# OCEAN DRILLING PROGRAM

## LEG 121 PRELIMINARY REPORT

## BROKEN RIDGE AND NINETYEAST RIDGE


Dr. John Peirce
Co-Chief Scientist, Leg 121
Petro Canada
P. O. Box 2844
Calgary, Alberta T2P 3E3
Canada

Dr. Jeffrey Weissel
Co-Chief Scientist, Leg 121
Lamont-Doherty Geological
Observatory
Palisades, NY 10964

Dr. Elliott Taylor
Staff Scientist, Leg 121
Ocean Drilling Program
Texas A&M University
College Station, TX 77840


Philip D. Rabinowitz
Director
ODP/TAMU

Audrey W. Meyer
Manager of Science Operations
ODP/TAMU

Louis E. Garrison
Deputy Director
ODP/TAMU

August, 1988

Preliminary Report No. 121
First Printing 1988

Distribution

Copies of this publication may be obtained from the Director, Ocean Drilling Program, Texas A&M University Research Park, 1000 Discovery Drive, College Station, Texas 77840. In some cases, orders for copies may require a payment for postage and handling.

DISCLAIMER

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:

Department of Energy, Mines and Resources (Canada)
Deutsche Forschungsgemeinschaft (Federal Republic of Germany)
Institut Francais 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, Greece, the Netherlands, Norway, Spain, Sweden, Switzerland, and Turkey)

PRELIMINARY REPORT

The scientific party aboard _JOIDES Resolution_ for Leg 121 of the Ocean Drilling Program consisted of:


John Peirce (Co-Chief Scientist), Petro Canada, P.O. Box 2844, Calgary, Alberta T2P 3E3

Jeffrey Weissel (Co-Chief Scientist), Lamont-Doherty Geological Observatory, Palisades, New York 10964

Elliott Taylor (Staff Scientist), Ocean Drilling Program, 1000 Discovery Dr., Texas A&M University Research Park, College Station, Texas 77840

Jonathan Dehn, Institut Fuer Mineralogie, Ruhr-Universitaet Bochum, Postfach 10 21 48, D-4630 Bochum 1, F.R. Germany

Neal Driscoll, Lamont-Doherty Geological Observatory, Palisades, New York 10964

John Farrell, Brown University, Providence, Rhode Island 02912

Elisabeth Fourtanier, Lab. d'Etude des Diatomees, Ecole Normale Superieure, BP 81, 92266 Fontenay-aux-Roses Cedex, France

Fred Frey, Department of Earth, Atmospheric and Planetary Science, 54-1220, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Paul D. Gamson, Open University, Dept. of Earth Sciences, Walton Hall, Milton Keynes, United Kingdom

Jeffrey S. Gee, A-008, Scripps Institution of Oceanography, La Jolla, California 92093

Ian L. Gibson, Department of Earth Science, University of Waterloo, Waterloo, Ontario N2L 3G1 Canada

Thomas Janecek, Lamont-Doherty Geological Observatory, Palisades, New York 10964

Chris Klootwijk, Bureau of Mineral Resources, Geology and Geophysics, P.O. Box 378, Canberra ACT 2601, Australia

James R. Lawrence, Department of Geosciences, University of Houston, 4800 Calhoun, Houston, Texas 77004

Ralf Littke, Institute of Petroleum and Organic Geochemistry (ICH-5), Nuclear Research Centre (KFA), Postbox 1913, 5170 Juelich, Federal Republic of Germany

Jerry S. Newman, GECO Geophysical Company, 1325 S. Dairy Ashford, Houston, Texas 77077

Ritsuo Nomura, Department of Earth Sciences, Faculty of Education, Shimane University, Matsue, Shimane Prefecture, 690, Japan

Robert M. Owen, Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063

James J. Pospichal, Department of Geology, Florida State University, Tallahassee, Florida 32306

David K. Rea, Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063

Purtyasti Resiwati, Department of Geology, University of Nebraska, 214 Bessey Hall, Lincoln, Nebraska 68588-0340

Andrew D. Saunders, Department of Geology, University of Leicester, Leicester LE1 7RH, United Kingdom

Jan Smit, Geological Institute, Free University, P.O. Box 7161, 1007 MC, Amsterdam, Netherlands

Guy M. Smith, Department of Earth and Atmospheric Sciences, St. Louis University, P.O. Box 8099 Laclede Sta., St. Louis, Missouri 63156

Kensaku Tamaki, Ocean Research Institute, University of Tokyo, 1-15-1 Minami-dai, Nakano, Tokyo 164, Japan

Dominique Weis, Laboratoires Associés Géologie-Pétrologie-Géochronologie, C.P. 160 Universite Libre de Bruxelles, Avenue F.D. Roosevelt, 50 B.1050 Brussels, Belgium
Craig Wilkinson, Lamont-Doherty Geological Observatory, Palisades, New York 10964

## ABSTRACT

Ocean Drilling Program Leg 121 drilled a transect of four closely spaced sites (Sites 752-755) across the crest of Broken Ridge, and three widely separated sites (Sites 756-758) on a latitudinal transect along Ninetyeast Ridge. The principal drilling results show that rifting at Broken Ridge began about 47-50 Ma, lasted 3-7.5 m.y., and was preceded by mainly pelagic sedimentation in increasing water depths. During rifting, Broken Ridge was uplifted more than 2000 m at its south-facing escarpment, and wave-base erosion of subaerially exposed pre-rift strata created the truncation surface observed in seismic records. A thin layer of middle Eocene clastics was deposited on the subsiding crest of Broken Ridge, succeeded by upper Eocene through Holocene winnowed carbonate oozes punctuated by a mid-Oligocene hiatus. Rifting at Broken Ridge was initiated by an intraplate or far-field stress regime, rather than by a mantle convection process, which would require precursory shoaling of Broken Ridge not observed in the sediment record. Basaltic ashes in the lower Turonian to middle Eocene section at Broken Ridge record the eruption history of nearby Kerguelen hotspot volcanism.

Biostratigraphic estimates of basement ages at the ODP sites drilled on the Ninetyeast Ridge increase from south to north in a manner consistent with the predictions of the hotspot model. The lavas forming the Ninetyeast Ridge are moderately evolved tholeiites, with trace-element ratios indicative of mixed mid-ocean-ridge and Kerguelen Island magmas. The Ninetyeast Ridge was constructed by discrete volcanic centers that were mostly subaerial. Large amounts of basaltic ash were produced as these centers emerged and then subsided again. Marginal to the centers were deep water pillows and sheet flows. The preliminary interpretation is that the ridge formed as newly created Indian Plate material passed over the Kerguelen/Ninetyeast hotspot. The position of the segment of the Indian-Antarctic spreading center immediately south of the Ninetyeast Ridge may have been related to the position of the hotspot.

The sediments recovered along the south-to-north transect record Campanian to Miocene assemblage transitions from temperate to tropical forms. The sediments recovered from Site 758 include an upper Miocene to Holocene terrigenous clay component, presumably of Himalayan origin, and record a superb magnetostratigraphy over the last 7 m.y. as well as a tephrochronology of silicic volcanism from the Indonesian arc.

## INTRODUCTION

### Tectonic Setting

The Kerguelen-Heard Plateau, Broken Ridge and Ninetyeast Ridge (Fig. 1) all have tectonic histories which are derived from the history of the Kerguelen/Ninetyeast hotspot in the context of the evolution of the Indian Ocean (Sclater and Fisher, 1974; Schlich, 1982; Patriat, 1983; Patriat and Achache, 1984). Broken Ridge and the Kerguelen-Heard Plateau are conjugate rifted fragments of an oceanic platform (Fig. 2), which likely formed from intraplate volcanism in Early or mid-Cretaceous time (e.g., Morgan, 1981).

The basement rocks of both features are basaltic, based on the recovery to date from limited dredging (Leclaire et al., 1987; RC2708 Cruise Report, unpubl.) and ODP Legs 119 and 120 drilling results (Barron, Larsen, et al., 1988; Schlich, Wise, et al., in press). The Ninetyeast Ridge is interpreted to be a hotspot trace of mid-Cretaceous to Oligocene age produced when the Kerguelen hotspot was either under the Indian Plate or at the Indian/Antarctic spreading center (Luyendyk, 1977; Luyendyk and Rennick, 1977). Basement rocks recovered from the Ninetyeast Ridge on DSDP Legs 22 and 26 (von der Borch, Sclater, et al., 1974; Davies, Luyendyk, et al., 1974) are basaltic with geochemical affinities with Kerguelen (Frey et al., 1977; Mahoney et al., 1983; Weis et al., 1987). Furthermore, the increasing age to the north (Duncan, 1978) and the paleolatitudes near 50°S of the basalts (Peirce, 1978) indicate a genetic relationship between Ninetyeast Ridge and the Kerguelen-Heard Plateau.

## Broken Ridge

The present separation of Broken Ridge and the Kerguelen Plateau (the northern half of the Kerguelen-Heard Plateau) is due to lithospheric extension (i.e. rifting) and to seafloor spreading which began before anomaly-18 time (~42 Ma, Berggren et al., 1985; Mutter and Cande, 1983) and has continued to the present day. Since middle Eocene time, Broken Ridge has moved north by about 20° of latitude as part of the Indo-Australian Plate, while the Kerguelen-Heard Plateau, as part of the Antarctic Plate, has moved very little latitudinally.

Broken Ridge is particularly noteworthy because the effects of rifting are evident in its seismic stratigraphy (Fig. 3). Because Broken Ridge has remained a fairly shallow-water platform throughout its history, the stratigraphic section there has potential for providing a clear record of vertical motion as it responded to the rifting process. In particular, rift-related uplift exposed parts of Broken Ridge above sea level, and a distinctive angular unconformity was cut across the pre-rift strata by wave-base erosion.

## Drilling Objectives on Broken Ridge

The overall aim for drilling at Broken Ridge was to extract rift-related information from the preserved sedimentary record to help understand how the lithosphere responds to extension. Two major problems concerning lithospheric extension which were addressed through drilling at Broken Ridge are;

1. What is the role of the sub-lithospheric mantle in initiating lithospheric extension? This question concerns the nature and origin of the tectonic forces that "drive" extension, i.e., "active" vs. "passive" rifting.

2. What is the magnitude of vertical motion of rift flanks during (and after) extension, and what is the implication of such vertical motions for the mechanical strength of extended lithosphere? This problem concerns isostasy, in particular, understanding the isostatic response of the lithosphere to the redistribution of mass and perturbation of the lithospheric temperature structure that extension entails.

The specific objectives at Broken Ridge, designed to provide information on the response of the lithosphere to rifting processes, were:

1. To ascertain the age, lithology, and depositional depth of the sediments in the dipping and truncated sedimentary sequence at Broken Ridge.

2. To ascertain the age, lithology, and depositional depth of the sediments making up the subhorizontal sediments which cap the crest of Broken Ridge.

3. To determine, from these fundamental results, what parts of the total sedimentary section are pre-, syn-, and post-rift deposits.

4. To use the drilling results as constraints on the timing and duration of the rifting event, and to determine the vertical motion of Broken Ridge as it responded to the rifting process.

## Ninetyeast Ridge

The Ninetyeast Ridge is a major north-south lineament in the eastern Indian Ocean. It extends from about 34°S to about 10°N, a distance of almost 5000 km, before being buried by the sediments of the Bengal Fan (Fig. 1). The relief of the Ninetyeast Ridge varies from 1500 to 3000 m water depth; some peaks on its southern end shoal to 700 m. Its width is about 200 km, except for a 700-km-long section north of Osborne Knoll, where it is as narrow as 100 km. North of 8°S, the morphology of the ridge takes the form of a series of en-echelon blocks. The origin of this morphology is not understood.

Geophysical and petrologic results from previous studies suggest that the Ninetyeast Ridge formed as the trace of the Kerguelen/Ninetyeast hotspot on the Indian Plate (Luyendyk, 1977; Luyendyk and Rennick, 1977) before rifting along the incipient Southeast Indian Ridge separated Kerguelen from the Indian Plate in the middle Eocene (Chron 18, 42 Ma). The interpretation of the origin and structure of the Ninetyeast Ridge is complicated by a major left-lateral transform fault immediately east of the Ninetyeast Ridge. The history of the Ninetyeast Transform Fault is poorly understood, but in Late Cretaceous to Eocene time it is presumed to have connected the Indian-Antarctic Ridge to a then active spreading center in the Wharton Basin. This plate boundary was active until some time after Chron 20, when spreading in the Wharton Basin ceased and spreading on the Southeast Indian Ridge began (Luyendyk, 1977; Liu et al., 1983).

## Drilling Objectives on the Ninetyeast Ridge

Coring at three sites along the length of the Ninetyeast Ridge was aimed at understanding the origin and tectonic history of the ridge, documenting the northward motion of the Indian Plate and its collision with Asia, and studying the paleoenvironmental history of the eastern Indian Ocean. The major objectives at Ninetyeast Ridge were:

1. To obtain geochemical and petrological data from basement rocks in order to understand the origin of the Ninetyeast Ridge and its relationship to the Kerguelen Plateau.

2. To complete a high-resolution study of the northward motion of India by studying the paleomagnetic inclinations of the recovered sedimentary and basement rocks. These results are being combined with similar results obtained from the Chagos-Laccadive Ridge on ODP Leg 115 (Duncan, Backman, et al., in press) in order to improve our understanding of the Himalayan Orogeny and the sedimentary and tectonic histories of the surrounding basins.

3. To establish a south-north transect of sites with high core recovery in the Eastern Indian Ocean, thus providing the appropriate data base for studying spatial and temporal paleontological distributions and paleoclimatological changes. This transect would extend the results from ODP Legs 119/120 in the Southern Indian Ocean to the north and would parallel the transect obtained by ODP Leg 115 in the Western Indian Ocean.

## DRILLING RESULTS

Leg 121 sailed from Fremantle, Australia, on 30 April 1988 and drilled seven sites, four on Broken Ridge and three on Ninetyeast Ridge, to address these objectives (Figs. 2, 3, and 4; Table 1). During the 58.9 days of Leg 121 operations, 34.3 were spent on site while underway time added up to 19.4 days. Part of the underway time includes a magnetometer survey east of Ninetyeast Ridge and extending from Site 756 to Site 757 aimed at providing much needed constraints for tectonic models of that region.

### Site 752

Site 752 (proposed site BR-2) lies near the crest of Broken Ridge about 16 km north of the main southward-facing escarpment (Fig. 3). The site was positioned to penetrate the dipping reflector sequence midway between proposed sites BR-1 and BR-3. Site 752 coring, along with that from Site 753 (BR-1), Site 754 (BR-3), and Site 755 (BR-4), was designed to build up a continuous section through the northward-dipping sediments that underlie a prominent truncation surface. A thin (~100-m-thick) cap of subhorizontal pelagic sediments unconformably overlies the dipping units.

The site was picked at SP 945 on line 20 of the seismic reflection survey carried out during cruise RC2708. An approach survey of three lines crossing all possible locations for the Broken Ridge sites was made by JOIDES Resolution during the GPS window. Correlation between the two surveys was possible down to subtle features only a few meters across. Observed penetration of the 3.5-kHz echosounding system exceeded 0.08 seconds two-way traveltime (s TWT) bsf where hard reflectors were present.

Hole 752A was APC/XCB cored until refusal at 308 mbsf when an XCB cutting shoe sheared off while coring a particularly hard zone, presumably a chert stringer similar to those cored in overlying sediments. Average core recovery was 70.6% with only the first XCB core failing to recover at least one core section (1.5 m). Sites 753 and 754 were drilled next before we returned to complete the section at Site 752 by drilling Hole 752B to a depth to overlap in age with Site 754. Hole 752B was RCB cored to a total depth of 436 mbsf with recovery of 71% over the cored intervals.

The following lithostratigraphic units were recognized (Fig. 4):

Unit I: (0-113 mbsf) Holocene-uppermost Eocene nannofossil ooze with foraminifers. Oyster-like valves which are 1-3 cm across occur in the lower Miocene. A layer of limestone and chert pebbles up to 6 cm in diameter occurs at 94 mbsf. This layer marks a hiatus between the Holocene to uppermost Oligocene ooze above and the uppermost Eocene ooze, which lies at the bottom of the unit. A second pebble layer was the only sediment recovered (27 cm) in Core 752A-12X (103-113 mbsf). This layer contains reworked materials of late Eocene to Campanian/Maestrichtian age.

Unit II: (113-436 mbsf) lower Eocene-upper Maestrichtian nannofossil calcareous chalk with a silica-rich section, divisible into the following subunits:

Subunit IIa: (113-210 mbsf) lower Eocene-upper Paleocene nannofossil and micritic chalk. Two major ash layers over 5 cm thick with more than 50% volcanic debris, and pumice fragments occur in this subunit.

Subunit IIb: (210-289 mbsf) upper Paleocene-middle Paleocene nannofossil calcareous chalk containing as much as 40% radiolarians and diatoms, and numerous occurrences of volcanic ash. Chert stringers are common. Fine laminations occur in the lower part of the subunit, and some exhibit cross laminae and graded bedding. This subunit is particularly well defined on the downhole logs.

Subunit IIc: (289-436 mbsf) middle Paleocene-upper Maestrichtian hard chalk. Ash layers are common between 326 and 422 mbsf. Chert and porcellanite occur in places. The Cretaceous/Tertiary (K/T) boundary is located within this subunit at a depth of about 358 mbsf.

The lowermost (upper Maestrichtian) section was deposited in water depths of 200-600 m, based on benthic foraminifers and planktonic/benthic foraminifer ratios. Paleodepths gradually deepened with time to 500-1000 m in the early Eocene.

The average sedimentation rate throughout the interval spanned by Unit II was about 3.5 cm/k.y., which translates into a sediment-accumulation rate of nearly 6 $g/cm^2$/k.y. This is a remarkably high flux rate for pelagic sediment. For comparison, Upper Cretaceous carbonate fluxes on other shallow oceanic plateaus are commonly 1-2 $g/cm^2$/k.y. (e.g., Ontong-Java, Shatsky, Manihiki, and Magellan). Only the Hess Rise has similar flux values (3.8 $g/cm^2$/k.y. in Campanian-Maestrichtian carbonates and 7.6 $g/cm^2$/k.y. in the upper Albian-lower Cenomanian current-deposited carbonates). There is no evidence for significant reworking in the lower unit, indicating that the sediment supply was primarily biogenic and not clastic carbonate material eroded from an uplifted Broken Ridge as expected. This and the clear thinning of the strata to the north suggest that the sedimentation rate was controlled by a high productivity zone, modified by normal sediment distribution processes in an outer shelf/slope environment.

The lithologic expression of the K/T boundary occurs in Core 121-752B-11R-3 (357.8-359.3 mbsf), as a dramatic color change from the mottled, cream-colored Maestrichtian chalks to a dark green layer which is carbonate poor and ash rich. This lowermost Paleocene interval is 6-6.5 m thick, as defined by clear signatures on the downhole logs. The transition zone between these layers is not simple in structure, and it covers some 60 cm in the recovered core. The drop in diversity of Cretaceous species occurs abruptly at 358.75 mbsf, and the first paleontological definition of the Tertiary (first occurrence of *Biantholithus sparsus*) does not occur until 25 cm higher in the section. Sedimentation rates during the earliest Paleocene dropped by a factor of 3-5, primarily owing to the sudden absence of carbonate supply. The bloom in the diversity of Tertiary species occurs at 354.5 mbsf, and normal carbonate levels are restored by 352 mbsf. The recovery from the ecological shock which brought the Cretaceous epoch to an end lasted 0.5-1 m.y.--approximately 10 times longer than the equivalent process documented at lower latitude K/T boundary sites, indicating the relatively slower response time of this high-latitude site to environmental stress.

The ashes in Unit II have Nb/Zr ratios which are consistent with an origin from the Kerguelen/Ninetyeast hotspot. The ashes are primarily basaltic in composition, suggesting a relatively nearby source. At least one relatively silicic ash layer occurs in the section.

A reasonably complete paleomagnetic-reversal stratigraphy has been defined for Unit II, which correlates with that from Site 754 and is consistent with the paleontological and seismic-stratigraphic constraints. However, some uncertainty remains because highly variable sedimentation rates are implied.

Good assemblages of diatoms, radiolarians, and silicoflagellates are found throughout the Paleocene and lower Eocene section, allowing a unique correlation of Paleocene and Eocene siliceous microfossils with nannofossil and planktonic foraminiferal assemblages. A short survey of DSDP/ODP reports (especially from high latitudes) revealed no other continuous Paleocene-lower Eocene cores of this kind. This section will provide an extension to similar Neogene-upper Eocene sections drilled on ODP Legs 113, 119, and 120.

Parts of Broken Ridge were apparently uplifted to above sea level between the time the uppermost sediments in Unit II and the lowermost sediments in Unit I were deposited. The pebble layers bracket an upper Eocene, neritic section. Substantial amounts of reworked material as old as Campanian support this conclusion. The unconformity marked by the lower pebble layer in Unit I indicates wave base erosion sometime after the early Eocene (CP10, 54 Ma) and before late Eocene (CP15, P15-17, 38-41 Ma). Seismic correlation with the drilling results at Site 753 indicates that the unconformity is younger than middle Eocene (CP13b, P11/12, 47 Ma). Thus, this unconformity is not much older than 42 Ma (magnetic anomaly 18) when seafloor spreading began between Broken Ridge and Kerguelen. The upper pebble layer marks a hiatus which appears to be coincident with the mid-Oligocene low eustatic sealevel stand. Paleodepths gradually deepen upsection from 200-600 m just above the unconformity to present depths of about 1000 m.

## Site 753

Site 753 (proposed site BR-1) is situated near the northern margin of the crest of Broken Ridge, about 28 km north of the main southward-dipping escarpment (Fig. 3). The site is positioned to penetrate the youngest of the sediments that are unambiguously truncated by the prominent unconformity developed on Broken Ridge. Coring at Site 753, along with that at Sites 752, 754, and 755, was designed to provide a continuous section through northward-dipping sediments below the truncation surface. The thickness of the subhorizontal pelagic sediments above the unconformity is less than 50 m at Site 753.

The site was selected at SP 820 on line RC2708-20. Individual seismic reflectors can be correlated with confidence between the RC2708 survey and that made by *JOIDES Resolution* prior to drilling on Broken Ridge. The truncation surface can be identified at 0.052 s TWT bsf on the 3.5-kHz echosounder record, and traces of northward-dipping reflectors are discernible below the unconformity.

Hole 753A was APC cored to 62.8 mbsf, at which point the piston core barrel became stuck and could not be retrieved. Hole 753B, which is about 50 m north of 753A, was washed down to 62 mbsf and XCB cored to 100 mbsf without significant recovery. Absence of cores at Hole 753B is attributed to failure of the hinge pin holding the flapper of the float valve, and resulting blockage of the core barrel.

Two lithostratigraphic units are recognized at Site 753 (Fig. 4):

Unit I: (0-43.6 mbsf) Pliocene-lower Miocene foraminifer/nannofossil ooze. The nannofossil ooze in the bottom 10 m of this unit is notably stiffer than that above, and contains two closely spaced layers of limestone pebbles with 10% quartz. Trace amounts of volcanic glass, opaques, quartz, and radiolarians are present throughout the unit. Individual grains are sand- to silt-sized.

Unit II: (43.6-62.8 mbsf) middle Eocene calcareous and foraminifer-bearing nannofossil chalk. Sediment texture is similar to that in the overlying unit, but a 5% clay-sized fraction occurs at the top of the unit, increasing to 11% at the bottom. Trace amounts of quartz, opaques, and volcanic glass (in the lower chalks) occur throughout.

The truncation surface, observed in the seismic reflection and 3.5-kHz echosounder data, occurs at the top of Unit II. It represents a depositional hiatus between nannofossil zones CP13b and CN1,2 (47-49 Ma and 17-23.5 Ma). Other hiatuses are suspected in the Neogene Unit I: nannofossil zone CN3 is missing at 34 mbsf and zones CN5-7 are missing at 24 mbsf.

Planktonic/benthic foraminifer ratios suggest that Unit I was deposited in water depths of 600-2000 m (mid-low bathyal), whereas middle Eocene Unit II was deposited in depths of 500-1000 m (upper-mid bathyal). However, the presence of limestone pebbles just above the truncation surface in Unit I suggests clastic deposition in shallow water.

Paleomagnetic measurements on Site 753 cores suggest that a zone of normal polarity occurs below the unconformity from the top of Unit II (43.6 mbsf) to 47 mbsf. Reversed polarity characterizes the underlying interval down to the base of the recovered section. Tentative correlation of the normal and reversed intervals as Chrons 20 and 20R is made using the observed biostratigraphy.

On the basis of downhole temperature measurements in Hole 752A and Hole 753A and thermal conductivity measurements on recovered sediments, heat flow at Broken Ridge is estimated to be 43.4 $mW/m^2$ (1.01 HFU). This value lies between two measurements reported previously for Broken Ridge, and is consistent with a thermal age of about 115 Ma using the empirically determined global heat flow vs. age curve.

The principal result from Site 753, in the light of drilling at Hole 752A, is that Broken Ridge was uplifted by approximately 1 km between the deposition of middle Eocene Unit II at Site 753, which lies below the truncation surface, and the upper Eocene shallow-water sediments overlying the unconformity at Hole 752A. The age difference between these units is small (<~5 m.y.), reflecting rapid tectonic uplift during a middle Eocene rifting event, and fast erosion of the subaerially exposed crest of Broken Ridge.

Site 754

Site 754 (proposed site BR-3) was positioned to penetrate the maximum thickness (0.175 s TWT bsf) of the subhorizontal pelagic sequence which caps the erosional unconformity at Broken Ridge. The site selected is at SP 1040 on Line 20 of the single-channel seismic survey conducted in 1986 by R/V Conrad during cruise RC2708. It is located near the center of the crest of Broken Ridge, about 14 km north of the main south-facing escarpment (Fig. 3).

The principal objectives at Site 754 were to (a) sample the oldest material deposited on the truncation surface in order to compare its age, lithology, and paleodepth with the youngest material clearly below the unconformity drilled at Site 753, and (b) to penetrate and sample a prominent seismic reflector at about 0.3 s TWT bsf, which represents a surface of downlap in the truncated, northward-dipping sedimentary section at Broken Ridge. Unfortunately, the second objective was not met because the RCB bit failed in a lower Maestrichtian chert/chalk sequence at a depth of 355 mbsf in Hole 754B, still above the target reflector.

Hole 754A was APC/XCB/NCB cored to a depth of 172 mbsf. In following this coring sequence, Site 754 became the first ODP drill site to make true operational use of the Navidrill in sediments. Although core recovery was good with the NCB (73%), the penetration rate proved slow in the Maestrichtian chalk/chert sequence, and Hole 754A was terminated after drilling 12.3 m with the NCB. Hole 754B was spudded nearby, and after washing down 123 m, the hole was RCB cored to a total depth of 355 mbsf at which point the bit failed. The bit was then released, the drill string pulled to a depth of 160 mbsf (to cover a potentially unstable zone above the unconformity), and two logging runs were made. The first run, with the geochemical string, proceeded without incident, but after a successful run with a modified seismic stratigraphy string, the drill string was found to be stuck, and logging was terminated so that the pipe could be freed.

Two lithostratigraphic units are recognized at Site 754 (Fig. 4):

Unit I: (0-132 mbsf) Holocene-upper Eocene foraminifer nannofossil ooze in which foraminifers become less abundant and micrite becomes more abundant with depth. Two subunits can be identified:

Subunit Ia: (0-83.2 mbsf) Holocene-lower Miocene foraminifer-nannofossil ooze.

Subunit Ib: (83.2-132 mbsf) lower Miocene-upper Eocene oozes, similar in composition to the overlying subunit, but with fewer foraminifers (10-15%) and more micrite (10-20%). Scattered, thin ash layers and pockets occur in this subunit. Shell fragments are found in the lower 10 m.

A layer of quartz sand, pebbles and cobbles of limestone, chert, and shell fragments occurs at the base of Unit I. Although little of this basal layer was actually recovered, its thickness may be as much as 29 m (122-151 mbsf). A hiatus occurs at the top of this basal layer of Unit I (122 mbsf), representing a depositional break spanning late Eocene to late Oligocene time.

Unit II: (151-355 mbsf) upper to lower Maestrichtian (Campanian?) chalks and limestones with chert and volcanic ash. Three subunits can be identified:

Subunit IIa (151-190 mbsf) is a hard, upper Maestrichtian calcareous chalk.

Millimeter-scale planar and cross-bedded laminae are common, mottling occurs throughout the subunit, and chert and pyrite fill many burrows. Ash layers occur regularly, many containing up to 10% ash (maximum: about 50%). Chert layers several centimeters thick occur in this subunit.

Subunit IIb (190-287 mbsf) Maestrichtian limestone with laminae. Incipient stylolite seams and microfractures occur in places. Ash layers, some with ash contents up to 75%, are common and noticeably darken the host sediment. Chert fragments occur in the upper part, and several chert layers are found between 258 and 268 mbsf. Pyrite blebs and Inoceramus shell fragments occur throughout the subunit.

Subunit IIc (287-355 mbsf) is a lower Maestrichtian limestone and chert sequence in which core recovery was generally poor. Chert occurs in layers up to 20 cm thick and as fragments up to 5 cm in diameter. Inoceramus fragments, microfaults, and calcite and silica-filled fractures are common. Rare vugs are lined with white or black quartz microcrystals. Millimeter-scale rhombs of dolomite have replaced about one third of the limestone in a 2.1-m-long core at 316 mbsf.

The angular unconformity observed in seismic profiles over Broken Ridge coincides with the top of Unit II (151 mbsf). At Site 754, the depositional hiatus across this truncation surface spans late Maestrichtian to late Eocene time. As at Site 752, a second hiatus (late Eocene-late Oligocene) occurs in the subhorizontally layered Unit I sediments deposited above the truncation surface. While the angular unconformity is probably related to the uplift of Broken Ridge during rifting and subsequent subaerial erosion of its exposed crest, the origin of the younger hiatus remains speculative. The younger hiatus is possibly related either to the mid-Oligocene eustatic sea-level fall or to enhanced current activity at that time.

Physical properties of the sediments are dramatically different above and below the angular unconformity. As the unconformity is crossed from above, bulk density increases from about 1.8 to 2.4 $g/cm^3$ although the grain density remains roughly constant, and the porosity decreases from 60 to 30%. In a similar way, the percentage of $CaCO_3$ in recovered cores decreases from an approximately constant level of 96% in lithologic Unit I, to a mean level of about 70% in the upper Maestrichtian, further declining to about 60% in the lower Maestrichtian.

A surprise from drilling at Broken Ridge was the amount of ash encountered in the section, particularly as the corresponding Upper Cretaceous-Paleogene section on the Kerguelen Plateau appears, from Legs 119 and 120 drilling, to contain much less ash. Because these ashes are mainly basaltic in composition, magnetic susceptibility data from core samples provide a rapid, qualitative measure of the variation with depth of volcanic ash in the section. Preliminary calculations show that ash accumulation rates increase downsection, and that the relative proportion of ash in the sediment similarly increases. We note the possibility of using the ash content in the stratigraphic section at Broken Ridge as a long-term record of eruptive activity of the Kerguelen-Ninetyeast Ridge hotspot.

Paleomagnetic data, biostratigraphy, and synthetic seismograms (determined from both downhole logging and sample properties) indicate that the sediments at the base of Hole 752B overlap stratigraphically with the upper Maestrichtian chalks encountered immediately below the truncation surface at

Site 754. The exact amount of overlap is being debated, but it is likely to be in the range of 20-40 m. Thus, Sites 752 and 754 provide about 500 m of composite, but continuous, section of the lower Maestrichtian to lower Eocene portion of the truncated, northward-dipping sediments at Broken Ridge.

Site 755

Site 755 (proposed site BR-4) is situated about 4 km north of the south-facing escarpment of Broken Ridge at a location designed to sample the basal part of the dipping and truncated sedimentary section (Fig. 3). The main drilling objective was to penetrate through and sample a particularly prominent seismic reflector which crops out at the tip of Broken Ridge and lies 0.180 s TWT bsf at Site 755. Owing to time constraints, however, drilling at Site 755 was terminated after penetrating 208 mbsf, slightly above the estimated level of the target reflector.

The site is located at SP 1237 on line RC2708-20. The actual site location was chosen to avoid a buried talus deposit probably eroded from the tip of the ridge that is evident in the pre-site 3.5-kHz echosounder profiles. The basal part of the dipping and truncated sequence is unconformably overlain by about 60 m (0.08 s TWT bsf) of subhorizontally layered Neogene foraminifer-nannofossil ooze.

Site 755 consists of one hole, Hole 755A. After punching a mud line core and washing to 36 mbsf, Hole 755A was RCB cored to a total depth of 208 mbsf before drilling was terminated. As at Sites 752 and 754, the layer containing detrital sand, gravel, and shelly material immediately above the erosional unconformity proved very difficult to recover (about 2% recovery in the interval 36-65 mbsf). The Neogene/Cretaceous unconformity was penetrated at about 65.5 mbsf.

Two lithostratigraphic units are recognized at Site 755 (Fig. 4):

Unit I: (0-65.5 mbsf) Holocene-middle Miocene foraminifer nannofossil ooze and nannofossil ooze with foraminifers. The base of Unit I is defined by a layer of fossiliferous shelly foraminifer grainstone, in places stained a rusty red from oxidized iron.

Unit II: (65.5-208.4 mbsf) Lower Santonian-lower Turonian tuff containing varying amounts of micrite, glauconite, and ashy limestone (in the upper part). This unit can be divided into three subunits:

Subunit IIa (65.5-140.8 mbsf) lower Santonian-lower Coniacian/upper Turonian tuff (50-90% volcanic ash) with interbedded ashy limestone. The uppermost 2.5 m of ashy limestone is iron-stained along bedding planes and fractures, the degree of staining decreasing over that interval. Sand-size clastic grains and Inoceramus shell fragments are common. Micrite decreases in abundance downsection. Thin layers of porcellanite with small chert fragments occur sporadically.

Subunit IIb (140.8-189 mbsf) lower Coniacian-upper Turonian/lower Turonian-tuff (40-80% ash) containing glauconite which decreases in abundance downsection. The glauconite grains are large, up to coarse sand size. The subunit is moderately bioturbated and mottled. A 2-3 cm-thick gypsum layer fills a fracture at 151.7 mbsf.

Subunit IIc (189-208.4 mbsf) consists of Turonian tuffs (60-90% ash) with varying amounts of micrite. Coarse-grained, glauconite-rich layers found in the upper 10 m of this subunit have sharp basal contacts and fine upward. Some microfractures and vugs are filled with secondary and authigenic minerals, calcite, gypsum and pyrite. Three nodules of recrystallized sparry calcite occur in the basal 10 m of the subunit.

The carbonate content of the Upper Cretaceous sediments at Site 755 is significantly lower than in younger parts of the dipping and truncated sequence drilled at the other Broken Ridge sites. Carbonate content increases upsection from an average of 10% in the lower Turonian to about 30% in the lower Santonian sediments. The mean accumulation rate for volcanic ash for the same interval decreases from about 9 to 3 g/cm2/k.y. A significant change in sedimentation on Broken Ridge apparently took place between deposition of the lower Turonian-lower Santonian tuffs sampled at Site 755 and the Maestrichtian limestones found at Site 754. Biological productivity increased markedly over the intervening and unsampled 10 m.y., while ash accumulation and hence nearby eruptive activity waned (see below).

On-board discussions focused on the significance of recrystallized calcite nodules in the tuffs immediately above the prominent seismic reflector on seismic reflection line 20. Because P-wave velocity in these nodules is high (~4100 m/s) and velocities in the primarily tuffaceous lithologies drilled between 160 and 208 mbsf at Site 755 are considerably lower (~2600 m/s), it is possible that a lithologic change downsection from tuff to completely recrystallized limestone produces the strong reflections observed in the seismic data.

Depositional depths at Site 755 were outer shelf/upper slope during early Turonian to early Santonian time, according to planktonic/benthic foraminifer ratios. Benthic foraminifer assemblages, however, indicate deposition in slightly deeper water (mid-upper bathyal depth) during that time interval. According to benthic foraminifer studies of sediments in the dipping, truncated section at Broken Ridge, depositional depths appear to have been in the range of 200-600 m during the Late Cretaceous and early Paleogene, deepening to mid-bathyal depths by middle Eocene time. Above the angular unconformity, depositional depths in the Neogene were mid-bathyal, about the same depth as at present. However, a reworked assemblage of molluscs, bryozoans, and coral fragments indicative of a shallow-water environment were found mixed with oozes in a sample from 45-56 mbsf, which is in the interval above the unconformity where core recovery was extremely poor.

Remanent magnetization measurements at Site 755 show that all sediments recovered from below the angular unconformity are normally magnetized as expected from the early Turonian-early Santonian age range obtained from the micropaleontology. Susceptibility measurements from these Upper Cretaceous samples are used as a guide to volcanic-ash content in the section. If valid, this approach suggests increasing volcanic activity from the bottom of the cored section (208 mbsf) to a paroxysmal eruptive phase recorded at 190 mbsf. The ash content suggests that activity waned gradually upsection to about 150 mbsf, followed by more sporadic eruptive phases of either lesser magnitude, or possibly occurring at greater distances from Site 755.

Microscopic examination of polished sections reveals traces of terrestrial organic matter (inertinite and vitrinite) in the lower Turonian-lower Santonian sediments at Site 755. These fragments are up to 50 μm in size, suggesting that the plant particles were not transported a great distance from their land source area. In addition, apatite grains (probably authigenic) are found in smear slides of volcanic ashes from Sites 752, 754, and 755 on Broken Ridge. Shore studies could therefore include apatite fission track analysis for either additional age dating in the relatively unfossiliferous tuffs at Site 755, or thermal history studies of the sedimentary section at Broken Ridge.

## Site 756

Site 756 (proposed site NER-5A) lies near the crest of the southern end of the Ninetyeast Ridge. Together, the three drilling locations of Leg 121 on the Ninetyeast Ridge (Sites 756-758) were designed to sample the basement through time and the sedimentary section through both time and latitude. Site 756 provides the southern and youngest end of that transect, and it is positioned midway between DSDP Sites 253 and 254.

The proposed location was picked at shotpoint 13920 on the seismic reflection survey carried out during cruise RC2708. The approach site survey was oriented at an angle to the original site survey in order to obtain seismic data along dip lines normal to a N50°E structural grain which cuts across the ridge in this area. The final site location is about 500 m northwest of the proposed location, avoiding a small intra-sedimentary fault. Site 756 is located on a sedimented bench on the eastern side of the Ninetyeast Ridge, in an area of rugged terrain. Numerous pinnacles near the site rise to water depths of as shallow as 750 m. A fault 3 km southeast of Site 756 has a throw of about 500 m.

Hole 756A missed the mud line. Hole 756B was APC cored to 104 m, and then the next APC parted on excessive overpull. Hole 756C was spot cored and washed to 101 m and then XCB cored to 150 m, where no further penetration could be made. The Navidrill was then deployed for its second use on Leg 121 and cut three cores, for a total penetration of 159 mbsf. Hole 756D was spot cored and washed to 139 m, where hard drilling was encountered. RCB coring to 221 m total depth recovered basaltic flows with 36% recovery.

In retrospect, the chemistry data indicate that the mud line core at Hole 756D was too deep by about 4 m. Therefore all depths in Hole 756D may be about 4 m too shallow. Detailed correlations between holes should make allowance for this possible discrepancy.

The following lithostratigraphic units (Hole 756D depths) were recognized (Fig. 5):

Unit I: (0-139 mbsf) Pleistocene (CN13) to upper Eocene (CP15b/P16) nannofossil ooze with foraminifers. The entire unit is homogeneous in texture, heavily bioturbated, and with trace amounts of altered volcanic glass. A minor subunit, which occurs immediately above the first volcanic unit, is an upper Eocene very hard, pale yellow limestone with planktonic foraminifers and nannofossils. Recovery was limited to a few pieces in both Holes 756C and 756D. Although the limestone cannot be thicker than about 30 cm, the contact with the underlying basalt was not recovered intact.

Unit II: (139-221 mbsf) Basaltic flows with intercalated ash and soil layers. A total of 16 flow units were recovered, two from Hole 756C and 14 at Hole 756D. The flows are estimated to be 2-5 m in thickness and their degree of alteration ranges from slight to high. Petrographically, the majority of the lavas are sparsely plagioclase phyric basalts and a few are aphyric, although most appear to be aphyric in hand specimen. No glassy selvages or pillow-like jointing patterns are observed. Vesicles and large cavities are common, up to 20% of the rock volume. They are usually lined with saponite and about 20% are infilled with calcite or goethite. Native copper was observed in one core section.

The material between the flows includes tephra, with the largest pieces being 1-2 cm in size, red soil layers with montmorillonite clay and hematite, and basaltic rubble layers. Only small amounts of the interflow material were recovered, but it probably makes up more than 50% of the section.

Preliminary shipboard analysis indicates that the lavas are distinct from Indian Ocean MORB basalt and that they resemble the basalts drilled previously on the Ninetyeast Ridge. They form a series of discrete flows with brecciated tops which apparently were erupted in a subaerial environment.

The lowermost soft sediments overlying the thin limestone layer indicate deposition in an upper bathyal environment, suggesting that initial subsidence was very rapid. The oldest sediments are late Eocene (38 Ma) in age. This is some 10 m.y. younger than the predicted basement age using a hotspot model, but it is not inconsistent with such a model if subsidence below wave base did not occur for several million years.

Very well preserved late Eocene to Pleistocene assemblages of calcareous nannofossils and planktonic foraminifers occur at Site 756, including a complete Eocene/Oligocene boundary sequence. Subtropical and temperate assemblages dominate the section in the middle Miocene and above, with only rare occurrences of fully tropical species, while in the Eocene to lower Miocene the assemblages are more completely temperate. The temperate, austral marker species used to date the section at Broken Ridge occur in combination with known, low-latitude, subtropical marker species throughout, thereby providing a bridge between widely used, low-latitude, biostratigraphic zonations and the more temperate zonation schemes of the Southern Hemisphere.

The calcium ion concentration in the pore waters at Hole 756B reaches a high value of 33 mmol/L, whereas in Hole 756C, 200 m to the northeast, it reaches 13 mmol/L, only slightly above that of seawater. In Hole 756D, halfway between the first two holes, the maximum calcium concentration is intermediate. These results indicate a complex pattern of alteration and water transport in the basement which is reflected in the sediment column of this small bench (approximately 6 x 6 km), and large changes occur on a scale as small as 200 m.

## Site 757

Site 757 (proposed site NER-2C) lies near the crest of the Ninetyeast Ridge, about 230 km southeast of Osborne Knoll. Site 757 is the midpoint of the Ninetyeast drilling transect (Fig. 1), and it is roughly halfway between DSDP Sites 253 and 214.

The proposed location was picked at SP 2660 on the seismic reflection survey carried out during cruise RC2707. The approach survey was somewhat longer than usual in order to resolve uncertainties regarding the structural grain in the area of the site. The final site location is about 2800 m northwest of the proposed location, but in the same tectonic position as proposed. Site 757 is located on the eastern edge of the summit horst on this part of the Ninetyeast Ridge, but downdip to the southeast from the structural crest.

Hole 757A missed the mud line. Hole 757B was APC/XCB cored 1 m into basement. The Navidrill was deployed for the third time and it cut two cores. Hole 757C was spot cored and washed to 363 m and then RCB cored to 421 m. Actual basement penetration was 42 m below the depth where the driller first felt hard rock. A medical emergency terminated drilling at this point, precluding chances for an excellent basement hole and eliminating logging.

The following lithostratigraphic units were recognized (Fig. 6):

Unit I: (0-212 mbsf) Pleistocene (CN15) to lower Eocene (CP10/P8) nannofossil ooze which can be divided into two subunits:

Subunit Ia: (0-169 mbsf) Holocene-middle Eocene (CP13b) bioturbated nannofossil ooze, with foraminifers in the upper 40 m.

Subunit Ib: (169-212 mbsf) middle to lower Eocene calcareous ooze with nannofossils in the upper portion and ash in the lowermost portion. It is strongly bioturbated and mottled. Lithification generally increases downcore and the ooze grades to chalk at the bottom of the subunit.

Unit II: (212-369 mbsf) upper Paleocene volcaniclastics which can be subdivided into two subunits:

Subunit IIa: (212-250 mbsf) upper Paleocene volcanic ash with glauconite and foraminifers at the top, lapilli (2-5 mm in diameter), shell fragments, and basalt pebbles. Faint horizontal bedding and laminae occur in this subunit, and one interval of cross-bedding was observed.

Subunit IIb: (250-369 mbsf) undated volcanic tuff, half of which contains coarse lapilli (2-5 mm diameter) and the other half of which is massive and homogeneous. Rounded basalt pebbles, shell fragments, butterscotch-brown pebbles of flint, and sedimentary structures such as millimeter-scale laminae and sharp contacts also occur. The tuff immediately overlying the basalts contains shelly material.

Unit III (369-421 mbsf) Basaltic flows with minimal evidence of intercalated ash material. A total of 20 flow units were recovered, one from Hole 757B and 19 from Hole 757C. The majority of the flows are thinner than 1 m in thickness, including several where the entire unit was recovered. The maximum flow thickness is 5.5 m. The flows are all plagioclase phyric; several contain more than 20% phenocrysts. The degree of alteration varies from slight to high, with pervasive replacement of the groundmass by smectite. The majority of the flows are vesicular. Vesicles and veins are infilled with a variety of minerals, including calcite, limonite, chlorite, smectites, and, particularly in the lower units, zeolites.

Geochemically, the basalts at Site 757 are less enriched in incompatible elements (thus somewhat closer to MORB composition) than those at Site 756 or elsewhere on the Ninetyeast Ridge. The differences downhole are also significant in that the two lowermost flow units (5.87 m recovery) are geochemically distinct (relatively enriched in incompatible elements) and must have had a different magmatic parent than the lavas higher in the section.

These flows were erupted subaerially, and the ashes above the flows are the product of phreatic volcanism near the wave base. The phreatic phase of volcanism must have continued for a considerable period of time as there are at least one normal and portions of two reversed polarity intervals within the ash section. The upper Paleocene sediments immediately above the basalt indicate a very shallow environment that quickly deepened to bathyal depths by early Eocene time. Thus it appears that Site 757 was subsiding as volcanism waned, and subsidence to moderate depths occurred quickly after ash production ended. The late Paleocene age of the oldest datable sediments is the same as the age predicted using a hotspot model.

Recovering the paleomagnetic record in the Eocene-Oligocene section was a key objective, as it should define the manner in which the Indian Plate slowed down as it collided with Asia. Unfortunately, paleolatitudes may not be recoverable from this section because the magnetization is very soft and unstable, with large changes in both declination and inclination observed after a few hours of laboratory storage. A stable signal may yet be resolvable with shore-based studies done in a magnetically clean environment.

The microfossil assemblages at Site 757 were expected to have more tropical affinities than earlier sites, as the location is 1200 km farther along the south-north transect than Site 756. The paleontological assemblages in the Paleocene and Eocene at Site 757 are temperate to subtropical, and the assemblages are identical to those seen at Broken Ridge in the same age range. Indications of tropical to subtropical assemblages occur in the middle Oligocene to Holocene, and few of the higher latitude species seen at Broken Ridge in this age range are present at Site 757.

## Site 758

Site 758 (proposed site NER-1C) is positioned on the southeast side of one of the large en-echelon blocks which characterize the Ninetyeast Ridge between the Equator and 10°N. The three Ninetyeast Ridge sites are designed to sample the basement through time and the sedimentary section through both time and latitude. Site 758 is the northern point of that transect, and it lies roughly halfway between DSDP Sites 216 and 217.

The proposed location was picked at time 1730UTC on the seismic reflection survey line RC2705. The original plan was to drill two sites--one for Neogene objectives and one for Paleogene and basement objectives. Because of severe time constraints and increased faith in the minicone system for reentry, a single combined location was chosen in order to save several days of drilling time at the expense of condensing the Neogene section by 20%.

The site survey tracks are widely spaced. The approach survey is oriented at an angle to the perceived structural grain (N45°E) picked from the combination of seismic, Sea Beam, and Seasat data. The survey was conducted outside the GPS window and is much less accurately positioned than previous surveys on Leg 121. The area around the site is much more heavily faulted (usually to surface) than was apparent from the original site survey.

Hole 758A was APC/XCB cored to refusal at 422 mbsf. A minicone was set onto a relatively hard bottom, the ship was offset, and Hole 758B was HPC cored 96 mbsf to overlap the coring interval in Hole 758A. Hole 758C was a mudline core, taken because of correlation uncertainties which became evident when Core 121-758B-1H was split.

Hole 758A was reentered and RCB cored to a TD of 677 mbsf. The logging program was incomplete because of poor hole conditions. The logs run were seismic stratigraphy and geochemistry combinations (40-405 mbsf) and BHTV (525-610 mbsf). The quality of the on-board BHTV log was not adequate for interpretation; post-cruise processing may improve it.

Five lithostratigraphic units are recognized at Site 758 (Fig. 7):

Unit I: (0-122 mbsf) Holocene-upper Miocene nannofossil ooze which can be divided into two subunits:

Subunit Ia: (0-25 mbsf) Holocene-lowermost Pleistocene alternating layers of light gray, nannofossil ooze with clay and foraminifers, and dark gray, nannofossil ooze with foraminifers. Layers are 10-110 cm thick with gradational contacts. This subunit contains six major ash layers 5-34 cm thick and several thin green ash layers 1-2 cm thick. The thicker ash layers are graded, fine upward, commonly have sharp basal contacts, and in places contain pumice fragments.

Subunit Ib: (25-122 mbsf) lowermost Pleistocene-upper Miocene nannofossil ooze with clay, foraminifers, and micrite. The calcium carbonate content of this unit is greater than in subunit Ia, and it increases downhole as the clay content decreases. Gray ash beds, 2-15 cm thick, and thin, green ash beds, 1-2 cm thick, are less common in this subunit than in the one above.

Unit II: (122-367 mbsf) middle Miocene-lower Maestrichtian chalk which can be subdivided into two subunits:

Subunit IIa: (121-296 mbsf) middle Miocene-lower Paleocene nannofossil and calcareous nannofossil chalk which is mottled and bioturbated, and has a calcium carbonate content >80%. Rare chert pebbles occur.

Subunit IIb: (296-367 mbsf) upper to lower Maestrichtian, greenish gray, calcareous chalk with nannofossils, foraminifers, and clay. There are some occurrences of pyrite, chert pebbles, dark ash layers, and porcellanite intervals up to 11 cm long. Inoceramus and other shell fragments occur commonly. The calcium carbonate content decreases from near 90% to less than 60% within this subunit.

Unit III: (367-431 mbsf) lower Maestrichtian to Campanian calcareous clay. This unit contains several chert pebbles, porcellanite stringers up to 20 cm long, Inoceramus and other shell fragments, some ash beds, and rare microfaults.

Unit IV: (431-499 mbsf) Campanian tuff with minor interbeds of ashy calcareous chalk. There are also some beds of silt to lapilli-sized lithic and pumice fragments, and these beds display graded bedding. This subunit contains pyrite, rounded basalt pebbles <1 cm in diameter, and minor amounts of shell fragments.

Unit V: (499-677 mbsf) Campanian(?) basalts, medium-grained, petrographically uniform, and aphyric to sparsely plagioclase and clinopyroxene phyric. A total of 29 flow units were recovered, including 5 pillowed flows. Vesicles and amygdules are rare in the upper units and common in the lower units. Eight intervals of interbedded tuff similar to Unit IV were recovered, including one layer at 602 mbsf dated as younger than Turonian. The length of these volcaniclastic intervals is no more than a few meters, and they become less numerous with depth. Pillows are interbedded with 1-m-thick flows below 640 mbsf. The lower units are <3 m thick and are characterized by sharp, cryptocrystalline selvages. The units become thicker and more massive upsection until the average thickness exceeds 10 m. One unit is >20 m thick. Shipboard analyses do not indicate any significant geochemical trends with depth.

The upper units are interpreted as ponded sheet flows; the lower units are thin sheet flows interbedded with pillowed flows. The ashes are geochemically distinct from the flows. Some were deposited by falling through the water column and others as turbidity flows. No accretionary lapilli were recovered, indicating that the sources of the ashes were more than 10 km distant. We interpret these observations to mean that the ashes were produced at volcanic islands not immediately adjacent to the site, whereas the lavas were erupted locally in deep water. There is no indication that any of the basaltic units were erupted subaerially.

The Cretaceous/Tertiary boundary sequence is incomplete, and the best estimate of the actual boundary is between cores at 296 mbsf. The uppermost Maestrichtian and the lowermost Paleocene appear to be absent. There is a change from tropical to higher latitude fossil assemblages at about 305 mbsf.

The site was originally chosen to penetrate an expanded Paleogene section at the northern end of the Ninetyeast Ridge. This was especially important, as neither DSDP Site 216 or 217 recovered a complete Paleogene section. Unfortunately, the Paleogene section at Site 758 is also incomplete with several unconformities. Preliminary indications based on nannofossil dates are that all or parts of the following zones are missing in the Paleogene: below CP1b; CP3(?); CP9-14.

In contrast to the poor quality of the Paleogene section, the Neogene section appears to be excellent. The double APC cores over the upper 100 m (Holocene to upper Miocene) are correlatable on a cm-scale using magnetic-susceptibility profiles. The magnetostratigraphic record is superb down to the top of Chron 6. All known geomagnetic reversals are clearly recorded except the two Reunion events. Below this depth the quality of the paleomagnetic record deteriorates as calcium carbonate content increases and clay content decreases. Visible alternations in Subunit Ia may be correlatable with climatic variations and/or tectonic events in the Himalayas. This section also contains a complete tephra record, from Holocene to Miocene, of silicic ashes from the Indonesian arc. The Toba ash (~70,000 yr) is tentatively identified at 1.5 to 1.8 mbsf. This replicated section is an excellent example of the value of double HPC coring. The second core demonstrated that 1-2 m of section often either was not cored or was highly disturbed between every pair of piston cores. The double APC section is three times as valuable as a single HPC section.

## SUMMARY

The drilling results from Leg 121 provided the needed sediment and rock to satisfy nearly all the objectives established at the beginning of the cruise. Our studies at Broken Ridge indicate:

1. Rifting at Broken Ridge occurred over a very short time interval, beginning at approximately 47-50 Ma, and lasting only 3 to 7.5 m.y. Furthermore, this rifting event seems to be a result of "passive" mechanisms, or far-field stress, rather than "active" thermal doming. This is implied from

increasing water depths prior to rifting, the lack of a thermal signal in magnetic overprinting, low heat flow, and the brevity of the rifting event.

2. The Cretaceous/Tertiary boundary at Broken Ridge is marked by a loss of typical Cretaceous taxa, and the predominance of hardy opportunistic survivor species over Tertiary forms several meters into the Tertiary section. Lithologically, the Cretaceous chalks are overlain by a thick ash layer that represents more than a million-year period following the Cretaceous/Tertiary event, during which time the amount of carbonate production/deposition was 8 times lower than during the Maestrictian or later Paleocene. The longer recovery process for biota following the K/T event may reflect the greater ecologic stress on higher latitude forms compared to the lower latitude "Tethyan" species.

3. Ash layers recovered from lower Turonian to middle Eocene beds in the dipping and truncated section record 40 m.y. of eruptive volcanic history, probably related to the then nearby Kerguelen/Ninetyeast hotspot. The waning supply of ash thoughout that section reflects the decrease in hotspot volcanic activity, or its migration away from Broken Ridge.

Drilling on the Ninetyeast Ridge indicates:

1. Biostratigraphic ages increase from south to north. Those ages together with the ages predicted by the hotspot model are: Site 756, >38 Ma actual, 48 Ma predicted; Site 757, >58 Ma actual, 58 Ma predicted; Site 758, >80 Ma actual, 80 Ma predicted.

2. The lavas forming the Ninetyeast Ridge are moderately evolved tholeiites, with trace-element ratios indicative of a mixing of mid-ocean ridge and Kerguelen Island magmas. The preliminary interpretation is that the ridge formed as newly created Indian Plate material passed over the Kerguelen/Ninetyeast hotspot. Gravity measurements indicate that isostatic compensation is local, this being consistent with constructing the ridge on young, weak oceanic crust.

3. The magnetic anomaly pattern on either side of the Ninetyeast Ridge requires asymmetric spreading (or ridge jumps) of the spreading center segment which was at the southern end of the ridge. It appears that this asymmetry may have been related to the position of the hotspot. The position of the Galapagos hotspot near to, but not coincident with, the spreading center may be a good analog.

4. The large volume of basaltic ash recovered on both Ninetyeast Ridge and Broken Ridge is an important feature of the Kerguelen/Ninetyeast hotspot relative to other hotspot volcanoes. These ashes formed in shallow marine environments as individual volcanic centers emerged and then subsided again. Apparently the ridge was constructed by discrete volcanic centers which were mostly subaerial (Sites 756, 253, 757, 214, 216). Marginal to these centers were deep-water pillows and sheet flows (Site 758).

5. The sediments recovered along the south-north transect record Campanian to Miocene assemblage transitions from temperate to tropical forms. Paleogene recovery at the northern site was abbreviated because of hiatuses. These fossil assemblages provide material to extend the more detailed tropical zonations to higher latitudes, and to unravel paleoenvironmental changes in the Eastern Indian Ocean.

6. The upper ten cores at Site 758 contain a terrigenous clay component that first appears in the upper Miocene. This section has preserved a superb magnetostratigraphy over the last 7 m.y. as well as a tephrochronology for volcanism in the Indonesian arc. The Toba ash (70 k.y.) is tentatively identified at 1.5 to 1.8 mbsf.

7. Very large differences in chemical gradients were observed at Site 756 in holes only 200 m apart.

8. Several cruise objectives can only be addressed by post-cruise analysis:

a. Paleolatitude determinations. No serious attempt was made to determine paleolatitudes on board because of concerns about the quality of demagnetization which could be achieved on board. Many of the carbonate cores were magnetically unstable in the ship's environment, but it may be possible to recover a stable signal in a magnetically clean laboratory.

b. Eolian studies.

c. Study of the intensification of the monsoonal climate pattern (Site 758).

d. Study of glacial/interglacial climatic variations. Alternating layers of light gray and darker gray material recovered in the upper 25 m of the double HPC cores at Site 758 suggest that there is excellent material to work with.

e. Analysis of the BHTV logging at Site 758 to look for breakouts as an indicator of in-situ stress.

## Engineering

The Navidrill coring (NCB) system was deployed three times with mixed success. It worked very well when drilling in competent rock, but it tended to plug up in clayey material. The lack of any real-time feedback on drilling performance during each run seriously hinders effective use of the tool. From a scientific perspective its chief limitation is the excessive time to cut cores, followed by reaming out the hole with the XCB bit to get ready to cut the next core. In its current configuration, the NCB system is suitable for cutting short amounts of basalt or other hard rock at the end of an XCB hole or for cutting a pilot hole ahead of the XCB bit for setting instrumentation. Addition of the extendable coring rod system may make the NCB system time effective for moderate penetration (50 m), but the lack of effective feedback of downhole performance is a limitation which must be overcome.

The Multishot core orientation device was used successfully at Site 758 after several problems were encountered. Procedural errors in the way the tool was used were corrected on the leg, and these may have contributed to past problems. Carbonate sediments are so magnetically soft that we found it impossible to recover a reliable magnetic signal. The double APC cores show a long-term drift of about 80° in the declination of the reversed polarity intervals over 10 cores. The sign of this drift is opposite in two adjacent holes. We have no explanation for this behavior.

## REFERENCES

Berggren, W. A., Kent, D. V., Flynn, J. J., and van Couvering, J. A., 1985. Cenozoic geochronology. Geol. Soc. Am. Bull., 96:1407-1418.

Davies, T. A., Luyendyk, B. P., et al., 1974. Init. Repts. DSDP, 26: Washington (U.S. Govt. Printing Office), 281-294.

Duncan, R. A., 1978. Geochronology of basalts from the Ninetyeast Ridge and continental dispersion in the eastern Indian Ocean. J. Volcanol. Geotherm. Res., 4:283-305.

Frey, F. A., Dickey, J. S., Thompson, G., and Bryan, W., 1977. Eastern Indian Ocean DSDP sites: Correlations between petrology, geochemistry and tectonic setting. In Heirtzler, J. R., Bolli, H. M., Davies, T. A., Saunders, J. B., and Sclater, J. G., (Eds.), Indian Ocean Geology and Biostratigraphy: Washington (Am. Geophys. Union), 189-257.

Leclaire, L., Bassias, Y., Denis-Clocchiatti, M., Davies, H., Gautier, I., Gensous, B., Giannesini, P.-J., Patriat, P., Segoufin, J., Tesson, M., and Wannesson, J., 1987. Lower Cretaceous basalt and sediments from the Kerguelen Plateau. Geomar. Lett., 7:169-176.

Leg 115 Shipboard Scientific Party, 1987. New studies of the Indian Ocean. Nature, 329:586-587.

Leg 119 Shipboard Scientific Party, 1988. Early glaciation of Antarctica. Nature, 333:303-304.

Liu, C. S., Curray, J. R., and McDonald, J. M., 1983. New constraints on the tectonic evolution of the eastern Indian Ocean. Earth Planet. Sci. Lett., 65: 331-342.

Luyendyk, B. P., 1977. Deep-sea drilling on the Ninetyeast Ridge: Synthesis and a tectonic model. In Heirtzler, J. R., Bolli, H. M., Davies, T. A., Saunders, J. B., and Sclater, J. G., (Eds.), Indian Ocean Geology and Biostratigraphy. Washington (Am. Geophys. Union), 165-187.

Luyendyk, B. P., and Rennick, W., 1977. Tectonic history of aseismic ridges in the eastern Indian Ocean. Geol. Soc. Am. Bull., 88:1347-1356.

Mahoney, J. J., MacDougall, J. D., Lugmair, G. W., and Gopalan, K., 1983. Kerguelen hot-spot source for Rajmahal traps and Ninetyeast Ridge?. Nature, 303:385-389.

Morgan, W. J., 1981. Hotspot tracks and the opening of the Atlantic and Indian Oceans. In Emiliani, C. (Ed.), The Sea, 7, The Oceanic Lithosphere: New York (Wiley), 443-487.

Mutter, J. C., and Cande, S. C., 1983. The early opening between Broken Ridge and Kerguelen Plateau. Earth Planet. Sci. Lett., 65:369-376.

Patriat, P., 1983. Evolution du systeme de dorsale de l'ocean Indien [These d'etat]. Univ. Paris.

Patriat, P., and Achache, J., 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature, 311:615-621.

Peirce, J. W., 1978. The northward motion of India since the Late Cretaceous. Geophys. J. R. Astron. Soc., 52:277-312.

Sclater, J. C. and Fisher, R. L., 1974. The evolution of the East Central Indian Ocean, with emphasis on the tectonic setting of the Ninetyeast Ridge. Geol. Soc. Am. Bull., 85:683-702.

Schlich, R., 1982. The Indian Ocean: aseismic ridges, spreading centers, and oceanic basins. In Nairn, A.E.M., and Stehli, F. G., (Eds.), Ocean Basins and Margins, 6: New York (Plenum), 51-147.

Schlich, R., Wise, S. W., et al., in press. Deep sea drilling on the Kerguelen Plateau, Nature.

von der Borch, C. C., Sclater, J. G. et al., 1974. Init. Repts. DSDP, 22: Washington (U.S. Govt. Printing Office), 413-447.

Weis, D., Beaux, J. F., Gautier, I., Giret, A., and Vidal, P., 1987. Kerguelen Archipelago: geochemical evidence for recycled material. NATO Advanced Workshop, Abstracts, May 25-29, Antalaya, Turkey, 122-125.

## Table Caption

Table 1. ODP Leg 121 operational site summary.

## Figure Captions

Figure 1. Index map of the Indian Ocean, showing major bathymetric plateaus and ridges, and DSDP/ODP sites.

Figure 2. Paleogeographic reconstruction of Broken Ridge and the Kerguelen-Heard Plateau at the time of magnetic anomaly 18 (ca. 42 Ma) (simplified from Royer, personal comm., 1988).

Figure 3. Single-channel seismic reflection line 20 obtained during RC2708. The Leg 121 drill sites shown were located to ensure that the entire stratigraphic section could be drilled with modest penetration at each site. A prominent angular unconformity separates a thin, sub-horizontal capping sequence above from northward-dipping reflector sequences below.

Figure 4. Summary stratigraphic columns of the Broken Ridge drill sites.

Figure 5. Summary stratigraphic column of the southernmost site on Ninetyeast Ridge, Site 756.

Figure 6. Summary stratigraphic column of the central Ninetyeast Ridge site, Site 757.

Figure 7. Summary stratigraphic column of the northernmost Ninetyeast Ridge site, Site 758.

Figure 8. ODP Leg 121 time breakdown.

Table 1.

ODP OPERATIONS
SITE SUMMARY REPORT
LEG 121

15-Jul-1988

| HOLE | LATITUDE | LONGITUDE | DEPTH METERS | NUMBER OF CORES | METERS CORED | METERS RECOVERED | PERCENT RECOVERED | METERS DRILLED | TOTAL PENETRATION | TIME ON HOLE | TIME ON SITE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 752A | 30-53.475S | 93-34.652E | 1097 | 033 | 308 | 217 | 71% | 0 | 308 | 60.50 | |
| 752B | 30-53.483S | 93-34.652E | 1097 | 017 | 158 | 112 | 71% | 278 | 436 | 99.25 | 159.75 |
| 753A | 30-50.340S | 93-35.394E | 1187 | 007 | 63 | 61 | 97% | 0 | 63 | 13.75 | |
| 753B | 30-53.310S | 93-35.394E | 1187 | 005 | 48 | 0 | 0% | 52 | 100 | 11.25 | 25.00 |
| 754A | 30-56.439S | 93-33.991E | 1076 | 023 | 170 | 128 | 76% | 2 | 172 | 34.75 | |
| 754B | 30-56.439S | 93-33.954E | 1076 | 024 | 232 | 91 | 39% | 123 | 355 | 76.00 | 110.75 |
| 755A | 31-01.786S | 93-32.803E | 1069 | 019 | 178 | 80 | 45% | 30 | 208 | 40.25 | 40.25 |
| 756A | 27-21.330S | 87-35.805E | 1529 | 001 | 10 | 10 | 100% | 0 | 10 | 1.00 | |
| 756B | 27-21.330S | 87-35.805E | 1529 | 011 | 104 | 106 | 101% | 0 | 104 | 14.00 | |
| 756C | 27-21.253S | 87-35.890E | 1527 | 011 | 77 | 62 | 81% | 82 | 159 | 30.25 | |
| 756D | 27-21.288S | 87-35.843E | 1524 | 011 | 101 | 46 | 46% | 120 | 221 | 39.25 | 84.50 |
| 757A | 17-01.458S | 88-10.899E | 1663 | 001 | 9 | 9 | 100% | 0 | 9 | 1.00 | |
| 757B | 17-01.458S | 88-10.899E | 1663 | 043 | 375 | 272 | 73% | 0 | 375 | 75.00 | |
| 757C | 17-01.389S | 88-01.812E | 1655 | 011 | 106 | 68 | 64% | 315 | 421 | 36.00 | 112.00 |
| 758A | 5-23.049N | 90-21.673E | 2935 | 073 | 677 | 454 | 67% | 0 | 677 | 269.00 | |
| 758B | 5-23.037N | 90-21.670E | 2937 | 010 | 96 | 99 | 103% | 0 | 103 | 11.25 | |
| 758C | 5-23.043N | 90-21.668-E | 2933 | 001 | 9 | 9 | 100% | 0 | 9 | 7.75 | 288.00 |
| | | Totals : | | 301 | 2721 | 1824 | 67% | 1002 | 3730 | | 820.00 |

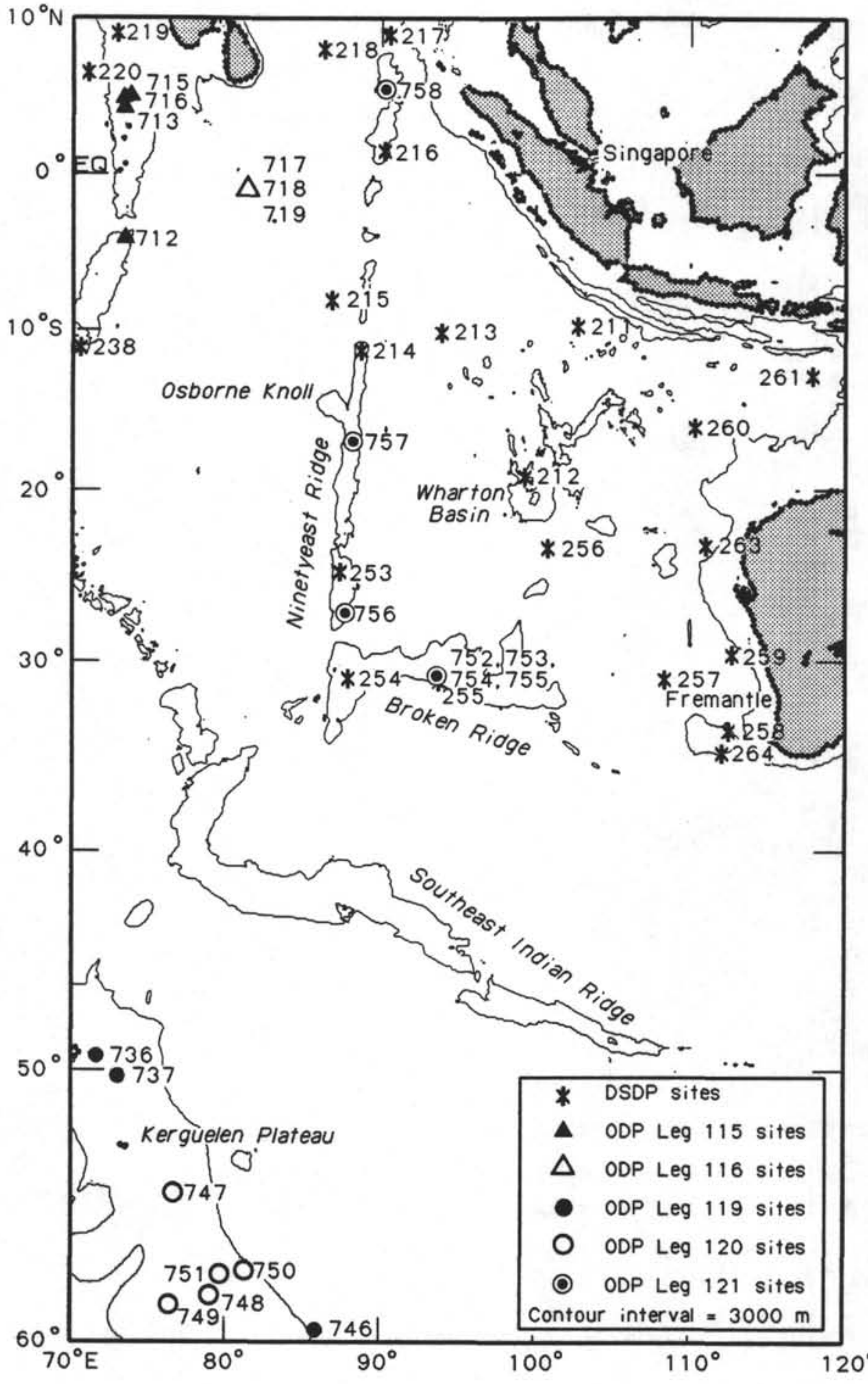
10°N
0° EQ
10°S
20°
30°
40°
50°
60°
70°E
80°
90°
100°
110°
120°
219
220
715
716
713
218
217
758
216
Singapore
717
718
719
712
215
238
213
214
211
261
Osborne Knoll
757
260
Ninetyeast Ridge
212
Wharton Basin
256
263
253
756
752,753,
754,755
255
254
259
257
Fremantle
258
264
Broken Ridge
Southeast Indian Ridge
736
737
Kerguelen Plateau
747
751
750
748
749
746
DSDP sites
ODP Leg 115 sites
ODP Leg 116 sites
ODP Leg 119 sites
ODP Leg 120 sites
ODP Leg 121 sites
Contour interval = 3000 m

Figure 1

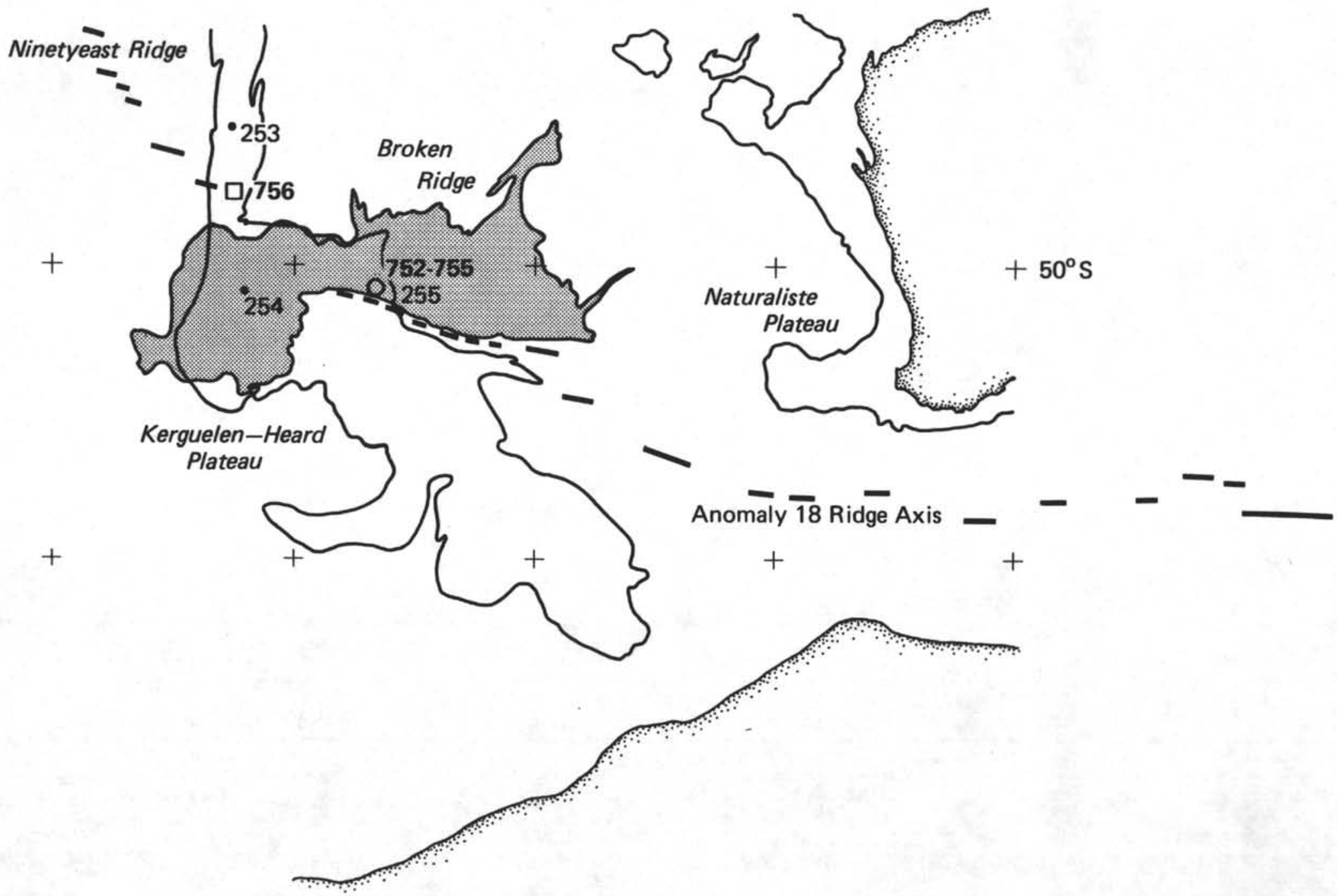
Ninetyeast Ridge
253
756
Broken
Ridge
752-755
255
254
50° S
Naturaliste
Plateau
Kerguelen—Heard
Plateau
Anomaly 18 Ridge Axis

Figure 2

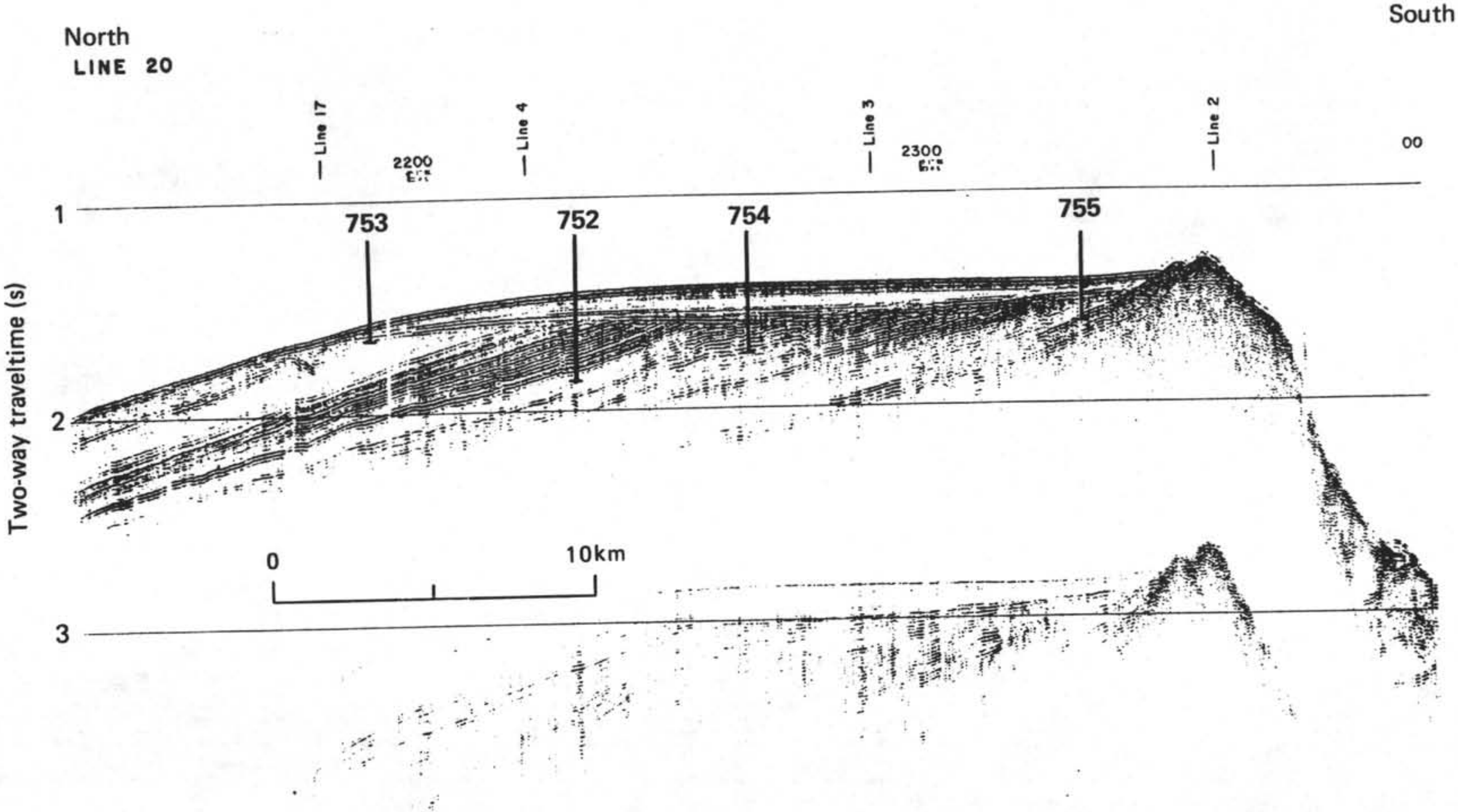
North
LINE 20
South
Line 17
2200
Line 4
Line 3
2300
Line 2
00
1
2
3
753
752
754
755
Two-way traveltime (s)
0
10km

Figure 3

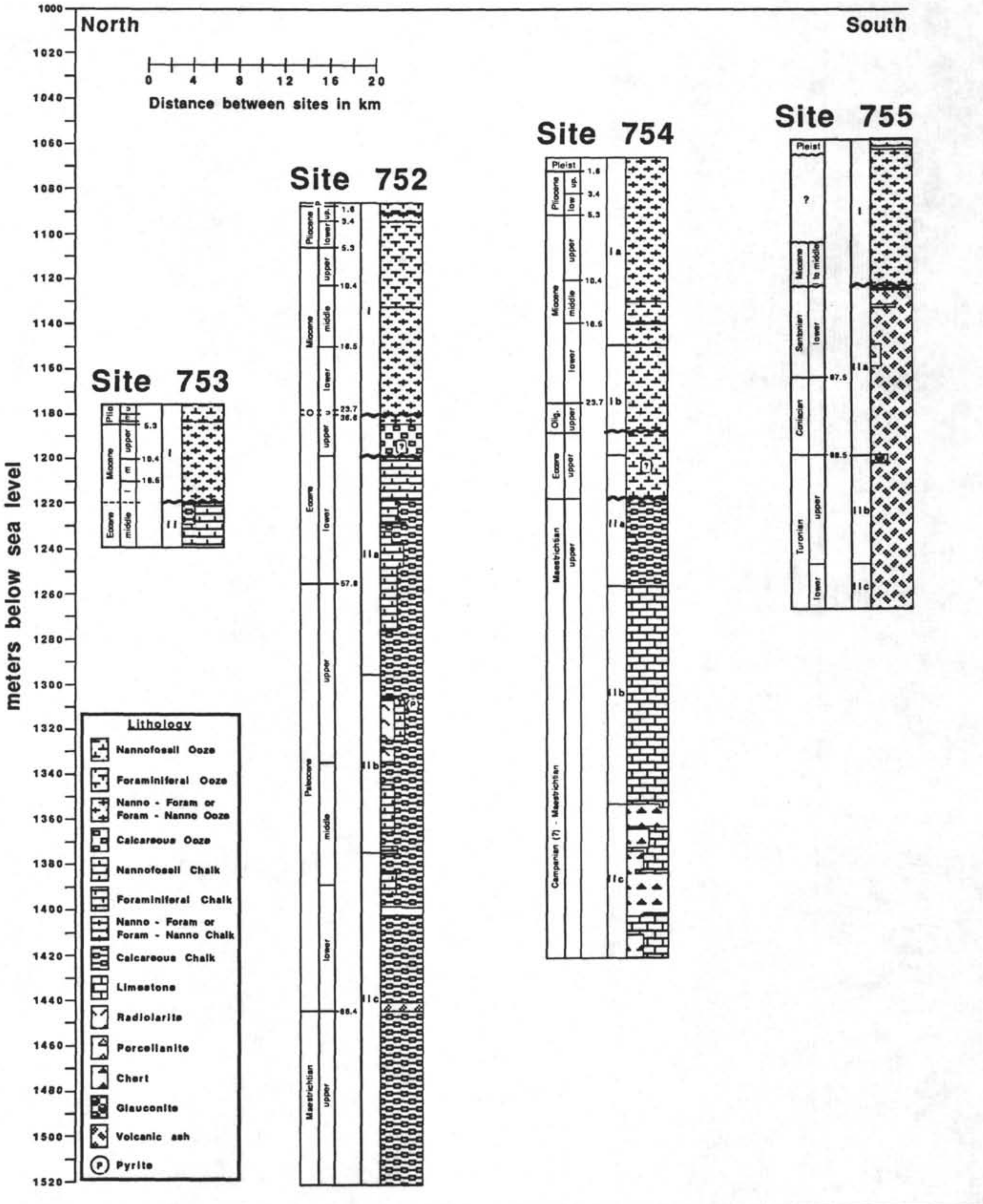
North
South
Distance between sites in km
0 4 8 12 16 20
Site 753
Site 752
Site 754
Site 755
meters below sea level
Lithology
Nannofossil Ooze
Foraminiferal Ooze
Nanno - Foram or Foram - Nanno Ooze
Calcareous Ooze
Nannofossil Chalk
Foraminiferal Chalk
Nanno - Foram or Foram - Nanno Chalk
Calcareous Chalk
Limestone
Radiolarite
Porcellanite
Chert
Glauconite
Volcanic ash
Pyrite

Figure 4

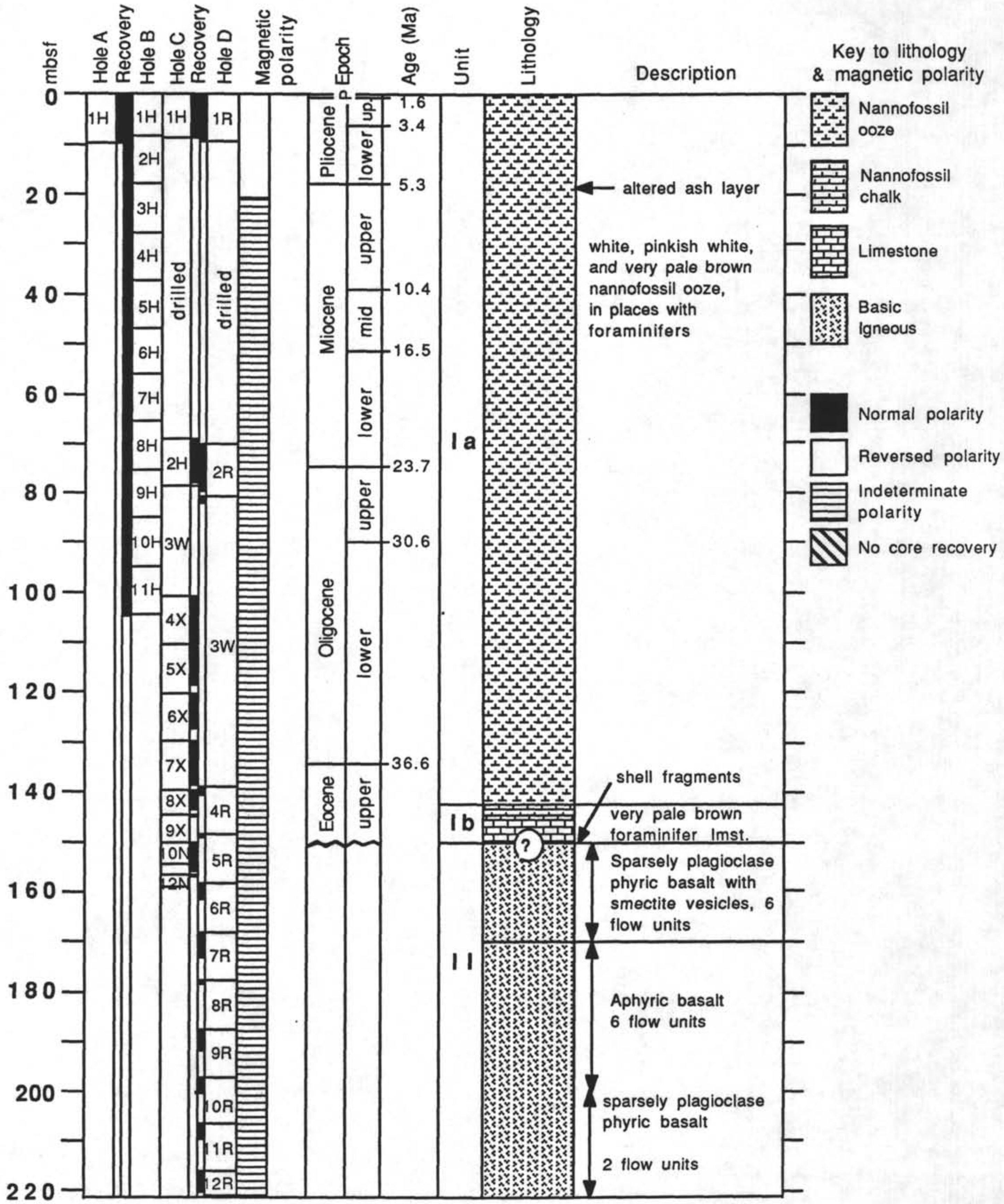
mbsf
Hole A
Recovery
Hole B
Hole C
Recovery
Hole D
Magnetic polarity
Epoch
Age (Ma)
Unit
Lithology
Description
Key to lithology & magnetic polarity
Pliocene
Miocene
Oligocene
Eocene
up.
lower
upper
mid
lower
upper
lower
upper
1.6
3.4
5.3
10.4
16.5
23.7
30.6
36.6
Ia
Ib
II
drilled
drilled
altered ash layer
white, pinkish white, and very pale brown nannofossil ooze, in places with foraminifers
shell fragments
very pale brown foraminifer lmst.
Sparsely plagioclase phyric basalt with smectite vesicles, 6 flow units
Aphyric basalt 6 flow units
sparsely plagioclase phyric basalt
2 flow units
Nannofossil ooze
Nannofossil chalk
Limestone
Basic Igneous
Normal polarity
Reversed polarity
Indeterminate polarity
No core recovery

Figure 5

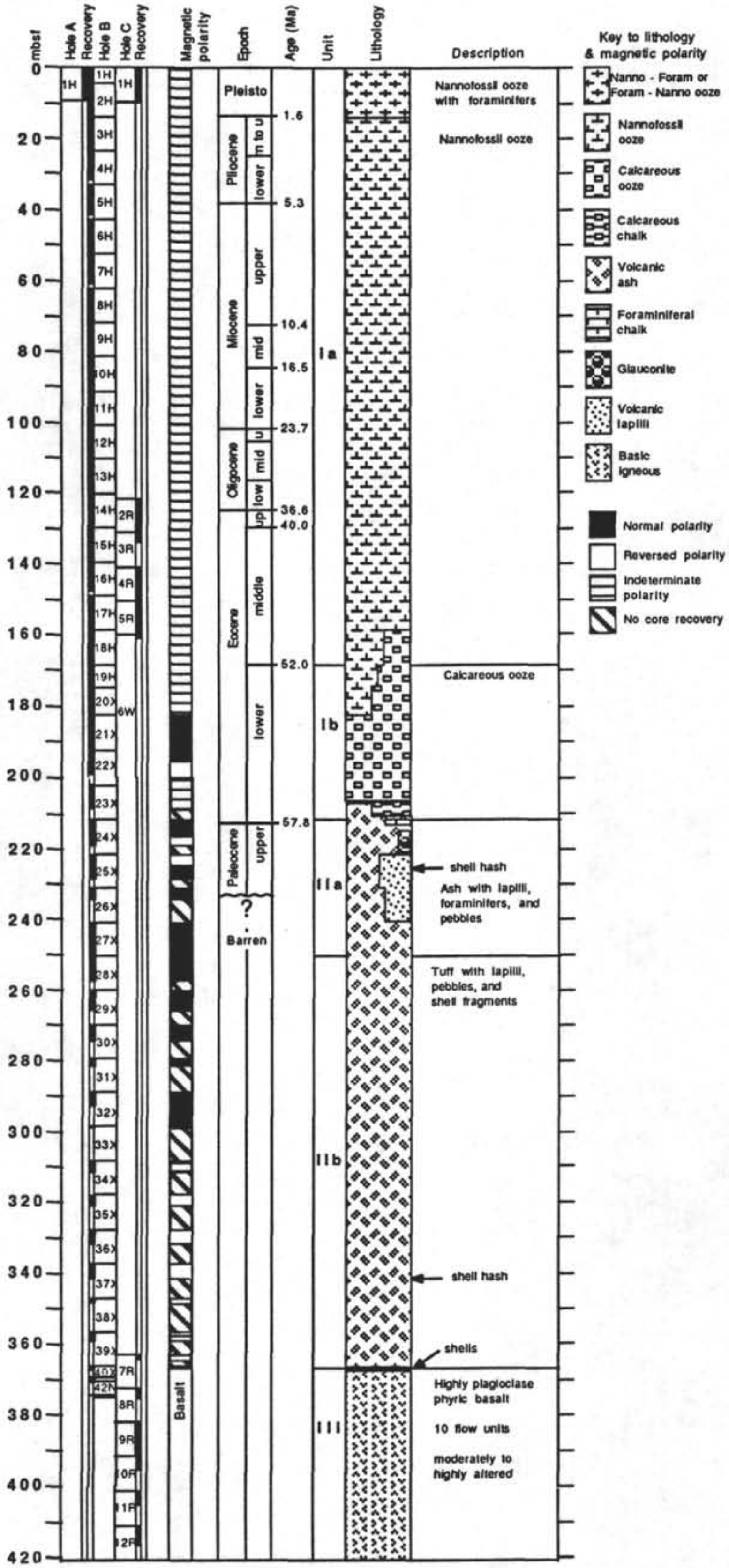
mbsf
Hole A
Recovery
Hole B
Hole C
Recovery
Magnetic polarity
Epoch
Age (Ma)
Unit
Lithology
Description
Pleisto
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Barren
Basalt
1.6
5.3
10.4
16.5
23.7
36.6
40.0
52.0
57.8
Ia
Ib
IIa
IIb
III
Nannofossil ooze with foraminifers
Nannofossil ooze
Calcareous ooze
shell hash
Ash with lapilli, foraminifers, and pebbles
Tuff with lapilli, pebbles, and shell fragments
shell hash
shells
Highly plagioclase phyric basalt
10 flow units
moderately to highly altered
Key to lithology & magnetic polarity
Nanno - Foram or Foram - Nanno ooze
Nannofossil ooze
Calcareous ooze
Calcareous chalk
Volcanic ash
Foraminiferal chalk
Glauconite
Volcanic lapilli
Basic igneous
Normal polarity
Reversed polarity
Indeterminate polarity
No core recovery

Figure 6

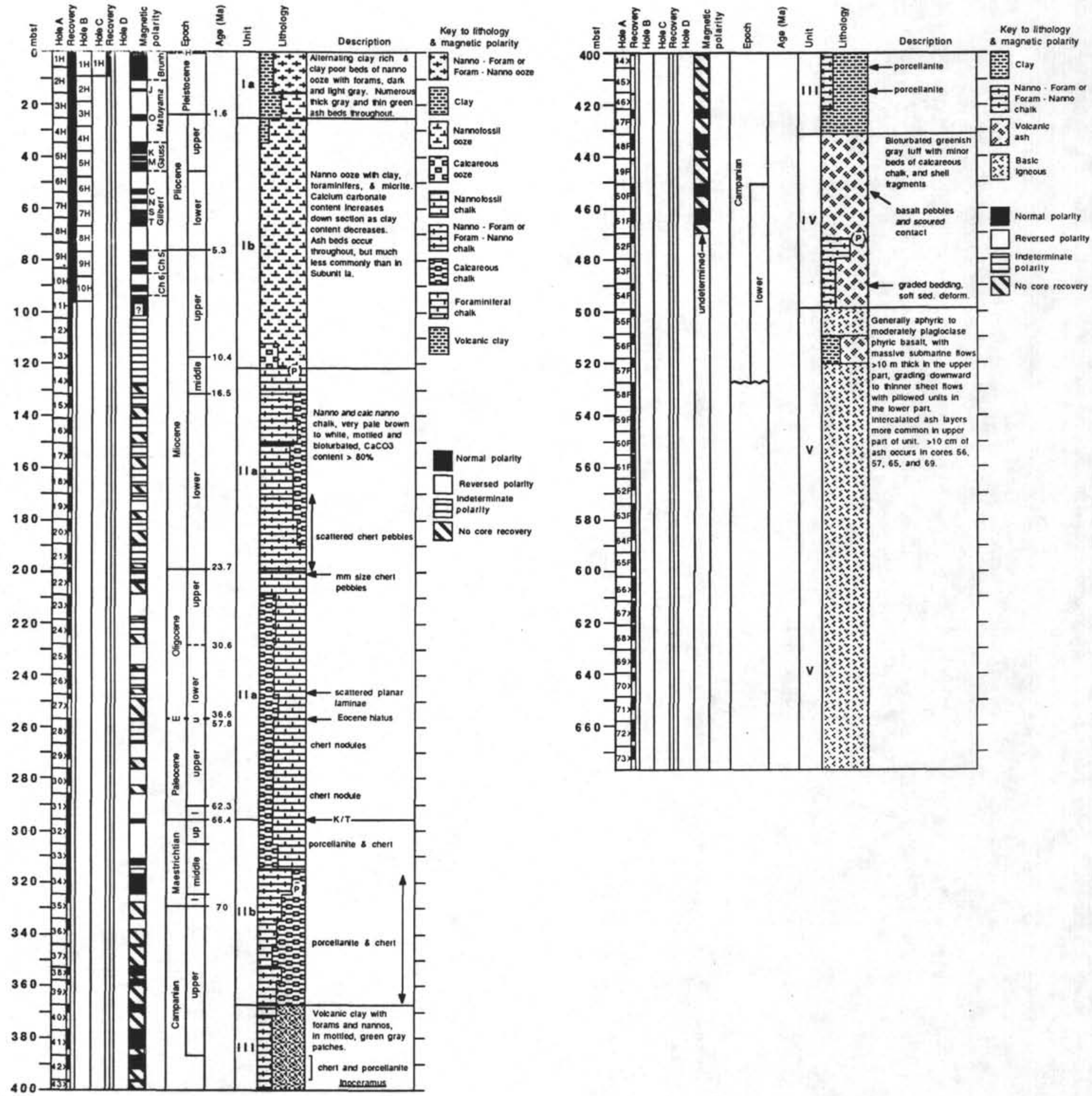
mbsf
Hole A Recovery
Hole B
Hole C Recovery
Hole D
Magnetic polarity
Epoch
Age (Ma)
Unit
Lithology
Description
Key to lithology & magnetic polarity
Alternating clay rich & clay poor beds of nanno ooze with forams, dark and light gray. Numerous thick gray and thin green ash beds throughout.
Nanno ooze with clay, foraminifers, & micrite. Calcium carbonate content increases down section as clay content decreases. Ash beds occur throughout, but much less commonly than in Subunit Ia.
Nanno and calc nanno chalk, very pale brown to white, mottled and bioturbated, CaCO3 content > 80%
scattered chert pebbles
mm size chert pebbles
scattered planar laminae
Eocene hiatus
chert nodules
chert nodule
K/T
porcellanite & chert
porcellanite & chert
Volcanic clay with forams and nannos, in mottled, green gray patches.
chert and porcellanite
Inoceramus
Pleistocene
Pliocene
Miocene
Oligocene
Paleocene
Maastrichtian
Campanian
upper
lower
middle
1.6
5.3
10.4
16.5
23.7
30.6
36.6
57.8
62.3
66.4
70
Ia
Ib
IIa
IIb
III
IV
V
Nanno - Foram or Foram - Nanno ooze
Clay
Nannofossil ooze
Calcareous ooze
Nannofossil chalk
Nanno - Foram or Foram - Nanno chalk
Calcareous chalk
Foraminiferal chalk
Volcanic clay
Volcanic ash
Basic igneous
Normal polarity
Reversed polarity
Indeterminate polarity
No core recovery
porcellanite
porcellanite
Bioturbated greenish gray tuff with minor beds of calcareous chalk, and shell fragments
basalt pebbles and scoured contact
graded bedding, soft sed. deform.
Generally aphyric to moderately plagioclase phyric basalt, with massive submarine flows >10 m thick in the upper part, grading downward to thinner sheet flows with pillowed units in the lower part. Intercalated ash layers more common in upper part of unit. >10 cm of ash occurs in cores 56, 57, 65, and 69.
undetermined

Figure 7

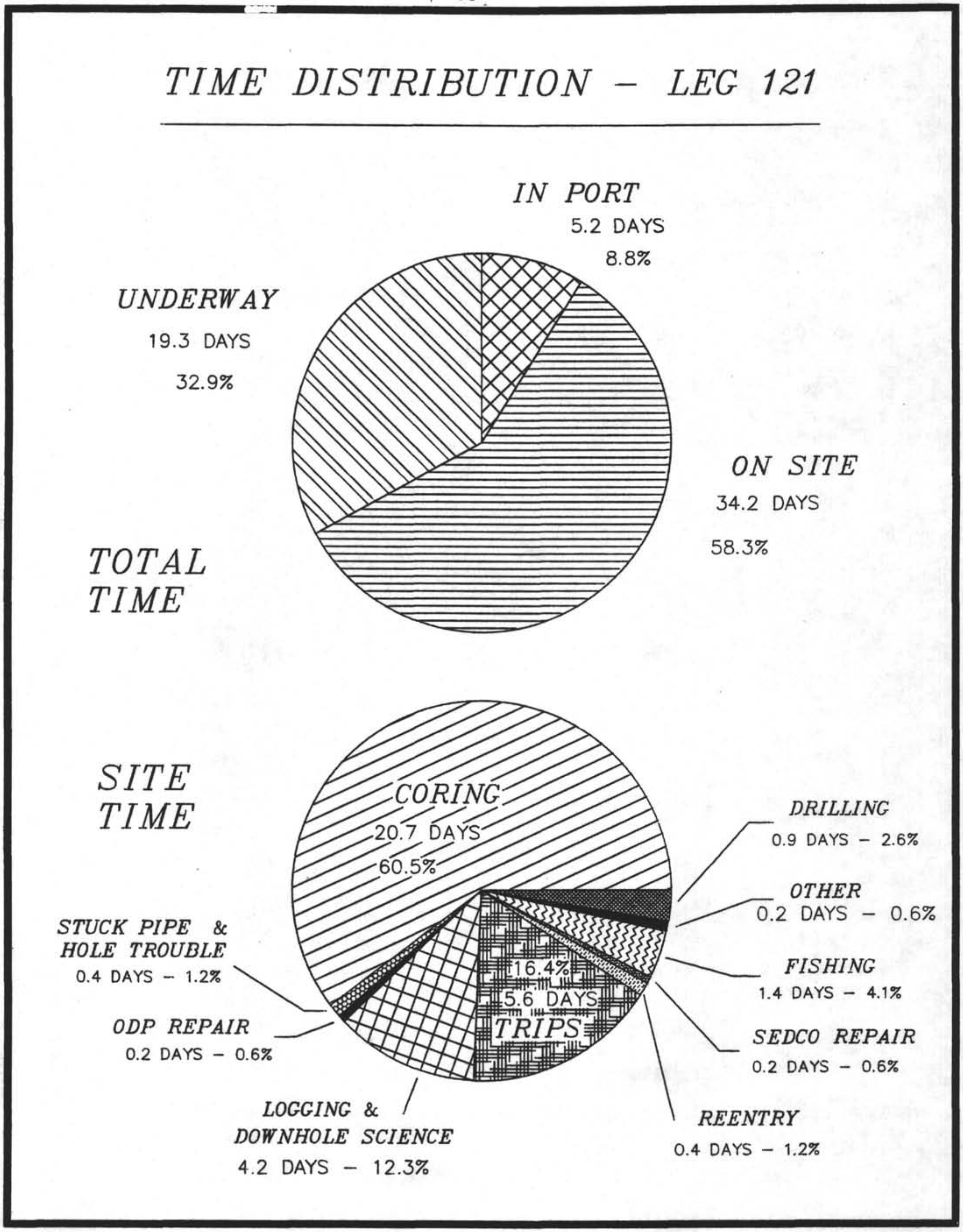
TIME DISTRIBUTION - LEG 121
IN PORT
5.2 DAYS
8.8%
UNDERWAY
19.3 DAYS
32.9%
ON SITE
34.2 DAYS
58.3%
TOTAL TIME
SITE TIME
CORING
20.7 DAYS
60.5%
DRILLING
0.9 DAYS - 2.6%
OTHER
0.2 DAYS - 0.6%
STUCK PIPE & HOLE TROUBLE
0.4 DAYS - 1.2%
16.4%
5.6 DAYS
TRIPS
FISHING
1.4 DAYS - 4.1%
ODP REPAIR
0.2 DAYS - 0.6%
SEDCO REPAIR
0.2 DAYS - 0.6%
LOGGING & DOWNHOLE SCIENCE
4.2 DAYS - 12.3%
REENTRY
0.4 DAYS - 1.2%

Figure 8

OPERATIONS REPORT

The ODP Operations and Engineering personnel aboard <u>JOIDES</u> <u>Resolution</u> for Leg 121 were:

| | |
|---|---|
| Operations Superintendent: | Dave Huey |
| Special Tools Engineer: | Mark Robinson |

Other operations and engineering personnel aboard <u>JOIDES</u> <u>Resolution</u> for Leg 121 were:

| | |
|---|---|
| Schlumberger Logger: | Steve Diana<br>Schlumberger Offshore<br>369 Tristar Drive<br>Webster, Texas 77598 |

## LEG 121 OPERATIONS SYNOPSIS

Leg 121 of the Ocean Drilling Program involved two separate but related areas of drilling operations: Broken Ridge and Ninetyeast Ridge. The first portion of the voyage was spent at Broken Ridge, where seven holes were drilled at four sites. The second portion of the leg was spent drilling ten holes at three sites in a south-to-north transect along Ninetyeast Ridge.

Leg 121 officially began when JOIDES Resolution (SEDCO/BP 471) reached Fremantle, Australia at 0915 hours, 30 April 1988, and ended with arrival in Singapore on 28 June 1988.

Much of the preliminary operational planning for the Broken Ridge drilling campaign was based on the expectation of unstable hole conditions based on DSDP Leg 26 results, where the drill string had to be severed after becoming hopelessly stuck at Site 255, just a few km from the Leg 121 chosen sites. The Leg 121 operations in the area were successful, with no unusual loss of equipment or operating time. An estimated 80% of the scientific objectives at Broken Ridge were achieved. In total, 690 m of core was recovered, four combination heat flow and pore water samples were taken, and two holes were logged. In addition, one of the holes was reentered twice via a freefall funnel to fish out a lost string of Schlumberger logging tools and to complete logging operations.

The operations at Ninetyeast Ridge were equally successful. About 80% of the scientific objectives for the three-site transect were achieved. The remaining 20% were characterized by poor luck in the logging program and a missing Paleogene section that was hoped for at the northern site (758) but did not exist at the drill location chosen. A total of 1134 m of core was recovered, one hole was drilled 178 m into basalt, and the northern site was logged. A side trip to Cocos Island for a medical evacuation prematurely terminated Site 757 and cost the chance to log that hole. A synopsis of Leg 121 operations time spent drilling, coring, logging, under way, and in port is shown in Figure 8 of the Science Report (see preceding section) and summarized in Table 1 of this operations synopsis.

## FREMANTLE PORT CALL

The vessel ended Leg 120 in Fremantle a day ahead of schedule because of a medical emergency. Despite some delays the work items to be accomplished during the stay were completed rapidly and the vessel was able to depart for Broken Ridge at 1345 hours on 5 May 1988.

During the port call, the normal operations of crew change, fueling, on- and off-loading of freight, and off-loading of cores were accomplished. Additionally, most of the Pro350 mini-computers on board were exchanged for IBM PC's or PC clones.

By 1030 hours on 5 May all work had been accomplished and the vessel was ready to depart. Harbor clearance was received a few hours later and the vessel got underway for the Broken Ridge operating area at 1345 hours.

## FREMANTLE TO SITE 752 (BR-2)

The transit to Broken Ridge was uneventful as the vessel made better than 11 kt in comfortable weather. The ship arrived in the vicinity of the Broken

Ridge drill sites at 1055 hr on 9 May. At 1408 hr the presite survey began, lasting until 0315 hr on 10 May. Prior to and during the survey, the bottom-hole assembly (BHA) and extended core barrel (XCB) were assembled and checked; a new version of the XCB was to be used for the first time on Leg 121. In addition, a Navidrill core barrel (NCB) deck test was conducted successfully. By the time the pre-site survey was completed all preliminary drill rig and coring systems checkouts had been accomplished.

The first beacon was dropped on Site 752 (BR-2) at 0135 hr on 10 May near the end of the survey. The vessel was ready to begin drilling operations at 0400 hr.

## SITE 752 (BR-2)

Site BR-2 was chosen for the first hole, instead of BR-1 as indicated in the prospectus, because it offered a thicker ooze section than BR-1.

### HOLE 752A

The drill string was run into the hole with the APC/XCB/NCB BHA and the mudline was established at 1097.2 m below the rig floor reference datum, with an APC core. Eleven piston cores were taken successfully to a depth of 103.3 mbsf, and two successful pore water sampler runs (WSPT) were made. At that point the change was made to the XCB coring mode with the new XCB-121. Core recovery was fair, being quite good in firm chalk, less satisfactory in sticky calcareous ooze and poor in zones where chert stringers were encountered. XCB core barrel 121-752A-34X became stuck in the BHA and could not be dislodged; a pipe round trip was made to handle the problem on deck. At the rig floor it was discovered that the XCB cutter shoe and spacer sub were missing along with the core catchers, so Core 121-752A-34X was not recovered. The broken end of the tool had flared out, accounting for the inability to recover the tool with the coring line. The bit had reached the rig floor at 1355 hr 12 May ending Hole 752A. Hole stability had been very good.

## SITE 753 (BR-1)

The vessel moved 3 nmi to proposed site BR-1 in dynamic-positioning (DP) mode with the hydrophones up. The end of the transit occurred during a GPS window, allowing an accurate beacon drop at 1630 hr 12 May while the ship held position over the site.

### HOLE 753A

The hole was spudded at 2020 hr with an APC core establishing mudline at 1187.0 m. Seven piston cores and two water samples were taken successfully. Core 121-753A-8H passed through the unconformity encountered slightly deeper at Hole 752A and became stuck. This time the core barrel parted with an overpull of more than 160,000 lb as the ship took a heave up while attempting to pull the core barrel loose. The junk terminated Hole 753A and the bit was pulled clear of the seafloor at 0615 hr 13 May.

HOLE 753B

The vessel was offset 100 m north and the pipe was washed to a depth of 24.4 mbsf to take a spot core. The XCB core barrel for Core 121-753B-2X came up empty and was dropped again to act as a wash barrel while the pipe was drilled down to 61.6 mbsf for resumption of XCB coring at a depth selected to slightly overlap the termination of piston coring in Hole 753A. The second wash core recovered only two or three small lumps of gritty chalk. From that point four XCB cores were attempted to a depth of 100.2 mbsf with only nominal traces of chalk and fine sand recovered. The site was terminated and the pipe was pulled with the bit arriving on deck at 1725 hr, 13 May.

On deck the problem with core recovery was found. The hinge pin of the standard float valve flapper was sheared and the flapper was bridged across the throat of the bit in such a way as to effectively prevent the XCB core barrel from extending beyond the bit, as well as inhibiting any core material from reaching the core barrel.

SITE 754 (BR-3)

While the post mortem of the flapper and hinge pin were conducted, the ship offset 6 nmi in DP mode to Site 754. As at Site 753, the vessel hove to over the site in DP mode during a GPS window and was able to make an accurate beacon drop at 1830 hr, 13 May.

HOLE 754A

The standard BHA used for APC/XCB coring was assembled with the enhancement of a latch sub required for operating the Navidrill coring system. After the drill pipe had been run to the seafloor, piston coring began with a successful mudline core establishing the operating water depth at 1076.4m. Routine APC cores were then taken to 112.3 mbsf. The change was made to the XCB coring system for the next six cores. Recovery during the XCB sequence was quite poor because of the presence of loose beach type gravel followed by chert-infested chalk.

Five NCB cores were taken with mixed success. The coring tool itself functioned perfectly from a mechanical point of view. Only Core 121-754A-20N achieved the full 4.5-m stroke. Results with the new tool were encouraging but the net penetration rate after five cores was only about 1 m/hr, including turnaround time on deck. This was not adequate to justify continuation of NCB coring. Thus, Hole 754A was terminated at 159.8 mbsf and the drill string was pulled in order to change over to the RCB coring system. The bit cleared the seafloor at 0150 hr on 15 May, ending Hole 754A.

HOLE 754B

A rotary coring system (RCB) BHA with hydraulic bit release was made up and run to the seafloor. The hole was spudded and quickly washed to 122.7 mbsf where coring resumed in an attempt to get more recovery from the presumed loose gravel zone at about 135-155 mbsf. Like the previous attempts with the XCB, the RCB system was also unable to capture any more than traces of the elusive gravel through cores 121-754B-2R to -4R. Chert and chalk were encountered in Core 121-754B-5R. A great deal of interbedded chert was drilled in the next twenty cores but recovery was at times extremely good. This good fortune began to fade after Core 121-754B-15R (257.9 mbsf), where chert began to predominate and control the drilling parameters such that it was no longer possible to obtain recovery in the softer layers between chert stringers. The core bit began to show signs of difficulty in penetrating during cores 121-754B-24R and -25R and would not make any hole when core 121-754B-26R was attempted. The bit was declared dead at 1431.1 m total depth (TD) (354.7 mbsf) and coring was terminated.

In preparation for downhole logging a full wiper trip was run and with the bit back at the bottom the hole was swept with polymer mud, flushed with seawater, and displaced with KCl-added mud. The bit was then released and the pipe was pulled to the initial logging depth of 160 mbsf.

The first logging run was the geochemical suite (GST-ACT-NGT). The hole was logged successfully from TD to the mudline with the upper 160 m being logged through the pipe twice. Logging run No. 2 was the seismic stratigraphy combination with resistivity added. Successful logs were recorded as the tool was run from bottom to the end of the pipe. The pipe was freed after a short stuck pipe incident and further plans to log the unstable hole were abandoned. The pipe was pulled and the end of the pipe was on deck at 0915 hr while the ship was under way in DP mode back to Site 752.

## RETURN TO SITE 752 (BR-2)

The ship returned to Site 752 and steadied on the still-active beacon at 0900 hr, 18 May. Time remaining for Broken Ridge operations was to be divided between a logged RCB single-bit hole at Site 752 cored to the 450 mbsf target, and a single-bit RCB penetration at proposed site BR-4 near the crest of the ridge to sample the oldest strata available under the Neogene cap.

## HOLE 752B

The RCB BHA was run to the seafloor and immediately washed without coring to 120 mbsf. Two spot cores were then taken across the Oligocene unconformity identified while coring Hole 752A. The hole was then washed to a depth of 297 mbsf where coring began to overlap Hole 752A by about one core length. Coring proceeded with very good results to 431.6 mbsf where the last core was to be taken before releasing the bit for logging. Core 121-752B-18R came up empty and one more short core was taken to end the hole at 435.6 mbsf TD.

A mud sweep was pumped and a wiper trip to 80 mbsf and back to TD was done before the bit was released. The hole was then displaced with seawater and filled with KCl-added mud in preparation for logging. With the end of the pipe stationed at 61.3 mbsf the first logging run was attempted using the seismic stratigraphy suite (DIT-LSS-CAL-NGT). After obtaining successful logs the tool would not reenter the drill pipe and parted at the cablehead weak point. It was found later that one caliper bow spring was broken, which accounted for the inability to get the tool back into the pipe.

The logging line was pulled to the deck where a portion of the cablehead still attached to the wire confirmed that the weak point had parted. Additional investigations confirmed that the logging tool was no longer stuck in the pipe.

A mini-cone was assembled around the pipe and dropped, and the pipe was tripped out of the hole. On deck a fishing assembly capable of snaring the lost logging tools was made up to the end of the BHA and run back to just above the seafloor. The Colmec underwater TV and Mesotech sonar were lowered down the outside of the drill string with the VIT frame and the seafloor was searched for the mini-cone and its floating glass balls.

HOLE 752B - FIRST REENTRY

The TV search for the hole turned out to be a difficult one because the glass balls were not identifiable on sonar and could not be identified visually. Eventually the pipe was stabbed into the center of a local depression, and reentered the unseen hole without any evidence of contacting the cone, at 0430 hr 21 May. The TV frame was recovered and the fishing assembly was lowered into the hole until contact was made with the fish at 408 mbsf indicating that the tool had fallen to the bottom of the hole. A perfect catch of the fish was made and the drill string was tripped out of the hole.

The entire logging tool was recovered. The bow springs of the caliper were distorted with one completely broken and twisted sideways. The LSS tool was bent unnaturally in two places. Neither tool could be used for the remainder of the leg.

A reentry/cleanout bit was made up to the BHA in place of the fishing tools and the drill string was again run to the seafloor.

HOLE 752B - SECOND REENTRY

The second attempt to reenter the invisible mini-cone was a repeat of the first exercise except that when the pipe was stabbed into what appeared to be the same spot the hole was not found and the bit took 10,000 lb WOB immediately. More than a dozen further stabs were made before the pipe once again found the hole and slipped into it without any evidence of contacting the cone. The successful stab was made at 1907 hr 21 May. The hole was still open and the cleanout bit was run in to a depth of 128 mbsf, across the unconformity, to begin the logging operations again.

The lithoporosity suite (LDT-CNL-NGT-DIT) was run successfully. The pipe was again run to the bottom of the hole to knock out bridges and the geochemistry logging suite was run before pulling out and abandoning Hole 752B. The cleanout bit was on deck at 1230 hr 22 May, as the vessel moved in DP mode to the final Broken Ridge site, 755 (BR-4).

SITE 755 (BR-4)

HOLE 755A

The short move to Site 755 was accomplished in 2-1/2 hr and the drill pipe was lowered to the seafloor with the RCB BHA and a new C-4 type 9-7/8" roller cone bit. A routine mudline punch core established DPM water depth to be 1068.8 m. Since the site was within a few miles of the other Broken Ridge sites and the Neogene cap had been sampled at each of the other sites, the bit was washed ahead to 36.1 mbsf before coring resumed. The elusive band of

Site 754

Site 754 (proposed site BR-3) was positioned to penetrate the maximum thickness (0.175 s TWT bsf) of the subhorizontal pelagic sequence which caps the erosional unconformity at Broken Ridge. The site selected is at SP 1040 on Line 20 of the single-channel seismic survey conducted in 1986 by R/V Conrad during cruise RC2708. It is located near the center of the crest of Broken Ridge, about 14 km north of the main south-facing escarpment (Fig. 3).

The principal objectives at Site 754 were to (a) sample the oldest material deposited on the truncation surface in order to compare its age, lithology, and paleodepth with the youngest material clearly below the unconformity drilled at Site 753, and (b) to penetrate and sample a prominent seismic reflector at about 0.3 s TWT bsf, which represents a surface of downlap in the truncated, northward-dipping sedimentary section at Broken Ridge. Unfortunately. the second objective was not met because the RCB bit failed in a lower Maestrichtian chert/chalk sequence at a depth of 355 mbsf in Hole 754B, still above the target reflector.

Hole 754A was APC/XCB/NCB cored to a depth of 172 mbsf. In following this coring sequence, Site 754 became the first ODP drill site to make true operational use of the Navidrill in sediments. Although core recovery was good with the NCB (73%), the penetration rate proved slow in the Maestrichtian chalk/chert sequence, and Hole 754A was terminated after drilling 12.3 m with the NCB. Hole 754B was spudded nearby, and after washing down 123 m, the hole was RCB cored to a total depth of 355 mbsf at which point the bit failed. The bit was then released, the drill string pulled to a depth of 160 mbsf (to cover a potentially unstable zone above the unconformity), and two logging runs were made. The first run, with the geochemical string, proceeded without incident, but after a successful run with a modified seismic stratigraphy string, the drill string was found to be stuck, and logging was terminated so that the pipe could be freed.

Two lithostratigraphic units are recognized at Site 754 (Fig. 4):

Unit I: (0-132 mbsf) Holocene-upper Eocene foraminifer nannofossil ooze in which foraminifers become less abundant and micrite becomes more abundant with depth. Two subunits can be identified:

Subunit Ia: (0-83.2 mbsf) Holocene-lower Miocene foraminifer-nannofossil ooze.

Subunit Ib: (83.2-132 mbsf) lower Miocene-upper Eocene oozes, similar in composition to the overlying subunit, but with fewer foraminifers (10-15%) and more micrite (10-20%). Scattered, thin ash layers and pockets occur in this subunit. Shell fragments are found in the lower 10 m.

A layer of quartz sand, pebbles and cobbles of limestone, chert, and shell fragments occurs at the base of Unit I. Although little of this basal layer was actually recovered, its thickness may be as much as 29 m (122-151 mbsf). A hiatus occurs at the top of this basal layer of Unit I (122 mbsf), representing a depositional break spanning late Eocene to late Oligocene time.

Unit II: (151-355 mbsf) upper to lower Maestrichtian (Campanian?) chalks and limestones with chert and volcanic ash. Three subunits can be identified:

Subunit IIa (151-190 mbsf) is a hard, upper Maestrichtian calcareous chalk.

firm chalk/limestone. XCB operations continued until very hard limestone, presumably overlying basement, was found to be impenetrable by the XCB system. The XCB tools were set aside and the Navidrill coring system was deployed.

Three Navidrill cores were taken in five attempts. The first NCB core was a perfect section of vesicular basalt 4.2 m long, 100% recovery, which demonstrated the potential of diamond coring technology in hard rock. The next two NCB runs did not recover any core and were assumed to represent problems of motor stallout. The next run recovered 1.13 m of soft soil/clay. The final core was a mere 0.4 m of basalt chunks. The NCB operations were then terminated. The pipe was tripped back to the deck for a changeover to the RCB coring system and BHA. The bit was on deck at 1845 hr, May 27.

HOLE 756D

An extra stand of drill collars and a rerun 9-7/8" C-57 hard rock bit were made up to the BHA and tripped back to the seafloor. The vessel was offset 100m back to the approximate beacon location and Hole 756D was spudded with a mudline punch core that established drilling depth at 1524.0 m. The bit was washed to 70.1 mbsf without coring and a spot core was taken. Washing then continued to 139 mbsf where coring resumed only inches above the basement contact.

Slow but acceptable progress was made into basement of vesicular basalt with core recovery about typical for the RCB system, ranging from 0.69 m to 5.25 m per core. Hole conditions began to deteriorate after penetrating about 30 m of basement. Regular mud sweeps were used to fight the recurring problems of excessive torque and 1-2 m of fill was found each time a new core was to be cut. After battling intermittent hole problems for seven RCB cores the scientific objectives were declared achieved and the hole was terminated. The drill pipe was pulled and the ship got under way for the central Ninetyeast Ridge site, NER-2C. Total depth for the hole was 221.0 mbsf with about 82 m penetration into basement.

SITE 757 (NER-2C)

With the pipe on deck at 1000 hr May 29, the vessel secured for sea and proceeded north to the central of the three Ninetyeast Ridge drilling locales. The route chosen was east of the direct course to the next site so that a magnetometer survey could be completed parallel to and east of the ridge. At 1700 hr May 31 the seismic gear was again streamed and the vessel slowed to 6 kt for the pre-site survey, which lasted some 10 hr. On the second pass over the site a Datasonics beacon was dropped at 0210 hr 1 June.

HOLE 757A

Since oriented piston cores were planned at this low-latitude site (17°S), the non-magnetic drill collar was included in the BHA with an additional stand of 8-1/4-in. drill collars to allow for more weight on bit during the Navidrill coring operations.

The drillpipe was run to the chosen depth for the mud line APC shot and the first piston core was taken. When recovered it was found to have captured a full core and thus missed the mud line despite a very conservative estimate of PDR depth.

HOLE 757B

The pipe was pulled clear of the seafloor and raised an additional 3 m. Two additional mudline cores were attempted. On the third attempt, in spite of a shattered core liner, a core was recovered, establishing a working water depth of 1663.0 m DES. This contradicted the apparent results of Hole 757A, which had achieved a full core with the bit poised at a depth of 1661 m. Rather than spend more time in search of an unambiguous mud line depth the results of the Hole 757B mud line core were accepted and coring continued. Nineteen piston cores were taken in calcareous ooze. Cores 121-757B-3H to -19H were oriented magnetically using the Multishot camera. Core recovery during the piston core sequence was near perfect.

The XCB-121 coring system was deployed and cores 121-757B-20X to -41X were taken. Recovery was good, with some cores suffering reduced recovery due to packing off in the cutting shoes. A few random chunks of basalt and chert were encountered in cores below 222 mbsf. Core 121-757B-40X took 55 min to penetrate just 3 m but when it was recovered the liner contained only hard, packed clay. A fresh XCB barrel was pumped down for Core 121-757B-42X and 1 m of penetration in basalt was achieved in 45 min.

The Navidrill coring system was deployed in hopes of coring 50+ m of basement without having to trip pipe for the RCB system. The first NCB coring run apparently penetrated 4.0 m but lost almost all of the cut core. The material recovered in the core barrel was only 0.65 m of basalt. A core catcher failure was declared as the best explanation for the missing core. The assumed 4-m deep "rathole" was drilled off feeling very much like hard basalt and the NCB was pumped down for the second and final time. The second NCB core attempt was a misrun with evidence of both improper seating of the core barrel in the BHA and probable stallout of the mudmotor. The material recovered was only three chunks of basalt. The NCB equipment was rigged down and the pipe was tripped out of the hole, with the bit reaching the rig floor at 0615 hr 4 June.

HOLE 757C

The ship was offset 200 m northwest and a conventional RCB BHA with a new 9-7/8-in. RBI C-4 bit was made up and run to the seafloor. A mudline punch core was taken which established the drilling depth at 1654.5 m DES. The hole was drilled to 121.5 mbsf without coring and cores 121-757C-2R to -5R were then taken in soft ooze to recover samples for geochemical and paleomagnetic comparison with Hole 757B. The bit was then washed to a depth of 362.9 mbsf where routine coring began just above basement to overlap the stratigraphy of Hole 757B. Cores 121-757B-7R to -12R were taken in basalt to a depth of 420.7 mbsf, some 48 m into basement with a recovery of 52%. At this point coring operations were abruptly terminated in order to proceed to Cocos Island for the medical evacuation of one of the crew. The pipe was pulled and as soon as the bit was on deck the vessel made preparations to get underway. Departure for Cocos Island was at 1845 hr 5 June.

## SITE 757 TO COCOS ISLAND

The ship proceeded at full speed to the Cocos Island atoll where a rendezvous with the Australian flying doctor service out of Perth had been arranged. At 0400 hr 8 June, the ship stopped off South Keeling Island of the Cocos group to take a launch alongside with the Australian doctor and local customs officials. At 0430 hr the group departed with the evacuee.

## COCOS TO SITE 758 (NER-1C)

The vessel departed from the Cocos island atoll immediately and sailed for the northern site of the Ninetyeast Ridge drilling campaign. On 11 June, one day before reaching Site 758, the ship crossed the equator and another batch of polliwogs was initiated into the Honorable Order of Shellbacks and introduced to the mysteries of Neptunus Rex.

At 0245 hr 12 June the seismic gear was streamed to begin the pre-site survey. The chosen site was designated NER-1C and constituted a change from the two planned sites in the prospectus, NER-1A and NER-1B. Since less time would be available than had been originally foreseen, NER-1C was positioned --and approved by the JOIDES Safety Panel--to achieve the scientific objectives in a single site that had been planned for both NER-1B and -1C. An ORE beacon was dropped at 1325 hr, beginning Site 758.

### HOLE 758A

An APC/XCB bottomhole assembly was made up with a non-magnetic drill collar and run to the seafloor. A successful mudline core 6 meters long established the working water depth at 2934.5 m and included an identifiable oxidized layer as the actual seafloor surface material. Eleven piston cores were then taken, with total recovery exceeding 100%. Cores 121-758A-3H through -11H were magnetically oriented using the Multishot camera system.

XCB coring advanced the hole from 102 mbsf to 421.5 mbsf. The first 220 m of this interval experienced unusually easy coring and recovery ranging from 5.0 to 9.8 m per core. Chert and porcellanite layers were encountered below this depth, which took their toll on both recovery and XCB cutting shoes. At Core 121-758A-46X the core barrel became stuck in the BHA and required continuous jarring for 30 min to dislodge. XCB coring was discontinued and hole was displaced with 12 ppg mud in preparation for later reentry.

Before the pipe was tripped out of the hole, a mini-cone was assembled and dropped to mark the hole for reentry and deepening with the RCB system. The pipe was pulled clear of the seafloor at 0440 hr and the vessel was offset 100 ft south in order to complete a double APC sequence.

### HOLE 758B

After determining that the PDR depth was 2 m deeper at Hole 758B, a mud line core was attempted to achieve both a mud line capture and an adequate overlap with the coring breaks of Hole 758A. The overlap and subbottom depth correlations were very good but the mud line core apparently missed about 0.5 m of the actual surface sediments. Nevertheless, ten APC cores were taken with good recovery and cores 121-758B-3H through -10H were magnetically oriented. The pipe was then pulled clear of the seafloor at 1558 hr and the vessel was offset 6 m north.

HOLE 758C

A final mud line APC core was taken to capture the elusive oxidized sediments at the seafloor. This was successfully achieved and the pipe was immediately pulled to the deck to change over to the RCB. The bit was on deck at 2350 hr June 15.

HOLE 758A (FIRST REENTRY)

A new bit was made up to a conventional RCB BHA and the pipe was tripped to the seafloor. The VIT frame with the TV and Mesotech sonar was made up around the pipe and lowered until the mini-cone and flotation balls could be seen as targets on the sonar. In twelve minutes the ship was maneuvered over the mini-cone and the drill pipe was stabbed successfully into the cone on the first attempt. Reentry occurred at 0615 hr on 16 June.

The TV frame was recovered and the drill pipe was run to the bottom of the hole. No fill or bridges in the hole were encountered. RCB coring commenced at 421.5 mbsf and continued to 583.2 mbsf. Cores 121-758A-47R to -53R were in easy-drilling limestone which was penetrated at about 30 m/hr. Basalt was first encountered in Core 121-758A-54R at 495 mbsf along with interbedded sediments, although acoustic basement showed on the seismic records at 650 mbsf. After Core 121-758A-57R the formation was all basalt with ROP ranging from 2 to 4 m/hr. The rock proved extremely conducive to coring, however. Several cores achieved near full recovery and contained unbroken pieces of basalt up to 3.3 m long. After Core 121-758A-63R the pipe was pulled to change bits; the bit reached the rig floor at 0115 hr 19 June.

HOLE 758A (SECOND REENTRY)

An identical RBI C-4 RCB bit was made up to the BHA along with a mechanical bit release (MBR) and the pipe was run back in to reenter the hole. The TV/Sonar frame was run after replacing the telemetry pod which had developed a problem in its internal power supply. The repaired TV/Sonar system was deployed and run to the bottom of the pipe with minimal difficulties despite a strong surface current (up to 3 kt) which developed while the ship occupied the site. The mini-cone was spotted immediately and maneuvering and stabbing required only three minutes.

The pipe was run to TD at 583.2 mbsf and only 10 m of easily washable fill was encountered enroute. RCB coring resumed in solid basalt with penetration rates as slow as 1.6 m/hr. Two more days of uninterrupted basalt coring ended at 676.8 mbsf when it was time to log the hole before departure for Singapore. Probable acoustic basement had been encountered at about the depth estimated from seismic analyses. Total basalt penetration after first contact was 178 m with an admirable recovery rate of over 69%.

The hole was conditioned for logging by sweeping mud and conducting a wiper trip which apparently encountered no bridges but 23 m of fill had accumulated and was readily pumped away. The bit was released and the hole was displaced with KCl-added gel mud and appeared to be in fine condition for the extensive logging program planned.

The end of the pipe was positioned at 42.7 mbsf. Log No.1 (DIL-SONIC-GR) was run but could not be calibrated. After some investigation the problem was determined to be an unexpectedly deep air-water interface and calibration had been attempted first in air. The tools were finally run into the pipe and stopped on an obstruction in the pipe more than 400 m above the end of the pipe. Circulation at 300-500 psi was enough to get the logging tools past the unknown obstruction and into the open hole, only to be stopped again by a firm bridge at 405 mbsf. The available sediment interval was logged and the tool was recovered.

Log No.2 (GST-ACT-NGT-CNL) was made up and run to log the same interval before another wiper trip was done to open more of the hole. This tool string also encountered the pipe obstruction at 2531m (apparently bent drill pipe) but was forced past with 250 gpm circulation. The bridge at 3340 m stopped this tool and the open hole interval up to the end of the pipe was logged. The second suite of logging tools was back on deck at 0520 hr 23 June.

A second hole-opening wiper trip was done and no bridges were felt. Basement appeared to be wide open and no fill was encountered as the MBR top connector reached TD easily. KCl-added mud was again pumped to replace the volume lost during the wiper trip.

For the next set of logging runs the pipe end was set at 525 mbsf, about 30 m lower than the first basalt contact. Log No.3 (DIL-SONIC-GR) was run in and again encountered the bent-pipe restriction before being lowered into open hole. One bridge or ledge was worked past just beyond the end of the pipe but another firm bridge at 545 mbsf stopped the tool. The open interval of basement to the end of the pipe was logged and the tools were retrieved.

A final attempt to achieve borehole televiewer logs of basement was made. A third short wiper trip to bottom succeeded in knocking out bridges at three locations in the basement section of the hole. The end of the pipe was set at 553 mbsf, theoretically exposing 123 m of ideal basement. The BHTV was made up and run but was quickly back on deck with a flooded cablehead. A new pigtail was installed and the tool was again lowered and worked into open hole to be stopped at 610 mbsf. The hole was logged from there up to the pipe-up position at 554 mbsf. A second run was made from 556 mbsf up to 526 mbsf. The BHTV appeared to be operating at less than optimum performance. No breakouts in the rock were immediately recognized. Total operating time had expired so the BHTV deployment was ended and the tool was returned to the rig floor. The drill pipe was pulled for the final time. Three obviously bent joints of 5-in. drill pipe were found in the drill string, accounting for the recurring obstruction detected on each logging run. The end of the pipe was on deck at 1330 hr 24 June, ending Leg 121 drilling operations.

## LOGGING

Three holes were logged and two others where logging was planned had to be abandoned without logging. Logging was successfully completed at Holes 752B, 754B, and 758A. Plans to log Hole 755A were cancelled because of poor hole conditions and lack of time. Hole 757C was left abruptly because of a medical emergency requiring immediate departure from the site. Those logs which were acquired were good quality but the time and effort spent did not match the quantity of downhole data we had expected.

A summary of logging runs follows:

752B: Log No.1 Seismic Stratigraphy string
Down log: 38 masf to 435 mbsf
Up log: 435 mbsf to 62 mbsf
Useful logged interval: 0-422 mbsf
Data quality: Good

Log No.2 Litho-porosity string
Up log: 339 mbsf to 97 mbsf (127-97 mbsf thru pipe)
Useful logged interval: 128-320 mbsf
Data quality: Good

Log No.3 Geochemical string
Up log: 425-87 mbsf (127-87 mbsf thru pipe)
Up log: 32 mbsf to 8 masf (all thru pipe)
Data quality: Very good over open hole interval 129-422 mbsf

754B: Log No.1 Geochemical string
Up log: 355 mbsf to 16 masf (160 mbsf to 16 masf thru pipe)
Up log: 184 mbsf to 26 masf (160-16 mbsf thru pipe)
Data quality: Good

Log No.2 Seismic Stratigraphy string
Down log: 16 masf to 322 mbsf (16 masf to 160 mbsf thru pipe)
Up log: 322 mbsf to 52 mbsf (160-52 mbsf thru pipe)
Up log: 321-186 mbsf
Data quality: Good except the 286-300 mbsf interval of borehole roughness

758A: Log No.1 Seismic Stratigraphy string
Down log: 42-405 mbsf
Up log: 405 mbsf to 40 masf (42 mbsf to 40 masf thru pipe)
Data quality: Good

Log No.2 Geochemical string
Down log: 35 masf to 95 mbsf (35 masf to 42 mbsf thru pipe)
Up log: 397 mbsf to 35 masf (42 mbsf to 35 masf thru pipe)
Data quality: Good over interval 45-375 mbsf

Log No.3 Borehole Televiewer
Up log: 610-525 mbsf
Up log: 555-525 mbsf
Data quality: Fair, complicated by erratic compass firing. No breakouts or fractures identified on the photo images.

Table 1.
OCEAN DRILLING PROGRAM
OPERATIONS RESUME
LEG 121

| | | |
|---|---|---|
| Total Days (30 April - 28 June 1988) | | 58.7 |
| Total Days in Port | | 5.2 |
| Total Days Under Way (including survey) | | 19.3 |
| Total Days on Site | | 34.2 |
| Trip Time | 5.6 | |
| Coring Time | 20.7 | |
| Drilling Time | 0.9 | |
| Logging/Downhole Science Time | 4.2 | |
| Reentry Time | 0.4 | |
| Mechanical Repair Time (contractor) | 0.2 | |
| Fishing | 1.4 | |
| ODP Repair Time | 0.2 | |
| Stuck Pipe/Hole Trouble | 0.4 | |
| Other | 0.2 | |
| Total Distance Traveled (nautical miles) | | 5100.0 |
| Average Speed (knots) | | 11.3 |
| Number of Sites | | 7 |
| Number of Holes | | 17 |
| Total Interval Cored (m) | | 2721.7 |
| Total Core Recovery (m) | | 1824.4 |
| Percent Core Recovered | | 67.0 |
| Total Interval Drilled (m) | | 1001.2 |
| Total Penetration (m) | | 3722.9 |
| Maximum Penetration (m) | | 676.8 |
| Maximum Water Depth (m from drilling datum) | | 2936.5 |
| Minimum Water Depth (m from drilling datum) | | 1068.8 |

TECHNICAL REPORT

The ODP Technical and Logistics personnel aboard <u>JOIDES</u> <u>Resolution</u> for Leg 121 were:

| | |
|---|---|
| Laboratory Officer: | Burney Hamlin |
| Chemistry Technician: | Valerie Clark |
| Chemistry Technician: | Katie Tauxe |
| Computer System Manager: | John Eastlund |
| Curatorial Representative: | Bob Wilcox |
| Electronics Technician: | Jim Briggs |
| Electronics Technician: | Dwight Mossman |
| Photographer: | Stacey Cervantes |
| X-ray Technician: | Bettina Domeyer |
| Yeoperson: | Alison Craig |
| Marine Technician: | Daniel Bontempo |
| Marine Technician: | Roy Davis |
| Marine Technician: | Kazushi "Kuro" Kuroki |
| Marine Technician: | Mark "Trapper" Neschleba |
| Marine Technician: | John Tauxe |
| Marine Technician: | Sherry Williams |
| Marine Technician: | Dawn Wright |

# LEG 121 TECHNICAL REPORT

## PORTCALL

Crossover began on 1 May. On the same day, 100 liters of liquid helium was transferred into the cryogenic magnetometer. Five hundred boxes of cores were moved off the ship with the assistance of the Australia Union crane and dockworkers for shipment to the ODP repository. Freight dispersal began on 1 May and continued through 5 May.

Field representatives from Hewlett Packard and DEC came aboard to service shipboard computer systems. High-pressure nitrogen bottles were delivered to charge the wire line heave compensator; one bottle was used for the heave compensator and two others were brought aboard for the L-DGO logging system. The library copy machine was repaired with locally purchased parts.

The forward 12-kHz transducer was pulled to be moved to the aft position because the aft transducer had failed during Leg 120. At the same time we began to prepare the forward well for the Singapore II portcall installation of a sonar dome which will protrude below the ship and house 12-kHz and 3.5-kHz transducer arrays. However, the forward transducer would not fit in the aft well because the face protrusion would not allow the unit to seat. The E.T.'s repaired the failed transducer and re-installed it aft. The original failure was attributed to connectors.

## UNDERWAY

JOIDES Resolution sailed at 1345 hr on 5 May from the port of Fremantle, Australia, west 4+ days to Broken Ridge. Clocks were retarded an hour a day for three days to allow better communications with the United States. Header tapes were started in the harbor to collect navigation data and the magnetometer sensor was deployed a few hours later. The record from the aft (only) 12-kHz transducer faded away as the ship speed increased past 6 kt.

The pre-site survey began early in the afternoon on 9 May for a scheduled 11 hour survey at 6 kt. The starboard water gun was deployed with a new towing sled with depressors in an attempt to operate the guns at greater depth. The depth transducers were deck calibrated, but when the guns were pulled after the survey the calibration of all depth transducers was off several meters from zero. The Co-Chief Scientists and several other scientists took scheduled watches in the underway geophysics lab assisting the technician watchstanders and plotting navigation data on X-Y plotting sheets generated on the large HP plotter by our Systems Manager and an E.T.

The ship progressed from one Broken Ridge site to another using 12- and 3.5-kHz recorders with our seismic records and the site survey records as guides.

The transit to the southernmost Ninetyeast Ridge was 1 1/2 days long with navigation and magnetometer data recorded. A four hour seismic survey was made in the area. The beacon drop was attempted but the latching mechanism stuck and it was swung back aboard for repair. We proceeded with the survey, pulled gear and then returned, using GPS, to the selected spot to drop the beacon.

The 2 1/2 day transit to the middle Ninetyeast Ridge site concluded with a 9-hr seismic survey with GPS.

A medical emergency canceled the logging objectives planned for Site 757. A transit of 2 1/2 day brought the ship to Cocos Island to allow a CATERMAR employee to be evacuated by a Medical Emergency Flight to Perth, Australia. Approximately four days later the ship had traveled to our northerly site, 758, on the Ninetyeast Ridge. A 10-hr seismic survey was conducted there to verify the selected site.

This last survey was run with the depth depressor installed on the starboard gun and indications were that it was running two meters below the port gun. Initial indications then are that the depressors are adding 2-3 meters depth to guns being towed at 7 kt.

The last site ended on 24 June and the transit to port began. The clocks were advanced three hours to Singapore time. Approximately 2.5 days of transit navigation data were collected,although the magnetometer was pulled off the North tip of Sumatra in shallow water. We then entered the shipping lanes and traffic in the Straits of Malacca for the run to port at Singapore.

The Leg ended 28 June, arriving early in the morning in the port of Singapore after 54 days at sea.

## CORE LAB

Demands on the core lab were varied, with the mixed cruise objectives of coring to basement with the APC and XCB system, and then rotary drilling into basalt. Some 40 hard rock and 270 sediment cores were recovered, and 14,865 samples were taken to support the scientific objectives of the leg.

The paleomagnetists and technician calibrated the cryogenic magnetometer electronics and made software changes to reflect an extensive suite of measurements of the Minispin uniaxial standard. They arrived at new calibration constants for the unit, and the cryomag produced some of the best results to date. The AF demagnetizer was found to impart remnant magnetism on some weakly magnetized samples, and will be sent back to the factory for reconditioning when a new unit arrives. It is still useful for basalt.

Susceptibility measurements on APC cores from the last site revealed that up to 2 m of hole can be left uncored between cores, making double APC programs mandatory for many objectives.

The physical properties area worked smoothly. A device using a Wayne-Kerr circuit analyser was used this leg to make discrete resistance measurements by placing electrical probes into the sediment. These measurements will be related to values derived from logging runs. The motorized vane shear was used successfully.

Some basalt cores recovered were over 3 m long and competent enough to be cut on the super saw without the liner. Pieces were labeled with small tags produced on the laser printer and encapsulated with two-part epoxy. This process reduced much of the tedium of hand producing these miniature labels.

## CHEMISTRY LAB

Many sediment squeezes were made to support water chemistry studies. Water samples were taken with the downhole water sampler and the analytical results compared favorably with squeezed interstitial-water samples, thus eliminating the need for using the tool as frequently as anticipated. Over 600 samples where taken, mostly from physical properties samples, for inorganic and total carbon analysis with the Coulimetrics apparatus. A few samples of interest to our organic chemist were run on the ROCKEVAL and some gas samples were run for carbon dioxide determinations. Though recalibration was necessary for these runs the new Booker GC worked well.

A new chemistry technician was trained in all aspects of the equipment this leg.

## X-RAY LAB

Minor technical problems complicated use of the XRF but 130 runs were made for major elements and 110 runs were made for minor elements. An ARL field representative will service the unit at the end of Leg 121 in Singapore to optimize the vacuum system and to perform preventive maintenance.

A marine technician was trained in calibration, maintenance, and operation of the XRD and sample preparation for the XRF. She participated in preparing and analyzing 290 XRD samples.

## THIN SECTION LAB

The lab produced 200 thin sections during the cruise. Besides basalt with water-soluble smectite and chlorite there were many billets of ash and tuff. These required cutting and grinding with oil, which is more time consuming than using water. Some of the ashes required epoxy impregnation before they could be sectioned.

Training of another marine technician to operate the thin sectioning equipment was accomplished.

## SEM/MICROSCOPES

Scientists found the microscopes in good condition and nearly trouble free. One photoscope was reconfigured for reflected light work. Nearly 40 hours and 100 photos were logged on the SEM. The filament was replaced once.

## COMPUTER SERVICES

The transition from DEC terminals to IBM-compatible personal computers began this leg with the installation of 18 units, primarily as word processing work stations. The WordPerfect software supplied with them was well received and, because many were already familiar with it, reduced the time spent learning the computer system. New versions of several VAX based programs were installed which required modifications in automated plotting routines. The wiring under the machine room sub floor was untangled and readied for the upcoming MICROVAX upgrade.

Discussions about the shipboard computer system focused on how the system had changed from a data collection and archiving system to one that includes data processing and presentation. The additional use has slowed the system. Two MacIntosh computers brought by members of the scientific party were used continuously for data processing and presentation graphics.

## PHOTO LAB

Routine photographic science support kept the photo lab busy. Water samples were collected from the tap and filter and analysed for pH, particle size and an XRD analysis made for evaluation ashore in order to decide what treatment and filters are appropriate to solve the problem of rusty water in this lab.

## ET SHOP

The engineers brought a mud flowmeter which was installed in the derrick, a difficult area to work in with difficult explosion-proof connectors. Installation and calibration of the instrument were accomplished.

New 1050 XEROX machines were installed. The new units feature variable magnification and increased versatility in a range of paper sizes. This series of XEROX copiers seems to have weak boards that failed on ship's regulated power, although they remained operational on auxiliary power supplies.

The geostationary satellite receiver was repaired, with two new gear boxes installed.

## STOREKEEPER

MATMAN computerized updates of the oncoming surface and air freight shipments worked smoothly. New XEROX 1050 copier parts were added to the inventory, and old XEROX parts were removed from MATMAN.

## GYM

Early in the leg the new white framed exercise bike's crank bearings were modified to accommodate standard ball bearings and soon the serious riders were making 50 km a day. The gym sound system was modified in the amplifier to limit output and there have been no failures since. The facilities were used daily throughout the leg until the last week.

## SPECIAL PROJECTS

As ODP is in the process of switching from DEC PRO terminals to IBM compatibles the paleomagnetics lab was asked to rewrite the lab programs to accommodate the change. The cut was accomplished in MICROSOFT QuickBASIC. The rewritten programs will be available for the 122 scientists and technicians to use. The lab manual was also extensively rewritten to help them understand and use the lab.

The modular STEELCASE shelves in the co-chiefs office were replaced with wall hung units. This will allow charts to be layed out without interference from a shelf divider. A shelf was also built in the library to accommodate the work station behind the XEROX machine.

A regulated power receptacle was provided for the main deck XEROX machine and a longer power cord was used for the library unit. Installation of UPS power to the MARISAT communications equipment and to paging override circuits were also wired.

Plumbing was installed to pipe rig 150-psi air into the underway lab. It will be used to clean off equipment.

The current meter was deployed on our last site where strong surface currents were suspected. Measurements at 20 ms ran 1.5-1.7 kt rather than the suspected 4.0 kt. The bearing of the current and the ship heading appeared to be in disagreement but were not investigated.

Ship motion data tapes and records were collected and sent to the Institut Francais du Petrole in France.

## SAFETY

The METS team this leg included Davis, Eastlund, Briggs, Bontempo and Hamlin. Work with the SEDCO Emergency Squad was restricted to one member of the METS team, the first one to the scene of the drill. The rest of the METS team was responsible for clearing the lab stack of personnel. In lab stack drills we also staged water hoses, SCOTT air packs, and fire extinguishers.

Short meetings were held after drills to review the drill. Routine safety assignments were made to check flammable lockers, electrical panels and fire extinguisher.