable seat on the shelf in the Core Tech shop for potential use on future legs, such as Leg 179, when the oversized VSP may again be deployed. This same VSP tool would also not fit through the TAM straddle packer assembly. Without a casing hanger installed in the HRB, there was no way to isolate drill string noise during the VSP experiment.

POSITIONING BEACONS AND AUTOMATIC STATION KEEPING (ASK)

Only two beacon deployments were made during the leg, and both were successfully released and recovered. Using GPS, we deployed an initial beacon (S.N. 2040, 205 dB, 14.0 kHz) at the original SatNav coordinates for the hole reported by Leg 118. Positioning on this beacon, we conducted an expanding box search pattern until the guide base was located. We then dropped a second beacon (S.N. 2025, 208 dB, 16.0 KHz), which was used as the primary positioning beacon for the remainder of the leg. The primary beacon rested ~13 m from the HRB, and the back-up beacon was ~60 m away. Both beacons were deployed ~38 days, and we experienced no problems with either one.

The special tilt beacons sent out for use with the HRB were diagnosed with several problems. The Sedco Electronic Technicians (ETs) made several modifications to S.N. 1040, and it now functions correctly. It was left aboard for possible use on Leg 179. Since we did not have to set a new HRB, we never had occasion to deploy any tilt beacons during Leg 176. The second beacon, S.N. 1039, would only operate at 195 dB. All other output power settings caused the battery fuse to blow. The third beacon, S.N. 1137, would not be recognized by the ship’s RS/906 receiver. Both of the later beacons were returned to shore for repair by Datasonics.

The ASK system functioned well throughout the leg. During one force 8/9 gale, there were several yellow and red positioning alarms, but we anticipated this because of the very small operating window resulting from the shallow (731 m) water depth. For normal (deep water) operations the alarms are set at 2% and 3%, respectively. For Leg 176, because of the shallow water, the alarms were set at 3% (22 m) and 5% (37 m). Additional details are included in the body of this report.

REENTRY EQUIPMENT

We made 31 reentries during the leg, averaging 0.3 hr for each. The first reentry took approximately 1 hr because of the requirement to search for the HRB. After that, nearly every other reentry took a mere 15 min from the time the drill string was spaced out until the bit entered the HRB funnel.

No problems were experienced with the coaxial cable or winch. The sonar system was used effectively to aid in initially identifying the HRB. After that, all reentries were made using the subsea television camera. One camera was replaced and returned to shore for repair. We suspect that part of the problem was caused by inadequate shock protection from the Vibration-Isolated Television (VIT) sleeve. The bungy cords on the VIT are quite worn out and were scheduled for replacement at the beginning of the leg. Unfortunately, the replacement cords were too long to work. At the request of shore, these bungy cords were returned and we used the old worn-out cords. The correct bungy cords are supposed to be delivered prior to Leg 177. It should be noted that a through-the-pipe television camera would have been incredibly valuable on this leg as an aid in identifying the orientation and condition of the failed drill pipe fish. This should be investigated as a possible purchase, as the technology is available in the oil industry.

BULK PRODUCTS

Bentonite gel mud was used exclusively during the leg. The immediate concern was to use up the 10 MT of excess bentonite stored in P-Tank #7 that was delivered to our embarkation port call in Cape Town I . Since P-tank #7 is normally a sepiolite tank, we needed to empty it prior to arrival back in Cape Town so the additional 27 MT of stored sepiolite could be loaded aboard. Once the tank was emptied, we continued using the gel mud from P-tank #1 for the following reasons: this was a less expensive sweep mud, we were drilling in a hard-rock (basement) hole without expanding clay concerns, and the Bentonite gel appeared to be effective because we were not seeing fill on connections or between bit trips.

WEATHER/CURRENT/SEA STATE

Leg 176 Operational Weather/Sea States

The weather and sea state conditions were extremely variable throughout the leg. Large, long-period swells from the south were prevalent much of the time, leading to large vessel heave (2-3 m) on occasion. These swells were often from two different directions, and when coupled with moderate winds (20-30 kt) and an erratic current (0.7-3.2 kt), they created some difficulty for the dynamic positioning (DP) operators in minimizing vessel roll and pitch. On one occasion, gale force 8/9 winds and seas caused us to pull out of the hole. Because of the shallow water, we were getting several yellow (3%) and red (5%) positioning alerts. We felt that it was too rough to safely handle drill collars, so the BHA was left hung off on the elevators for several hours until conditions moderated. All total, one half day was lost due to WOW.

Because of the relatively shallow water, the ASK operating window was very tight. The vessel could only move off station 22 m before a yellow (2%) alarm would trigger. Consideration should be given to relaxing the 2%-4% guidelines somewhat because of the unique circumstances of operating at Site 735.

Current conditions at the site varied significantly and seemed to be driven more by environmental conditions (i.e., the transiting of low pressure cells) rather than tidal or other factors. Currents ranged from nonexistent to as much as 2.3 kt. Generally, the currents were in the 1-2 kt range and originated within a 45° quadrant either out of the north or out of the south.

LAWS/QFAX Weather System

An upgraded LAWS weather system was installed by ODP ET Eric Meissner and is considered to be fully operational. We are now able to capture NOAA 12, NOAA 14, Meteor 3-5, Meteor 3-6, and Meteor 2-21 satellites. We have also been able to collect Wefax data from the geostationary satellite Metrosat 6. The GMS satellite was too low on the horizon for us to capture on this leg.

The last function needed is an audio line connected to the radio room so that the radio operator can use the system to capture the NFAX weather maps. The new system is also able to receive GPS input. Another possible modification would be connecting up a GPS so that position and time updates would not have to be input by keyboard. In addition to hardware installation, the mates have also been trained on how to use the new system.

JANUS

During this leg, ODP/TAMU developer/programmer David Fackler sailed and worked with various shipboard entities on JANUS refinements. For the most part, all JANUS systems pertaining to Drilling Operations worked well. We did identify one glitch when we discovered that JANUS would not allow us to enter "NONE" under core liner options. As we were operating without core liners for most of the leg, this was a potential problem. David was able to correct the problem quickly, however, and "no" core liner option is now available.

CORING WINCH AND LINES

We experienced no problems with the coring winch or coring lines during the leg. We used the aft core line exclusively. Two cuts of 150 m were made and one big cut of 1200 m, leaving the current total length at 6600 m. The forward core line was newly installed at the end of Leg 175. This line was not used during Leg 176 and is currently 9525 m in length. Due to the circumstances under which we stopped coring, and the belief that coring would ultimately be resumed, the aft core line was not coated with rust inhibitor.

HYDROCARBON SAFETY

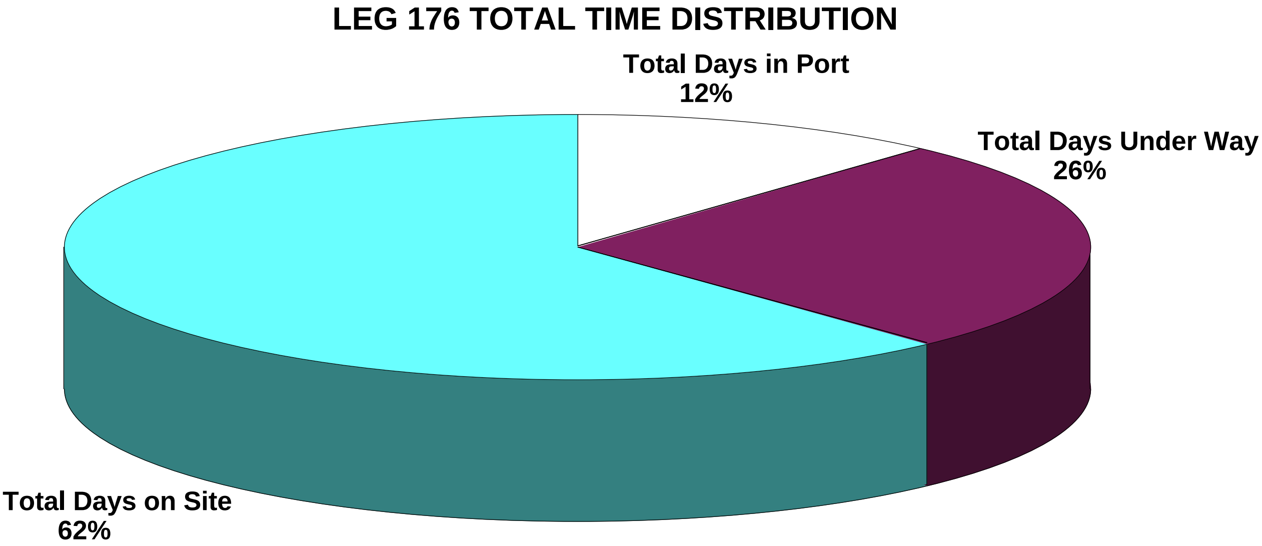
Hydrocarbon safety was not an issue on this leg because all coring operations were performed in basement formations.

Total Days (8 October 97 to 10 December 97)		61.6
Total Days in Port		7.1
Total Days Under Way		16.2
Total Days on Site		38.2

	days
Stuck Pipe/Downhole Trouble	0.3
Tripping	6.2
Other	1.1
Drilling	0.0
Coring	20.0
ODP Breakdown	0.1
Logging/Downhole Science	2.5
Fishing & Remedial	7.4
Development Engineering	0.0
Repair Time (Contractor)	0.0
Reentry	0.2
W.O.W.	0.5
Casing and Cementing	0.0

Total Distance Traveled (nautical miles)	3999.0
Average Speed Transit (knots):	10.0
Number of Sites	1
Number of Holes	1
Number of Reentries	31
Average Reentry Time (hours)	0.29
Number of Cores Attempted	122
Total Interval Cored (m)	1003.2
Total Core Recovery (m)	865.99
% Core Recovery	86.3%
Total Interval Drilled (m)	0.0
Total Penetration	1003.2
Maximum Penetration (m)	1508.0
Minimum Penetration	1508.0
Maximum Water Depth (m from drilling datum)	731.0
Minimum Water Depth (m from drilling datum)	731.0
Average Water Depth	731.0

APPENDIX I - RESUME



APPENDIX I - Time Distribution

HOLE	LATITUDE	LONGITUDE	SEA FLOOR (mbrf)	NUMBER OF CORES	INTERVAL CORED (meters)	CORE RECOVERED (meters)	PERCENT RECOVERED (percent)	DRILLED (meters)	TOTAL PENETRATION	TIME ON HOLE (hours)	TIME ON HOLE (days)
735B	32°43.3928 S	57°15.9606 E	731.0	122	1003.2	865.99	86.3%	0.0	1003.2	917.25	38.22
		SITE 735 TOTALS:		**122**	**1003.2**	**865.99**	**86.3%**	**0.0**	**1003.2**	**917.25**	**38.22**
				------------------	--------------------	-----------------------	-----------------------	-----------------	----------------------------	------------------	------------------
		LEG 176 TOTALS:		**122.0**	**1003.2**	**865.99**	**86.3%**	**0.0**	**1003.2**	**917.25**	**38.22**

APPENDIX I-Site Summary

LOCATION:	Latitude:	32° 43.3928' S	TIME:	Start Hole:	1345	24-Oct-97	Total:
	Longitude:	57° 15.9606' E		Spud Hole:	n/a	n/a	917.3 Hours
Territorial Jurisdiction:		International		End Hole:	1900	01-Dec-97	38.2 Days

DRILL PIPE DEPTHS:	Water Depth:	720.6 (mbsl)	Sea Floor Depth:	731.0 (mbrf)	Penetration Depth:	1508.0/**606.0**[1] (mbsf)	Total Depth:	2239.0/**1337.0**[1] (mbrf)

BIT DATA:	Bit Size:	Make:	Model No.:	Jets:	Serial No.:	Cum. Hours:	Cum. Mtrs:	Graded:
Core Bit No. 1	9-7/8"	RBI	C-7	4x16	BM109	25.9	51.5	4,1,FC,N,E(B3),1,WT,DTF
Core Bit No. 2	9-7/8"	RBI	C-7	4x16	BM111	36.0	86.4	5,2,FC,N,E(B4),1,WT,CD,HR
Core Bit No. 3	9-7/8"	RBI	C-7	4x16	BM114	43.8	109.4	8,3,FC,BT,N,E(B5),1,WT,HR
Core Bit No. 4	9-7/8"	RBI	C-7	4x16	BM113	46.8	137.2	8,3,FC,BT,N,E(B4),1,WT,HR
Core Bit No. 5	9-7/8"	RBI	C-7	4x16	BM115	47.3	98.2	8,3,FC,BT,N,E(B4),1,WT,TQ
Core Bit No. 6	9-7/8"	RBI	C-7	4x16	BM110	45.9	111.9	8,4,FC,BT,LT,G,E(B3),1,WT,TQ
Core Bit No. 7	9-7/8"	RBI	C-7	4x16	BM108	33.3	91.7	5,1,FC,N,E(B4),1,WT,TQ
Core Bit No. 8	9-7/8"	RBI	C-7	4x16	BM107	53.8	169.5	8,3,FC,BT,N,E(B4),1,WT,TQ/HR
Core Bit No. 9	9-7/8"	RBI	C-7	4x16	BM106	8.8	25.8	4,1,NO,N,E(B3),2/16,WC
Core Bit No. 10	9-7/8"	RBI	C-7	4x16	BM112	33.9	121.6	**bit left in hole**[1]

Note: The 2 tricone drill bits and 2 reentry cleanout bits for logging were excluded from this list since there was no applicable wear, hours, or footage.

BEACON DATA:		Model:	Serial No.	Frequency:	Power:	Deployed:	Recovered:	Total Hours:
Primary #1	Datasonics	354M	2025	16.0 kHz	208 dB	1825/24 Oct	1730/1 Dec	911.3
Back-up #2	Datasonics	354M	2040	14.0 kHz	205 dB	1345/24 Oct	1645/1 Dec	915.0

BOTTOM HOLE ASSEMBLY (BHA): '[1]**NOTE: Pin failure. Total of 26 stands 5" DP plus 172 m of BHA left in hole!**

Coring: Bit, Bit Sub, Outer Core Barrel, Top Sub, Head Sub, 10 each 8-1/4" Drill Collars, Tapered Drill Collar, 2 stands of 5-1/2" Drill Pipe, X/O
Fishing: Overshot w/bit sub as req'd., 10 ' 8-1/4" Drill Collar pup, 2-8 ea 8-1/4" Drill Collars, Tapered Drill Collar, 2 stands of 5-1/2" Drill Pipe, X/O
Logging: RE cleanout bit, 2 ea 8-1/4" Drill Collars, Landing/Saver Sub w/Mod. Land. Ring f/VSP, Tapered Drill Collar, 2 stands of 5-1/2" Drill Pipe, X/O
(Note: A total of 3 sets of drilling jars were used (placed in BHA w/2 collars above) until the units developed cracks and were taken out of service)

DOWNHOLE TOOLS/MEASUREMENTS (Orientation, temperature, water sampler, etc.):

Phase I of logging was conducted to 492 mbsf prior to coring. The BHA was placed at 49 mbsf and 3 tool strings were deployed: (1) natural gamma (NGS), accelerator porosity (APS), hostile environment lithodensity (HLDS), dual ateral log (DLL) and temperature tool; (2) NGS, dipole shear sonic imager (DSI) and formation microscanner (FMS). This run was aborted due to data aquisition difficulties; (3) NGT, general purpose inclinometry tool (GPIT), and DLL. After DP failure Phase II logging went to 595 mbsf. This consisted of 4 tool string deployments with the following tools: (1) HLDT, caliper, APS, and HNGS; (2) NGT,DSI, GPIT, and FMS (same problem as before w/FMS data); (3) NGT, GPIT, and DLL. (4) Schlumberger VSP-ASI .

DRILLING/CORING STATISTICS:

Coring System	Bit No.	No. of Cores	Meters Cored	Meters Recovered	Percent Recovery	Meters Drilled	Total Meters	Average (Range of ROP)
RCB	1	8	51.5	34.32	66.6%	0.0	51.5	**2.0** (1.3 - 2.9)
RCB	2	15	86.4	64.05	74.1%	0.0	86.4	**2.4** (1.3 - 4.9)
RCB	3	13	109.4	96.43	88.1%	0.0	109.4	**2.5** (2.1 - 4.3)
RCB	4	16	137.2	106.15	77.4%	0.0	137.2	**2.9** (1.9 - 4.9)
RCB	5	11	98.2	91.28	93.0%	0.0	98.2	**2.1** (1.6 - 2.6)
RCB	6	12	111.9	106.35	95.0%	0.0	111.9	**2.4** (1.9 - 3.2)
RCB	7	11	91.7	86.81	94.7%	0.0	91.7	**2.8** (1.8 - 4.3)
RCB	8	19	169.5	140.80	83.1%	0.0	169.5	**3.1** (2.1 - 6.1)
RCB	9	4	25.8	25.44	98.6%	0.0	25.8	**2.9** (2.0 - 3.2)
RCB	10	13	121.6	114.36	94.0%	0.0	121.6	**3.6** (2.9 - 5.2)

FORMATION DATA:

FORMATION DATA:	Cored Interval (mbsf) / Nature / Description:		Comments:
0 - 500.7 mbsf	Cored on Leg 118.	Gabbro/Olivine-Gabbro	Lower 0.7 m cored with 3-3/4" NCB.
504.8 - 1508.0 mbsf	Cored on Leg 176.	Gabbro/Olivine-Gabbro	Leg 176 tagged 4.8 m deeper than Leg 118.

MUD/CEMENT USAGE:

Bentonite gel mud weeps were pumped in volumes of 20-30 bbls every other core or after every core if rapid ROP or other hole conditions warranted.

WEATHER/SEAS:

Weather and sea state was variable throughout the leg. Large, long period, swells from the south were prevalent most of the leg creating large vessel heave (2-3 m). Swells were often from two different directions and when coupled with the moderate wind (20-30 kt) and erratic current (1-2 kt from a northerly or southerly direction) they created some difficulty for the DP operators in minimizing roll/pitch. Gale force 8/9 winds and seas were experienced at times during the leg. Due to the shallow water this led to several yellow and red positioning alerts.

Bit No.	Time/Date (TOD)	Core No.	Hours Since Last Core	Rotating Time (min)	Total Cores	Meters Cored	Meters Recovery	Percent Recovery	ROP (m/hr)	Bit Hours	Bit Total (hours)	Bit Total (meters)	Depth (mbsf)	Remarks
1	**26-Oct**	89R	n/a	70	1	3.0	2.05	68.3%	2.57	1.2	1.2	3.0	507.8	0.7m w/ncb
		90R	4.1	200	1	9.6	9.88	102.9%	2.88	3.3	4.5	12.6	517.4	55 rpm/22k
		91R	4.3	210	1	9.6	5.87	61.1%	2.74	3.5	8.0	22.2	527.0	liner jam
		92R	3.3	160	1	5.1	2.23	43.7%	1.91	2.7	10.7	27.3	532.1	liner jam
	27-Oct	93R	3.3	140	1	4.5	5.02	111.6%	1.93	2.3	13.0	31.8	536.6	60 rpm/22k
		94R	5.2	240	1	8.0	3.48	43.5%	2.00	4.0	17.0	39.8	544.6	liner jam
		95R	3.5	165	1	3.7	3.00	81.1%	1.35	2.8	19.8	43.5	548.3	20-30k
		96R	9.3	370	1	8.0	2.79	34.9%	1.30	6.2	25.9	51.5	556.3	**POOH**
2	**28-Oct**	97R	**13.3**	215	1	4.7	4.89	104.0%	1.31	3.6	29.5	56.2	561.0	**bit break in**
		98R	2.1	60	1	4.9	2.28	46.5%	4.90	1.0	30.5	61.1	565.9	liner jam
		99R	5.1	210	1	9.6	7.49	78.0%	2.74	3.5	34.0	70.7	575.5	w/o c/liner
		100R	4.2	210	1	9.6	3.00	31.3%	2.74	3.5	37.5	80.3	585.1	w/o c/liner
	29-Oct	101R	3.3	180	1	4.8	3.86	80.4%	1.60	3.0	40.5	85.1	589.9	w/o c/liner
		102R	2.5	115	1	4.9	3.53	72.0%	2.56	1.9	42.4	90.0	594.8	w/o c/liner
		103R	3.4	165	1	9.5	5.81	61.2%	3.45	2.8	45.2	99.5	604.3	w/o c/liner
		104R	2.3	100	1	4.5	2.53	56.2%	2.70	1.7	46.8	104.0	608.8	w/o c/liner
		105R	3.8	180	1	5.1	4.70	92.2%	1.70	3.0	49.8	109.1	613.9	w/o c/liner
		106R	3.3	160	1	5.6	4.91	87.7%	2.10	2.7	52.5	114.7	619.5	w/o c/liner
		107R	2.1	95	1	4.0	3.01	75.3%	2.53	1.6	54.1	118.7	623.5	w/o c/liner
		108R	3.3	140	1	5.2	5.05	97.1%	2.23	2.3	56.4	123.9	628.7	w/o c/liner
	30-Oct	109R	2.8	110	1	4.4	4.55	103.4%	2.40	1.8	58.3	128.3	633.1	w/o c/liner
		110R	2.8	130	1	4.9	5.18	105.7%	2.26	2.2	60.4	133.2	638.0	w/o c/liner
		111R	2.6	90	1	4.7	3.26	69.4%	3.13	1.5	61.9	137.9	642.7	**POOH**
3		112R	**16.7**	140	1	5.0	4.48	89.6%	2.14	2.3	64.3	142.9	647.7	**bit break in**
	31-Oct	113R	3.3	130	1	4.7	2.76	58.7%	2.17	2.2	66.4	147.6	652.4	w/o c/liner
		114R	5.4	280	1	9.6	7.92	82.5%	2.06	4.7	71.1	157.2	662.0	w/o c/liner
		115R	5.1	265	1	9.6	9.42	98.1%	2.17	4.4	75.5	166.8	671.6	w/o c/liner
		116R	4.5	225	1	9.6	7.96	82.9%	2.56	3.8	79.3	176.4	681.2	w/o c/liner
		117R	5.5	275	1	9.6	7.13	74.3%	2.09	4.6	83.8	186.0	690.8	w/o c/liner
	01-Nov	118R	5.2	275	1	9.6	9.50	99.0%	2.09	4.6	88.4	195.6	700.4	w/o c/liner
		119R	3.2	135	1	9.6	5.88	61.3%	4.27	2.3	90.7	205.2	710.0	w/o c/liner
		120R	4.1	215	1	9.7	9.27	95.6%	2.71	3.6	94.3	214.9	719.7	w/o c/liner
		121R	5.0	245	1	9.7	10.04	103.5%	2.38	4.1	98.3	224.6	729.4	w/o c/liner
		122R	4.0	190	1	9.6	9.28	96.7%	3.03	3.2	101.5	234.2	739.0	w/o c/liner
		123R	3.8	195	1	9.7	9.46	97.5%	2.98	3.3	104.8	243.9	748.7	w/o c/liner
	02-Nov	124R	2.1	55	1	3.4	3.33	97.9%	3.71	0.9	105.7	247.3	752.1	**POOH**

Bit No.	Time/Date (TOD)	Core No.	Hours Since Last Core	Rotating Time (min)	Total Cores	Meters Cored	Meters Recovery	Percent Recovery	ROP (m/hr)	Bit Hours	Bit Total (hours)	Bit Total (meters)	Depth (mbsf)	Remarks
4		125R	**15.0**	100	1	3.2	0.57	17.8%	1.92	1.7	107.3	250.5	755.3	**drift 4.50º**
		126R	3.4	140	1	9.6	7.90	82.3%	4.11	2.3	109.7	260.1	764.9	w/o c/liner
		127R	3.1	130	1	9.6	6.38	66.5%	4.43	2.2	111.8	269.7	774.5	w/o c/liner
	03-Nov	128R	3.6	165	1	9.7	6.16	63.5%	3.53	2.8	114.6	279.4	784.2	w/o c/liner
		129R	4.4	200	1	9.7	3.90	40.2%	2.91	3.3	117.9	289.1	793.9	w/o c/liner
		130R	4.4	230	1	9.6	4.30	44.8%	2.50	3.8	121.8	298.7	803.5	w/o c/liner
		131R	2.8	120	1	9.7	4.83	49.8%	4.85	2.0	123.8	308.4	813.2	w/o c/liner
		132R	4.2	200	1	9.7	9.46	97.5%	2.91	3.3	127.1	318.1	822.9	w/o c/liner
		133R	4.1	210	1	9.7	9.34	96.3%	2.77	3.5	130.6	327.8	832.6	w/o c/liner
	04-Nov	134R	4.6	220	1	9.6	9.60	100.0%	2.62	3.7	134.3	337.4	842.2	w/o c/liner
		135R	3.0	140	1	4.7	4.57	97.2%	2.01	2.3	136.6	342.1	846.9	w/o c/liner
		136R	2.4	100	1	4.9	4.69	95.7%	2.94	1.7	138.3	347.0	851.8	w/o c/liner
		137R	4.5	225	1	9.6	9.10	94.8%	2.56	3.8	142.0	356.6	861.4	w/o c/liner
		138R	4.7	230	1	9.7	8.78	90.5%	2.53	3.8	145.8	366.3	871.1	w/o c/liner
		139R	4.1	205	1	9.2	8.79	95.5%	2.69	3.4	149.3	375.5	880.3	w/o c/liner
	05-Nov	140R	4.1	190	1	9.0	7.78	86.4%	2.84	3.2	152.4	384.5	889.3	**POOH**
5	**06-Nov**	141R	**42.0**	105	1	3.6	2.54	70.6%	2.06	1.8	154.2	388.1	892.9	**bit break in**
	07-Nov	142R	4.9	240	1	9.7	8.97	92.5%	2.43	4.0	158.2	397.8	902.6	TQ/30 bbls
		143R	4.4	225	1	9.7	8.86	91.3%	2.59	3.8	161.9	407.5	912.3	TQ/30 bbls
		144R	4.7	230	1	9.6	8.81	91.8%	2.50	3.8	165.8	417.1	921.9	TQ/30 bbls
		145R	4.3	220	1	9.6	8.10	84.4%	2.62	3.7	169.4	426.7	931.5	TQ/30 bbls
		146R	5.0	255	1	9.7	8.48	87.4%	2.28	4.3	173.7	436.4	941.2	30 bbls
	08-Nov	147R	5.6	300	1	9.7	9.08	93.6%	1.94	5.0	170.75	426.8	931.6	30 bbls
		148R	6.3	335	1	9.6	9.18	95.6%	1.72	5.6	176.33	436.4	941.2	30 bbls
		149R	6.5	345	1	9.6	9.90	103.1%	1.67	5.8	5.75	9.6	9.6	20 bbls
		150R	5.7	300	1	9.7	9.56	98.6%	1.94	5.0	10.75	19.3	19.3	30 bbls
	09-Nov	151R	5.3	285	1	7.7	7.80	101.3%	1.62	4.8	15.50	27.0	27.0	**TQ +40**
6		152R	**15.6**	250	1	8.2	7.96	97.1%	1.97	4.2	19.67	35.2	35.2	**bit break in**
		153R	5.3	270	1	9.6	8.65	90.1%	2.13	4.5	24.17	44.8	44.8	20 bbls
	10-Nov	154R	5.4	275	1	9.7	8.34	86.0%	2.12	4.6	28.75	54.5	54.5	20 bbls
		155R	5.8	300	1	9.7	9.34	96.3%	1.94	5.0	33.75	64.2	64.2	20 bbls
		156R	5.1	265	1	9.6	9.86	102.7%	2.17	4.4	38.17	73.8	73.8	30 bbls
		157R	4.2	210	1	9.7	8.33	85.9%	2.77	3.5	41.67	83.5	83.5	20 bbls
		158R	3.8	215	1	9.7	9.54	98.4%	2.71	3.6	45.25	93.2	93.2	20 bbls
	11-Nov	159R	3.8	180	1	9.7	8.83	91.0%	3.23	3.0	48.25	102.9	102.9	20 bbls
		160R	4.5	210	1	9.6	9.33	97.2%	2.74	3.5	51.75	112.5	112.5	20 bbls
		161R	4.2	200	1	9.6	9.77	101.8%	2.88	3.3	55.08	122.1	122.1	20 bbls
		162R	4.2	205	1	9.6	9.59	99.9%	2.81	3.4	58.50	131.7	131.7	20 bbls
		163R	4.1	175	1	7.2	6.81	94.6%	2.47	2.9	61.42	138.9	138.9	**TQ +40**

Bit No.	Time/Date (TOD)	Core No.	Hours Since Last Core	Rotating Time (min)	Total Cores	Meters Cored	Meters Recovery	Percent Recovery	ROP (m/hr)	Bit Hours	Bit Total (hours)	Bit Total (meters)	Depth (mbsf)	Remarks
7	**12-Nov**	164R	**12.9**	115	1	5.9	4.61	78.1%	3.08	1.9	63.33	144.8	144.8	**10K/50 rpm**
		165R	4.0	190	1	5.6	7.00	125.0%	1.77	3.2	66.50	150.4	150.4	20 bbls
		166R	4.2	215	1	9.6	8.65	90.1%	2.68	3.6	70.08	160.0	160.0	20 bbls
		167R	4.9	250	1	9.6	9.05	94.3%	2.30	4.2	74.25	169.6	169.6	20 bbls
	13-Nov	168R	4.1	200	1	9.6	9.21	95.9%	2.88	3.3	77.58	179.2	179.2	20 bbls
		169R	5.1	225	1	9.6	8.39	87.4%	2.56	3.8	81.33	188.8	188.8	20 bbls
		170R	3.8	190	1	9.7	9.86	101.6%	3.06	3.2	84.50	198.5	198.5	20 bbls
		171R	4.7	235	1	9.7	9.66	99.6%	2.48	3.9	88.42	208.2	208.2	20 bbls
		172R	3.8	180	1	9.7	9.14	94.2%	3.23	3.0	91.42	217.9	217.9	20 bbls
		173R	2.9	135	1	9.7	8.54	88.0%	4.31	2.3	93.67	227.6	227.6	20 bbls
	14-Nov	174R	2.0	60	1	3.0	2.70	90.0%	3.00	1.0	94.67	230.6	230.6	**TQ +100**
8		175R	**-8745.3**	125	1	5.6	5.52	98.6%	2.69	2.1	96.75	236.2	236.2	**10K/50 rpm**
		176R	2.3	90	1	5.0	4.00	80.0%	3.33	1.5	98.25	241.2	241.2	20 bbls
		177R	3.1	140	1	9.6	9.23	96.1%	4.11	2.3	100.58	250.8	250.8	20 bbls
		178R	3.4	160	1	9.6	9.48	98.8%	3.60	2.7	103.25	260.4	260.4	20 bbls
	15-Nov	179R	3.4	160	1	9.6	9.92	103.3%	3.60	2.7	105.92	270.0	270.0	20 bbls
		180R	3.3	135	1	9.7	7.74	79.8%	4.31	2.3	108.17	279.7	279.7	20 bbls
		181R	2.4	95	1	9.7	4.89	50.4%	6.13	1.6	109.75	289.4	289.4	30 bbls
		182R	2.8	120	1	9.7	4.44	45.8%	4.85	2.0	111.75	299.1	299.1	30 bbls
		183R	3.4	160	1	9.6	7.34	76.5%	3.60	2.7	114.42	308.7	308.7	30 bbls
		184R	3.8	170	1	9.6	7.67	79.9%	3.39	2.8	117.25	318.3	318.3	30 bbls
		185R	3.9	185	1	9.6	8.61	89.7%	3.11	3.1	120.33	327.9	327.9	50 bbls
	16-Nov	186R	3.3	155	1	8.8	8.09	91.9%	3.41	2.6	122.92	336.7	336.7	50 bbls
		187R	5.2	165	1	9.7	7.25	74.7%	3.53	2.8	125.67	346.4	346.4	30 bbls
		188R	4.1	185	1	9.6	9.05	94.3%	3.11	3.1	128.75	356.0	356.0	20 bbls
		189R	5.2	270	1	9.6	9.22	96.0%	2.13	4.5	133.25	365.6	365.6	20 bbls
		190R	5.0	255	1	9.6	8.22	85.6%	2.26	4.3	137.50	375.2	375.2	20 bbls
	17-Nov	191R	5.2	260	1	9.6	9.22	96.0%	2.22	4.3	141.83	384.8	384.8	20 bbls
		192R	4.9	250	1	9.7	9.52	98.1%	2.33	4.2	146.00	394.5	394.5	20 bbls
		193R	3.3	150	1	5.6	1.39	24.8%	2.24	2.5	148.50	400.1	400.1	**TQ +/-50**
9	**18-Nov**	194R	**18.2**	70	1	3.5	3.48	99.4%	3.00	1.2	149.67	403.6	403.6	**10K/50 rpm**
		195R	4.3	180	1	9.6	9.13	95.1%	3.20	3.0	152.67	413.2	413.2	20 bbls
		196R	4.1	180	1	9.6	8.39	87.4%	3.20	3.0	155.67	422.8	422.8	20 bbls
		197R	3.1	95	1	3.1	4.44	143.2%	1.96	1.6	157.25	425.9	425.9	**WOW**

Bit No.	Time/Date (TOD)	Core No.	Hours Since Last Core	Rotating Time (min)	Total Cores	Meters Cored	Meters Recovery	Percent Recovery	ROP (m/hr)	Bit Hours	Bit Total (hours)	Bit Total (meters)	Depth (mbsf)	Remarks
10	**20-Nov**	198R	**37.7**	90	1	6.0	5.47	91.2%	4.00	1.5	158.75	431.9	431.9	**10K/50 rpm**
		199R	2.5	110	1	9.6	8.50	88.5%	5.24	1.8	160.58	441.5	441.5	20 bbls
		200R	2.9	120	1	9.6	8.98	93.5%	4.80	2.0	162.58	451.1	451.1	20 bbls
		201R	3.3	155	1	9.6	9.00	93.8%	3.72	2.6	165.17	460.7	460.7	20 bbls
		202R	3.8	175	1	9.6	9.75	101.6%	3.29	2.9	168.08	470.3	470.3	30 bbls
		203R	3.5	165	1	9.7	8.50	87.6%	3.53	2.8	170.83	480.0	480.0	30 bbls
	21-Nov	204R	3.7	165	1	9.7	8.99	92.7%	3.53	2.8	173.58	489.7	489.7	30 bbls
		205R	3.8	180	1	9.7	10.32	106.4%	3.23	3.0	176.58	499.4	499.4	30 bbls
		206R	3.7	160	1	9.6	8.07	84.1%	3.60	2.7	179.25	509.0	509.0	30 bbls
		207R	3.2	140	1	9.6	8.51	88.6%	4.11	2.3	181.58	518.6	518.6	30 bbls
		208R	4.6	185	1	9.6	9.57	99.7%	3.11	3.1	184.67	528.2	528.2	**drift 4.80º**
		209R	4.2	200	1	9.6	9.77	101.8%	2.88	3.3	188.00	537.8	537.8	30 bbls
		210R	4.1	190	1	9.7	8.93	92.1%	3.06	3.2	191.17	547.5	547.5	**DP failure**

TECHNICAL REPORT

The ODP technical and logistics personnel aboard *JOIDES Resolution* for Leg 176 were:

John Dyke	Marine Logistics Specialist (Storekeeper/Shipping)
Dave Fackler	Marine Computer Specialist (Programming)
Tim Fulton	Marine Lab Specialist (Photographer)
Dennis Graham	Marine Lab Specialist (Acting Lab Officer/ Underway/Chemistry)
Gus Gustafson	Assistant Lab Officer/Marine Lab Specialist (Downhole Tools)
Michelle Hardee	Marine Lab Specialist
Margaret Hastedt	Marine Computer Specialist
Michiko Hitchcox	Marine Lab Specialist (Yeoperson)
Melissa McEwen	Marine Lab Specialist (Physical Properties)
Eric Meissner	Marine Electronics Technician
Ofeigur Ofeigsson	Marine Lab Specialist
Bob Olivas	Marine Lab Specialist (X-ray)
Drew Patrick	Marine Lab Specialist (Assistant Curator)
Chieh Peng	Marine Lab Specialist (Chemistry)
Larry St. John	Marine Electronics Specialist
Don Sims	Marine Lab Specialist (Assistant Lab Officer/X-ray)
Lorraine Southey	Marine Lab Specialist (Curator)
Chris Stephens	Marine Computer Specialist

GENERAL LEG INFORMATION

The *JOIDES Resolution* docked in Cape Town, South Africa, on 8 October, ending Leg 175 two days earlier than scheduled. The Leg 176 technical crew boarded the vessel on the morning of 10 October for crossover activities with the off-going crew.

On 15 October, we departed Cape Town with a ship's complement of 114, 66 Sedco and 48 ODP. The technical staff consisted of 18 members. Four of the 18 technicians sailed for the first time on the *JOIDES Resolution*.

The transit to Hole 735B was hampered by strong winds and opposing current. The scheduled 7-day transit took 9 days. Drilling operations began on 24 October and ended on 2 December. The transit back to Cape Town took 7 days, thus, ending the leg on 9 December.

Port Call Activities Overview

The pacing item during this port call was Sedco's installation of radio equipment. Offloading Leg 175's 8 km of core took 2 days and filled four refrigerated containers. The process was smooth owing to the uninterrupted use of the Sedco crane. Other port call activities were routine and included loading of freight and supply distribution. Brad Julson, Supervisor of Technical Support, conducted a joint meeting with both technical crews and, later in the port call, met with a smaller group to discuss drydock matters.

Transit Activities

We collected navigation data at 1-min intervals for the entire leg. Bathymetry and magnetics data were collected on the transit from Cape Town to Hole 735B.

LAB ACTIVITIES

Following in the footsteps of Leg 175, a record-breaking core recovery leg, Leg 176 was a record-breaking hard-rock recovery leg. It was a beautiful sight to see 9.5 m of hard rock, core after core, but it put our procedures for handling hard rock to a test. Hard-rock curation had evolved from years of obtaining far less material per leg and, as a result, required procedures that were too time consuming for the amount of core we collected this leg. At the beginning of the leg, the co-chief scientists divided the scientists into three groups: igneous petrologists, metamorphic petrologists, and structural geologists. Each group worked a shift in the lab, leaving a 6-hr period at night when no scientists were working in the lab. This required that a core be in the lab for at least 18 hr. With cores coming up at approximately 3-hr intervals, the dilemma was obvious. The co-chiefs also decided to delay all personal sampling until the end of the leg, thereby requiring all the working halves to be brought back to the lab. This plan benefitted the scientists immensely because there were absolutely no disagreements between shifts as is common on legs where scientists cover the lab 24 hr per day with two shifts. Also, before any personal samples were taken, all the material had been recovered. From a core-flow perspective, this plan only worked for two reasons. First, bit changes were required at 3-day intervals, thereby providing a break where the lab could get caught up. Second, the drill string broke off in the hole, ending the coring a week early. If coring had proceeded normally until the end of the leg, there would not have been enough time to process all the personal samples and attend to normal end of the leg cleanup, reports, and organization, especially for the curatorial staff. As stated in the Leg 175 Lab Officer's report, record-breaking legs stress our technical staff to an unacceptable limit. The same can be said for this leg with the amount of hard rock recovered and the procedures imposed for handling the material. As an example, the technical staff glued approximately 15,000 hard-rock labels on pieces of rock, a very time-consuming and tedious task. Another example was the multiple handling of core boxes from the core lab to the reefer. The working sections were actually handled three times this leg: first to store them, second to bring them back to mark the samples, and third to cut the samples. Core lab manpower was limited during the night shift primarily because the thin sections and X-ray fluorescence samples required the full-time attention of three technicians. The overall result was that the scientists were able to work harmoniously at the expense of the technical staff, who came seriously close to having interpersonal conflicts get out of hand.

Chemistry Lab

X-ray fluorescence samples were analyzed for carbon, nitrogen, hydrogen, and sulfur (CNHS). Only one chemistry technician sailed this leg, and most of her time was spent helping with curation in the core lab. A chemistry instrument service tracking system was developed using FileMaker Pro.

Computer Services

Support for the increasingly complex shipboard computer system now requires two system managers and one programmer for JANUS support. With the exception of network crashes, the system was quite stable. Most of the time, allocation went to assisting scientists, technicians, and Sedco personnel with hardware and software problems, most falling into the category of user training. One of the system managers was new and overlapped 6 hr with the other system manager for training. The JANUS programmer covered the system for the other 6-hr period. Special projects included:

- The fiber optic network Cabletron equipment installation.
- Set up and testing the new server for the imaging system.
- Installing one of the new janusaxp servers.
- Testing the Ffastest high speed data (HSD) system on the SeaNet system. It worked fine. Procedures need to be determined for its use as an e-mail transfer system on future legs.

The special conditions and requirements of hard-rock operations brought to light an unexpected variety of software operation and design issues primarily concerning JANUS—data upload and data acquisition. The problems were resolved for the most part, but it called to attention the need for a JANUS programmer to sail on upcoming legs.

Core Lab

Lab procedures were modified significantly from the normal for this leg. After initial unsuccessful attempts to use core liners, all cores were drilled without a core liner. Because the quality of the core was good, this actually simplified our handling of the core, except that all the core had to be scrubbed with a brush to remove rust and dirt from the barrel. The core was video scanned (DMT Color CoreScan) and run through the multisensor track before being cut into working and archive sections. Paleomagnetic measurements, photography, and thermal conductivity measurements were done with the archive section. The scientists used the working half for descriptions, samples, and physical properties measurements. All personal samples were taken after the drill pipe broke off in the hole and coring operations ceased.

Curation

This was an unusually demanding leg for the shipboard curator and assistant curator because of the stringent guidelines and policies governing hard-rock curation and sampling. With normal hard-rock recovery these policies are reasonable, but the shear quantity of hard rock recovered made curation a tedious task. Because of the curatorial complexities, future hard-rock legs should read and take to heart the curatorial report from this leg. Cores from Leg 118 were shipped to Cape Town and studied on the transit to Hole 735B.

Downhole Measurements Lab

The Davis-Villinger temperature probe was tested in anticipation of needing an open hole temperature measurement. Because of hole problems the tool was not deployed.

Paleomagnetics Lab

The regularly scheduled technician was unable to make it to Cape Town to participate on this leg. The three scientists, however, had all sailed previously, and one of our computer techs was a former magnetics tech. Despite initial disappointment that the new cryomag's dynamic range was lacking on the higher end, a tremendous amount of data was acquired from the split sections and minicore samples.

Photography Lab and Microscope Services

Routine operations with no special projects or problems to report.

Physical Properties Lab

All whole-round sections of hard rock were measured on the multisensor track using the gamma-ray attenuation porosity evaluator (GRAPE) sensor, magnetic susceptibility sensor, and natural gamma sensor. Minicore samples were used for index properties and velocity measurements. Pieces from the archive section were used for thermal conductivity measurements. Resistivity was attempted but abandoned, because the values were not consistent.

Thin Section Lab

Making thin sections was a full-time effort for one technician. The coarse-grained gabbros often required oversized billets and sections.

Underway Geophysics and Fantail

The scientific plan did not require seismic surveys, but a VSP experiment required rigging and hanging a 1000-cubic-inch air gun and 400-cubic-inch water gun over the side using crane #3. An air-powered winch wrapped with a fuzz-fairing hydrophone cable was welded to the top of the welder's shack. The hydrophone was deployed during the VSP to a depth of 300 m. Bathymetry and magnetics were collected during the first transit. Navigation was continuously recorded during the leg. The equipment spare parts were relocated into new cabinets, and the area behind the equipment racks was cleaned out to make a safer and more efficient work space.

X-ray Lab

Preparing and analyzing samples took the full-time attention of two technicians, one for sample preparation and one to run the X-ray fluorescence equipment. Samples were prepared for both major and trace elements. The X-ray diffraction unit received limited use.

Electronic Services

Electronics maintenance required the support of two technicians to keep the lab equipment functioning on a 24-hr basis. In addition to routine maintenance and troubleshooting, the electronics techs installed a Quorum weather satellite system on the bridge, a weatherproof box on the Schlumberger maxi cab to plug guns, blast phones cables for VSP experiments, assisted in the installation of an EPC recorder for seismic display, and updated the lab stack electrical line drawings.

Safety

Four members of the technical staff participated on the marine emergency technical squad (METS). The team participated in all Sedco fire drills and staged a chemical spill in the lab stack for one of the drills.

LEG 176 STATISTICS

Sites:	1
Holes:	1
No. of Cores:	122
Meters Cored (m):	1003.2
Meters Recovered (m):	866
Number of General Samples:	3165
Whole Core Multisensor Track	
GRAPE (sections):	763
Natural Gamma Radiation (sections):	763
Magnetic Susceptibility (sections):	763
Physical Properties Lab:	
PVS #3 Velocity:	205
Resistivity:	40
Moisture-Density:	213
Thermal Conductivity:	218
X-ray Lab	
X-ray Fluorescence:	
Majors:	279
Trace:	196
X-ray Diffraction:	13
Thin Section Lab	
Thin Sections:	253
Chemistry Lab	
Carbon-Nitrogen-Hydrogen-Sulfur:	60
Underway Geophysics	
Total Transit (nmi):	4000
Bathymetry(nmi):	1900
Magnetics(nmi):	1900
Vertical Seismic Profile:	1
Paleomagnetic Lab	
Cryogenic magnetometer (sections):	763
Molspin:	346