SCIENCE PROSPECTUS

FY97 PROGRAM

Prepared from Original Proposals and Working Group Reports

Paul J. Fox

Jeff Fox
Director
Science Operations
ODP/TAMU

Jack Baldauf

Jack Baldauf
Manager
Science Operations
ODP/TAMU

TJG Francis

Timothy J.G. Francis
Deputy Director
Science Operations
ODP/TAMU

Compiled by:

Karen K. Graber
Staff Researcher, Science Operations ODP

and

Jack Baldauf
Manager, Science Operations ODP

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INTRODUCTION

This FY97 Science Prospectus presents the scheduled scientific operations for ODP Legs 171 through 176. These legs represent scientific cruises commencing September 1996 and continuing through December 1997.

The purpose of this document is to provide the reader with a brief overview of the scientific operations for each cruise as summarized from the initial JOIDES proposals or JOIDES Working Group results. All information included herein is correct at the time of writing but is subject to change.

Also enclosed with this document is information on how individuals can become involved with any of the above scientific programs. For additional information, please contact the Manager of Science Operations at the following address:

Dr. Jack Baldauf
Manager of Science Operations
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, TX 77845-9547
U.S.A.

Tel: (409) 845-9297
Fax: (409) 845-0876
E-mail: Jack_Baldauf@odp.tamu.edu

Ocean Drilling Program Cruise Participant Application Form

Name (first, middle, last) ______________________________

Institution (including address) ______________________________

____

Telephone (work) ____________ (home) ____________ **Telex/Cable** ____________ **Fax** ____________

Permanent Institution Address (if different from above) ______________________________

____

Bitnet or Internet Address ______________________________

Present Position ______________________________ **Country of Citizenship** ______________________________

Place of Birth ______________________________ **Date of Birth** ____________ **Sex** ______

Passport No. ____________ **Place Issued** ____________ **Date Issued** ____________ **Exp. Date** ______

Geographic Region(s), Scientific Problem(s) of Interest (Leg number(s) if known) ______________________________

____

Date(s) Available ______________________________

Reason(s) for Interest (if necessary, expand in letter) ______________________________

____

Expertise (petrologist, sedimentologist, etc.) ______________________________

Education (highest degree and date; see note below) ______________________________

Experience (attach curriculum vitae) ______________________________

____

____

Selected Publications You Have Written Relevant to Requested Cruise ______________________________

____

Personal and/or Scientific References (name and address) ______________________________

____

Previous DSDP/ODP Involvement and Nature of Involvement (i.e. cruise participant, shore-based participant, contributor, reviewer, etc.) ______________________________

____

____

Note: Graduate student applications should include a letter from their primary advisors, documenting the student's scientific experience and detailing how participation on the cruise would fit into their graduate degree programs.

Staffing decisions are made in consultation with the co-chief scientists and take into account nominations from partner countries; final responsibility for staffing rests with ODP at TAMU. Please return this form to:

Manager of Science Operations
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, TX 77845-9547
Fax: (409)845-0876

Applicants from JOIDES partner countries should send a **copy** of their applications to their respective national ODP offices.

PLEASE INDICATE YOUR AREAS OF EXPERTISE BY CHECKING THE APPROPRIATE BOXES

Biology/ Paleontology	Ecology	☐
	Hydrothermal vent communities	☐
	Invertebrate macrofossils	☐
	Microbiology/Micropaleontology	☐
Biostratigraphy	Calcareous nannofossils	☐
	Diatoms	☐
	Foraminifers (benthic)	☐
	Foraminifers (planktonic)	☐
	Palynology	☐
	Radiolarians	☐
	Silicoflagellates	☐
Downhole Measurements	Chemistry	☐
	Magnetic	☐
	Permeability	☐
	Sonic acoustic properties	☐
	Temperature & pressure	☐
Economic Geology	Hydrocarbons	☐
Geochemistry	Analytical elemental analyses	☐
	Low temperature/Hydrothermal diagenesis	☐
	Mineral deposits	☐
	Organic	☐
	Stable Isotope	☐
Geochemistry/ Geochronology	Radiometric	☐
Geophysics (Survey)	Bathymetry	☐
	Gravity	☐
	Magnetic	☐
	Seismic	☐
Hydrology	Rock/water interaction	☐
	Transport	☐
Mineralogy/ Petrology	Igneous	☐
	Metamorphic	☐
	Sedimentary	☐

Oceanography	Chemistry	☐
	Circulation & mixing	☐
	Continental shelf	☐
	Equatorial	☐
	Marginal seas	☐
	Nutrients	☐
	Paleoceanography	☐
	Paleoclimatology	☐
	Polar	☐
	Temporal cycles	☐
Paleomagnetics	Biomagnetism	☐
	Geomagnetic secular variation	☐
	Magnetic fabric	☐
	Magnetostratigraphy	☐
	Plate motions	☐
	Rock magnetism	☐
	Structural geology	☐
Physical Properties	Geotechnical properties	☐
	Particle size	☐
	Permeability & porosity	☐
	Rock mechanics	☐
	Sound velocity acoustic properties	☐
	Thermal properties	☐
Sediments	Airborne	☐
	Carbonaceous	☐
	Carbonate	☐
	Diagenesis	☐
	Evaporites	☐
	Hydrogenous	☐
	Siliciclastic	☐
	Stratigraphy	☐
	Turbidites	☐
	Volcaniclastic	☐
Tectonophysics	Lithosphere/upper mantle	☐
	Physics of magma bodies	☐
	Plate boundary structures & processes	☐
	Plate motions	☐
	Seismicity	☐
	Structural geology	☐
Volcanology	Ash deposits	☐
	Eruption mechanisms	☐
	Magma bodies & migration	☐

Responsibilities of Shipboard Scientists

Shipboard scientists collect, analyze and compile data conforming to ODP standards and format. They assist the co-chief scientists in producing shipboard scientific reports by recording data on standard ODP computerized and paper forms and writing a description of their disciplines' results for each site chapter of the *Initial Reports of the Proceedings of the Ocean Drilling Program.*

Scientists aid the curatorial technician by taking samples for themselves and others for later shore-based study. A team of highly trained marine technicians, some specializing in particular equipment areas, assist the shipboard scientists by maintaining the flow of core samples through the laboratories and helping with analyses.

At the end of the cruise, all shipboard scientists are requested to complete cruise evaluations. These evaluations guide ODP in upgrading laboratory equipment and procedures and in improving life on board ship.

Shipboard scientists are primarily on board to pursue their own scientific interests. After the cruise, they are responsible for analyzing their samples and reporting the results, which are included in the ODP database and published in the cruise volumes. Following is a brief description of the shipboard responsibilities of the scientific staff.

Sedimentologists provide accurate visual and written descriptions of the cored sediments and interpret the depositional and diagenetic history or other related sedimentological processes. They work as a team, designating a lead sedimentologist for each site and exchanging specific responsibilities from site to site. Sedimentologists' responsibilities include:

- written and graphic core descriptions on ODP data forms, including the sedimentologic portion of core description sheets (barrel sheets)
- smear-slide preparation and petrographic analysis of smear slides and thin sections
- selection of samples for shipboard analyses of XRD, XRF, carbonate percentage and thin sections

The **paleontologists'** chief responsibility is to assign an age to the core-catcher samples as soon as possible after cores are recovered. They may need to examine additional samples to provide as complete a biostratigraphic characterization of the cored section as possible within the time available, including recognition of boundaries and hiatuses.

A reference library with texts, journals and reprints is available to help shipboard paleontologists identify fossil groups that do not fall within their areas of expertise.

Petrologists classify thin sections and hand specimens and provide the written and graphic descriptions of all igneous and metamorphic rocks recovered on the cruise. Petrologists should be experienced in one or more of the following aspects of the petrology of oceanic rocks: chemical petrology, volcanology, mineralogy and petrography.

Paleomagnetists conduct or supervise all paleomagnetic measurements including the reduction of paleomagnetic data to intensities and direction of magnetization.

Paleomagnetists work with other shipboard scientists and the drilling crew to ensure that core material is not magnetically damaged by heating or exposure to strong magnetic fields and that core sections are not inverted.

Physical properties specialists select cores to determine velocities, shear strength, thermal conductivity and index properties (water content, porosity and bulk density). They also ensure that data are collected in a manner consistent with ODP format. The physical properties specialists and the sedimentologists select samples for carbonate analyses.

Organic geochemists monitor cores for gas and oil (hydrocarbon accumulations) and organic compounds. They advise when hydrocarbons in cores may constitute a safety or pollution hazard.

Inorganic geochemists are primarily responsible for conducting interstitial water, X-ray diffraction (XRD)and X-ray fluorescence (XRF) analyses. ODP chemists and marine technicians assist in these analyses.

Logging scientists advise the co-chief scientists on the logging program for the cruise. They work closely with the Schlumberger field engineer and the Lamont-Doherty Geological Observatory logging scientist in designing, implementing and interpreting the logging program.

OCEAN DRILLING PROGRAM
SHIPBOARD AND SHOREBASED CRUISE PARTICIPANT SAMPLE REQUEST

(Submit to the Curator *at least two months* before cruise departs.)

Please be aware of the current sample distribution policy, which is published in recent issues of *Proceedings of the Ocean Drilling Program.* You should complete a separate request form for each research topic you wish to propose.

To be completed by the Co-Chief Scientists:
Co-Chief Scientist, please indicate the fate of this request.
[ ] approved [ ] deferred [ ] rejected
If this request is rejected, please include a brief explanation that can be quoted to the requestor.

Co-Chief signature **Co-Chief signature**

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1. Proposed leg name (include number if known):

2. Name: ______________________________________

Office address: ____

Phone: __________________________

Fax: ___________________ E-mail:____________________________________

3. Purpose(s) of request: Please summarize the nature of the proposed research concisely in 5-7 lines. (This summary will be included in various official reports.) Provide a detailed description of the proposed research, including techniques of sample preparation and analysis, roles of individual investigators, etc., on an attached sheet. The detailed description of the project will be employed in reviewing the sample request and may be copied to other shipboard scientists.

revised 10/94

4. What specific cruise-related research do you plan to accomplish? A specific manuscript title is to be agreed upon by you and the Co-Chiefs before the end of the cruise. Investigators who receive samples or data on board the ship or during the first year post-cruise are obligated to produce a publishable manuscript for the ODP *Scientific Results.* Note: Chemists, please provide an explicit list of each chemical analysis that you plan to accomplish shipboard.

5. Please describe the proposed core sampling program in sufficient detail so that those who must carry it out on board ship will understand your needs.

Shipboard samples are limited to those people in support of papers for the *Proceedings*; other samples may be taken when 1 year has passed. Specify any other information that will be helpful in conducting your sampling program. Be aware that, if the number of samples which you are requesting is large, sampling for you is likely to be deferred until the cores reach the repository (4 to 6 months following the cruise), so it is to your advantage to keep the total number of samples small.

Sample Program: Number of samples_____per ☐ core
pilot study ☐ ☐ section
follow-up ☐ ☐ hole

Total number of samples you can analyze within 1 year __________

Particular stratigraphic or lithologic units to be sampled on the ship:

Sample size (cubic centimeter):________

6. Please describe any **specialized** sampling or processing techniques that you plan to use. List any specialized supplies or equipment that you want to use during the cruise. Will you bring these items with you, or do you think they will be available from ODP?

7. Please estimate the time it will require for you to obtain publishable results. For samples taken on board the ship or during the first year post-cruise, you must have publishable results ready for the *Scientific Results* volume within the first 18 months.

8. In what condition will the samples be, once your research is complete?
[ ] washed [ ] heated [ ] destroyed
[ ] sieved [ ] demag ____ a.f. other________________

Will they be useful to others? [ ] yes [ ] no other _______________

If so, for what kinds of research?

9. If you have ever before received samples from DSDP or ODP, please indicate the DSDP/ODP sample request number (if known), and the number and volumes of samples received. Were all of these samples analyzed? If not, were they returned to DSDP/ODP? If work is still in progress, please attach a brief (2-3 page) progress report. If the work has ended, please return the samples. Micropaleontologists may keep their processed residues until their professional use of the samples is completed, whereupon they must be returned to the Curator.

10. If you have ever before received samples from DSDP or from ODP, please attach a comprehensive list of the publications in journals, outside of the ODP volumes, which resulted from each sample request. If you have recently submitted such a listing, you may update it with only the new publications. If you reference publications which have not yet been forwarded to the Curator, please enclose five (5) reprints of each (no reprints are required for publications in the ODP volumes). If work is still in progress, please attach a brief (2-3 page) progress report. If the work has ended, please return the residues.

11. Please summarize on an attached sheet any other information that you feel would be useful in reviewing your request.

If you want something other than samples, check one:
[ ] thin sections [ ] smear slides [ ] view/photograph

[ ] other______________________________________

then skip to last page, for your signature and date.

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12. Samples taken on the ship are usually sealed in plastic bags, which are stored and shipped in cardboard boxes at ambient temperatures. If your samples require special storage or shipment handling, please describe how you want the samples handled. *Warning: If shipping delays from remote ports exist, you may want to make plans to hand-carry samples.*

cooled with blue ice [ ]
frozen with blue ice, may thaw a bit [ ] ______ hours
frozen - must remain frozen [ ]

13. If your samples will require special storage or shipment (for example, frozen organic samples), please complete the following:

Destination airport:____

Who can clear the shipment from customs and provide transportation to final destination?

Name:_______________________________ Phone:________________________________
Fax:__________________________________ E-mail:_________________________________

14. Would you prefer that we (circle one):
    a) ship your samples to you,
    b) give them to you at the end of the cruise so that you can put them in your suitcase, or
    c) pack them in a box and give them to you at the end of the cruise?

Acceptance of samples implies willingness and responsibility on the part of the Investigator to fulfill certain obligations:

(a) To publish the manuscript you agreed to produce in the ODP *Scientific Results* volume (the title will be listed on the final Cruise Sampling Program in the Hole Summary).

(b) To acknowledge in all publications that the samples were supplied through the assistance of the international Ocean Drilling Program and others as appropriate.

(c) To submit five (5) copies of reprints of all published works in outside journals to the Curator, Ocean Drilling Program, Texas A&M University Research Park, 1000 Discovery Drive, College Station, Texas 77845-9547, U.S.A. These reprints will be distributed to the repositories and to the ship. The bibliographies of all reprints received by the Ocean Drilling Program will be sent to the National Science Foundation. You need not send reprints from the ODP *Initial Reports*.

(d) To submit all final analytical data obtained from the samples to the Data Base Supervisor, Ocean Drilling Program, Texas A&M University Research Park, 1000 Discovery Drive, College Station, Texas 77845-9547, U.S.A. Please consult recent issues of the *JOIDES Journal* or call 409-845-2673 for information on acceptable data formats. Investigators should be aware that they may have other data obligations under NSF's Ocean Science Data Policy or under relevant policies of other funding agencies which require submission of data to national data centers.

(e) To return all unused or residual samples, in good condition and with a detailed explanation of any processing they may have experienced, upon termination of the proposed research. In particular, all thin sections and smear slides manufactured on board the vessel or in the repositories are to be returned to the Curator. Thin sections and smear slides used to describe the cores are unique representatives of the materials, and as such they are kept as components of the ODP reference collection. All unused or dry residual paleontological materials may be returned either to the Curator at ODP or to one of the designated paleontological reference centers upon completion of the investigator's use of the materials.

It is understood that failure to honor these obligations will prejudice future applications for samples.

All requests will be reviewed before the cruise, to begin preparing a preliminary sampling scheme. Approval/disapproval will be based upon the scientific requirements of the cruise as determined by the appropriate JOIDES advisory panel(s). In the case of duplicate proposals, shipboard scientists may be given priority over shorebased scientists. Requests for samples for post-cruise studies will be handled separately. Completion of this form in no way implies acceptance of your proposed investigation.

Date:____________________ ____

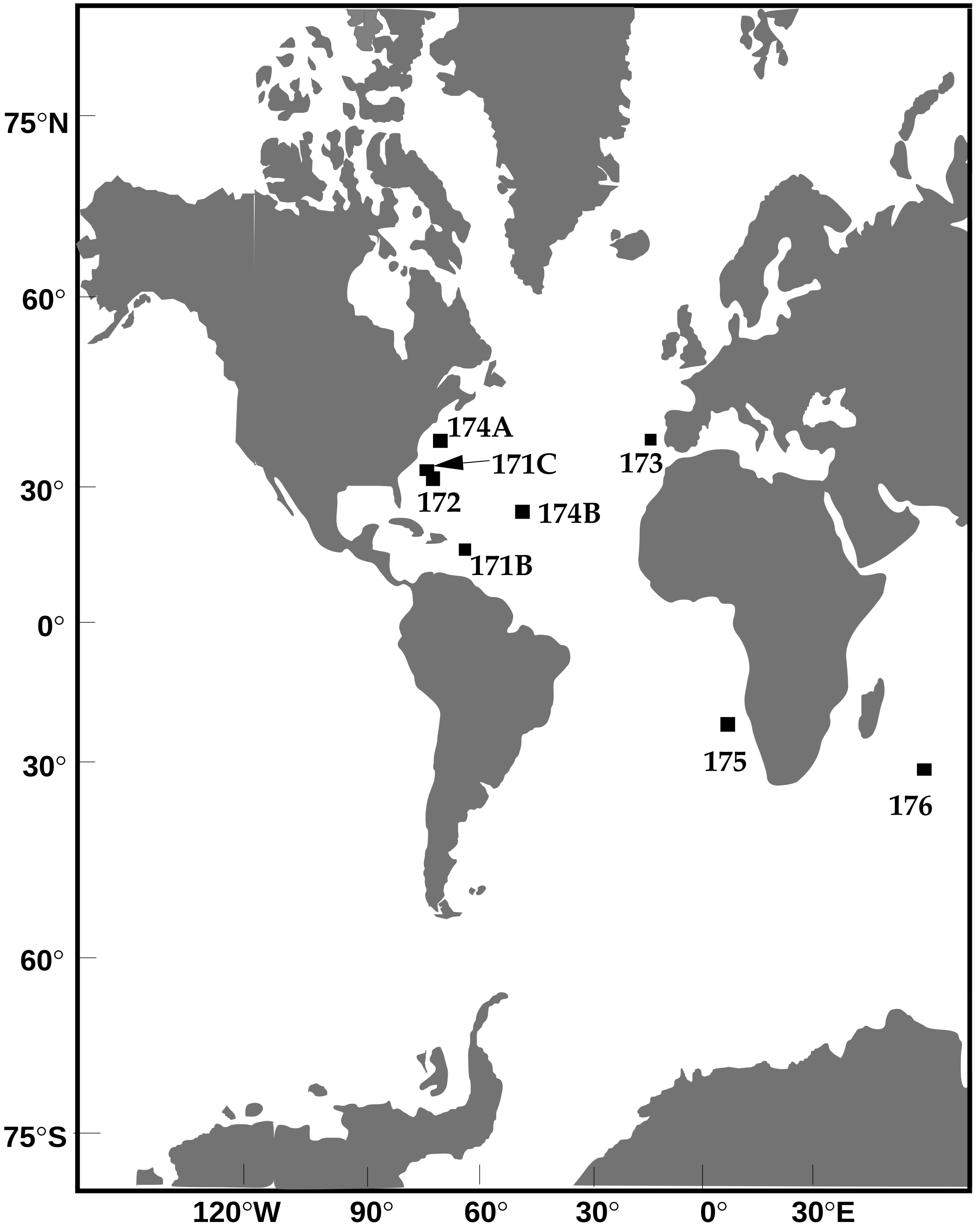
Date:____________________ ____

Date:____________________ ____

Signatures of Investigators

Send completed form to:

Curator
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, Texas 77845-9547
U.S.A.
Internet: CURATOR@ODP.TAMU.EDU
fax: (409) 845-1303
phone: (409) 845-4819



Location Map of Scheduled Legs 171B through 176

OPERATIONS SCHEDULE

LEG	PORT OF ORIGIN	CRUISE DATES	DAYS AT SEA	DAYS: TRANSIT/SITE (Estimated)
171A **Transit**	**Panama** **17-20 December 1996**	**21 December - 29 December 1996**	**8**	**8/0**
171B **Barbados LWD**	**Barbados** **29 December 1996***	**30 December '96 - 11 January 1997**	**12**	**1/11**
171C **Blake Nose**	**Barbados** **11 January 1997**	**11 January - 16 February 1997**	**36**	**6/30**
172 **NW Atlantic Sed. Drifts**	**Charleston** **16 - 20 February 1997**	**21 February - 18 April 1997**	**56**	**15/41**
173 **Iberia**	**Lisbon** **18 - 22 April 1997**	**23 April - 18 June 1997**	**56**	**10/46**
174A **New Jersey Shelf**	**Halifax** **18 - 22 June 1997**	**23 June - 17 July 1997**	**24**	**3/21**
174B **CORK/ Engineering**	**New York** **17 - 19 July 1997**	**20 July - 18 August 1997**	**29**	**14/15**
175 **Benguela**	**Las Palmas** **18 - 22 August 1997**	**23 August - 18 October 1997**	**56**	**19/37**
176 **Return to Hole 735B**	**Cape Town** **18 - 22 October 1997**	**23 October - 18 December 1997**	**56**	**16/40**

*** This port call may be avoided if LWD equipment is loaded during Leg 170 or in Panama.**

LEG 171B

BARBADOS LWD

Changes In Physical Properties In Accretionary Prisms

Modified from Proposal 475 Submitted By

J.C. Moore, N. Bangs, D. Goldberg, R. Jarrard, and E. Silver

Staff Scientist: Adam Klaus **Chief Scientist: J. Casey Moore**

ABSTRACT

Deformation and fluid flow in sedimentary sequences cause changes in physical properties. In situ measurement of physical properties evaluates processes (consolidation, cementation, dilation) operating during deformation, fluid flow, and faulting. Because seismic images are affected by changes in physical properties, their measurement allows for calibration of seismic data as a tool for remotely sensing processes of deformation and fluid flow. Logging While Drilling (LWD) provides an industry-standard tool for in situ evaluation of physical processes, including transient borehole conditions. Leg 171B will drill a series of LWD holes to measure the physical properties of sediments through deforming accretionary prisms and across plate-boundary faults off Barbados. Extensive drilling and 3-D seismic surveys provide a rich framework for log interpretation, seismic calibration, and process evaluation. The results will assist with the interpretation of similar, but less active, systems in sedimentary basins elsewhere, thereby contributing to the analysis of groundwater, hydrocarbon migration, and earthquake processes.

INTRODUCTION

Deformation of accretionary prisms changes the physical properties of sediments, thereby producing fluid, controlling fluid flow, altering rheologic properties, and affecting seismic arrival times and reflection characteristics. Consolidation and chemical diagenesis change the specific physical properties of porosity, density, and sonic velocity. These changes are both distributed (due to the loss of fluids in response to accumulating stresses; Bray and Karig, 1985; Bangs et al., 1990) and localized along discrete structures (such as faults) in response to overpressuring, fluid migration, or fault collapse (Shipley et al., 1994; Tobin et al., 1994). Because consolidation and fluid overpressuring affect seismic arrival times and seismic reflections, seismic data provide direct clues to physical property evolution and to physical property changes coupled to deformation.

Physical property evolution in sedimentary sequences cannot be comprehensively evaluated with recovered cores. Elastic rebound and microcracking of coherent sedimentary samples degrade shipboard physical property measurements. Fault gouge and other incoherent lithologies are either not recovered or cannot be measured after recovery; therefore, transient properties (e.g. overpressuring) must be measured in situ (Fisher et al., in press).

Sediments in tectonically active areas experience rapid changes in physical properties. Accretionary prisms are exceptional, natural laboratories to study these changes because of this rapid deformation and the shallow burial depth of the deformed features, which can therefore be drilled and imaged seismically. The information discerned at convergent margins about fault geology, overall sedimentary consolidation, in addition to seismic imaging of these processes, will be applicable to other less active sedimentary environments, and therefore impact our understanding of hydrocarbons, groundwater, and aspects of earthquake systems. To better understand the interrelationships of deformation, fluid flow, seismic imaging, and changes in physical properties, we propose a Logging While Drilling (LWD) transect of a setting dramatically influenced by pore fluids: the Barbados accretionary prism.

LOGGING WHILE DRILLING BACKGROUND

Logging While Drilling is the most effective tool for measurement of physical properties in poorly consolidated sediments. LWD acquires a continuous log of physical properties directly above the drill bit where hole conditions are optimal for logging. It is an "off the shelf" industry technology already used by the Ocean Drilling Program (ODP) during Leg 156 that can be directly applied to ODP operations without development costs. LWD will yield important results from accretionary prisms where wireline logging has failed.

LWD acquires data from sensors integrated into the drill string immediately above the drill bit, and records data minutes after cutting the hole when it most closely approximates in situ conditions. This technology provides high quality logging information in environments where standard wireline systems previously acquired either no data or poor quality data (Fig. 1). Specifically, LWD provides excellent quality results in the shallowest sediment sections and in holes with marginally stable conditions that preclude wireline log runs. Logging While Drilling compares to standard wireline logging as the Advanced Piston Coring System compares to standard rotary drilling.

A comparison of density data from cores, LWD, and wireline logs for the Barbados accretionary prism highlights the value of data acquisition during drilling (Fig. 1). The LWD data closely reproduce the individual core measurements but provide much more detail. The density data from LWD apparently "see" hydrofractures in the Barbados décollement zone (Fig. 2), which would either not be resolved by wireline data or would have closed due to fluid loss to the borehole. In the Barbados example (Site 948) the wireline density data are not usable, because density measurements require consistent pad contact and are very sensitive to changes in hole diameter (in comparison to resistivity or velocity measurements). However, for this study density is the most important measurement for analysis of consolidation.

Wireline tools are more sophisticated than LWD tools and in principle should yield more accurate measurement of physical properties. However, the difficult hole conditions encountered by drilling, especially at active margins, destroy the inherent advantage of wireline tools. In this type of environment, the excellent correlation of LWD density data to core sample density data clearly shows the superiority of LWD to wireline-measurements (Fig. 1).

Off-the-shelf LWD tools provide neutron porosity, resistivity, density, and gamma-ray data. An LWD sonic tool currently exists that can measure formation velocities greater than about 3 km/s. An improved version may be available for this cruise. Such a sonic velocity tool would be necessary to achieve the objectives of this cruise. Lacking this sonic tool, the velocity data would have to be acquired using wireline techniques in the LWD hole. Reentry of the LWD hole would be achieved by dropping a minicone and proceeding with a wireline velocity measurement, using the side-entry-sub if necessary. Because density and velocity are strongly correlated, synthetic seismograms can be created with knowledge of either; hence most of the objectives to determine the polarity and shape of the seismic waveform from fault zones could be met, even in the absence of velocity data.

BACKGROUND

The absence or failure of wireline logging operations means that hundreds of previously drilled Deep Sea Drilling Project (DSDP) and ODP holes provide scientifically exciting locales for LWD. Barbados is especially attractive for focused LWD investigation because:

- Drilling at Barbados has occurred with high quality structural, pore-water chemistry, heat flow, and shipboard physical property studies. Such information provides independent determinations of locations of faults, of fluid flow activity, and of correlative physical properties such as grain density. The subsequent scientific results from this information provide a rich framework for log interpretation.

- Previous studies of Barbados show physical properties are dramatically influenced by fluids. We anticipate observation of significant fluid-related effects from physical properties in LWD logs in this setting.

- The décollement zone occurs at easily drillable depths at Barbados and many previously drilled holes penetrate the décollement there. In contrast, thick turbidite-dominated sequences at many other convergent margins include unstable sand layers that hinder drilling and logging operations.

- Barbados is one of only two convergent margins with a 3-D seismic reflection survey. This extraordinary data set vastly expands the opportunity for core-log-seismic integration.

SCIENTIFIC OBJECTIVES

1) Overall Prism Consolidation and Velocity-Porosity Relationships

Porosity is the foundation for a variety of studies about the large-scale, long-term fluid budget of accretionary prisms. Logs can be used to determine a continuous record of density and porosity as a function of depth as was done on Leg 156 (Figs. 1 and 2). Between-site variation in the porosity-depth relationship provides an estimate of the amount of fluid expulsion (and therefore volumetric strain). Unfortunately, measurements of volume change are usually impossible with standard logs as they frequently fail due to bad hole conditions in this setting (Fig. 1). Even under ideal conditions wireline logs do not sense the top 60-120 m because the drill pipe extends below the seafloor, nor do they sense the bottom 60-120 m of the hole because of fill (Fig. 1). The shallowest hundred meters, where porosity reduction is the greatest, is of particular interest in this study. Only LWD can obtain reliable porosity logs from the entire depth range, including the critical top 100 meters.

Profiles of porosity versus depth provide a tantalizing but incomplete view of the fluid expulsion pattern of an accretionary prism. Velocity data, either from multichannel seismic data (Bray and Karig, 1985; Bangs et al., 1990; Cochrane et al., 1994) or ocean bottom seismograph (OBS) studies (Ye et al., submitted), is a powerful tool for studying prism porosity structure. The fundamental limitation in determining porosity from velocity is the conversion between these two parameters. This relationship is well known for normally consolidated, low-porosity sediments (e.g., Gardner et al., 1974), but it is much less certain for high-porosity sediments, where changes in terms of fluid production and volumetric strain are more important. Furthermore, our analysis of logs from the Cascadia accretionary prism indicates that prism deformation dramatically changes the porosity-velocity relationship (Jarrard et al., 1995). In contrast to pelagic sediments, accretionary prism sediments of the same porosity can exhibit a wide range of elastic moduli and, therefore, velocities; this complexity results from variability in cementation, compression-induced modification of intergrain contacts, and fracturing. Theoretical relationships of porosity to velocity (e.g., Gassman, 1951) are of little utility in this environment; we must determine the velocity-porosity relationship for each prism empirically, and we must investigate the possibility that this relationship changes laterally within a prism. In situ velocity and porosity logs that sample the section completely are the only means of reaching this objective.

The overall fluid budget of the Barbados prism requires analysis to evaluate the fluid loss and geochemical budgets (e.g., Bekins et al., in press). The series of LWD holes planned here, plus existing penetrations, will help constrain this problem.

2) Correlation of Physical Properties of Faults with Displacement and Fluid Flow

An LWD transect across the Barbadian décollement can address the following issues (1) do fault collapse and strain harden with displacement (e.g., Karig, 1986) and (2) does active fluid flow retard this process and are collapsed faults inactive with respect to fluid flow (e.g., Brown et al., 1994). Structural, biostratigraphic, and seismic reflection criteria identify faults. Anomalies in pore-water geochemistry (e.g., Kastner et al., 1991) and thermal anomalies (Fisher and Hounslow, 1990) indicate fluid flow. With the positive identification of faults, LWD can measure their physical properties. These properties then can be correlated to variations in displacement and fluid activity.

3) Consolidation State of Sediments in and Around Faults

At Site 948 in the Barbados prism, high quality density measurements demonstrated under-consolidation around faults, indicating the faults had recently loaded subjacent sediments. The consolidation state can also be interpreted in terms of effective stress and fluid pressure. Clearly consolidation varies around faults and should be defined in order to develop any tectonic-hydrologic model of the fluid expulsion system.

4) Polarity and Shape of the Seismic Waveform from Fault Zones

Seismic reflections are created by changes in physical properties that can in turn be measured in boreholes. In principle, the seismic data provide a proxy for these larger-scale changes in physical properties. The polarity and shape of the seismic waveform were mapped and various models formulated for the waveform across décollement zones beneath accretionary prisms (Bangs and Westbrook, 1991; Moore and Shipley, 1993). Negative polarity reflections have been interpreted as resulting from either (1) overthrusting of higher impedance sediment over lower impedance sediment in Costa Rica (Shipley et al., 1990) or (2) the reduction of fault zone impedance through dilation at Barbados (Figs. 3 and 4; Bangs and Westbrook, 1991; Shipley et al., 1994; Bangs et al., 1996). The modeling, however, is incomplete without ground-truthing through the in situ measurement of physical properties across fault zones in areas with good seismic data.

To date, logging data has only been acquired at one décollement locality (Leg 156 Shipboard Scientific Party, Site 948, 1995). This LWD data from Barbados is in an area of positive reflection polarity and shows impedance increases that reproduce the positive polarity in synthetic seismograms (Leg 156 Shipboard Scientific Party, Site 948, 1995). The LWD results also suggest thin (0.5-1.5 m) hydrofractures within the interval of positive polarity in the décollement zone. The hydrofractures apparently are too thin to be resolved seismically. A major question is whether negative polarities elsewhere in the Barbados décollement consist of thicker zones of hydrofractures.

LOGGING PLAN

LWD investigations of the Barbados prism will build on existing LWD measurements at Site 948 that penetrated the décollement where it is of positive polarity (Figs. 1 and 2). At Site 947 LWD penetrated a locality never cored because of the great depth to the décollement and unstable hole conditions discovered during the LWD penetration. Proposed LWD sites will focus on determining the characteristics of the negative polarity reflections at Barbados, measuring the physical properties of faults, and determining the physical properties of the incoming sedimentary sequence. The sum of all penetrations will provide an overview of prism consolidation and velocity-porosity relationships. In prior drilling through the North Barbados Ridge accretionary prism during Leg 156, 1,152 m of logs in Hole 947A and 948A were obtained using LWD technology. This proposal is specifically designed to acquire more LWD data in four additional holes in the Barbados accretionary prism. LWD tools are mounted in the rotating bottom-hole assembly, allowing estimates of porosity, fluid pressure, and seismic properties to be measured through the prism minutes after cutting the hole, closely approximating in situ conditions.

These additional LWD investigations of the Barbados prism will focus on determining the characteristics of the negative polarity reflections at two sites, building on existing data at Site 948 that penetrated the décollement where it is of positive polarity, and at Site 947 where unstable hole conditions limited penetration. Thin, low-density layers in the décollement zone, possibly hydrofractures at Site 948, were observed during Leg 156. One site as a reference section east of the deformation front and one site coincident with the CORK site (NBR-9) will also be drilled.

The proposed tools are the same as those used during Leg 156, directly measuring in situ resistivity, porosity, density, and natural gamma-ray. An LWD sonic tool is currently available from Anadrill for velocities >2,000 m/s, which may not be low enough for these sediments in the accretionary prism. The sonic tool will yield data on the higher velocity underthrust section and may be improved to measure the velocity of the prism by 1997. In the proposed program, the total logged interval is 2,335 m, ~2-2.5 times more section than drilled during Leg 156, generating a total operations time estimate of 10-12 days. Several days of transit and port calls associated with the tool logistics will also be required.

PROPOSED SITES

There will be no coring in this leg. In order of priority the sites are:

1) **NBR-8**: NBR-8 will establish the physical properties of the negative polarity reflections in the Barbados prism. It is located in an area of negative polarity about 2500 m west of the deformation front (Figs. 3 and 4). Shipley et al. (1994) predict that the negative polarities are dilatant zones. Accordingly they may be characterized by "hydrofractures" or zones of fluidized sediment more numerous than those encountered at Site 948. Because the depth of the décollement is 400 m as opposed to the more than 600 m at Site 947, and the negative amplitude is less than at Site 947, NBR-8 can be successfully completed. The site has never been cored; however, safety problems are not anticipated because nearby penetrations show negligible hydrocarbons. Correlations from nearby holes and the 3-D seismic data should provide basic lithologic information.

2) **NBR-9**: NBR-9, located at Cork Site 949 1800 m west of the deformation front, will establish the physical properties of a décollement zone with intermediate reflection polarity characteristics, and determine the physical property profile at this bore hole seal site. This site is also cut by an imbricate thrust fault that is actively deforming the accretionary prism and will provide information on the physical properties of thrusts.

3) **NBR-10**: NBR-10, located at Site 676, will determine the character of the initial deformation of the accretionary prism. This site is located about 800 m inboard of the deformation front and penetrates the incipiently developed décollement zone and several thrusts in the offscraped section.

4) **NBR-11**: NBR-11 is located at the oceanic "reference" Site 672, 6000 m east of the deformation front. This site showed incipient deformation and a geochemical anomaly at the stratigraphic level of the projected décollement zone. LWD here will provide information on the inception of deformation and fluid flow in the incoming sedimentary section as well as a general overview of physical properties of the oceanic sedimentary section.

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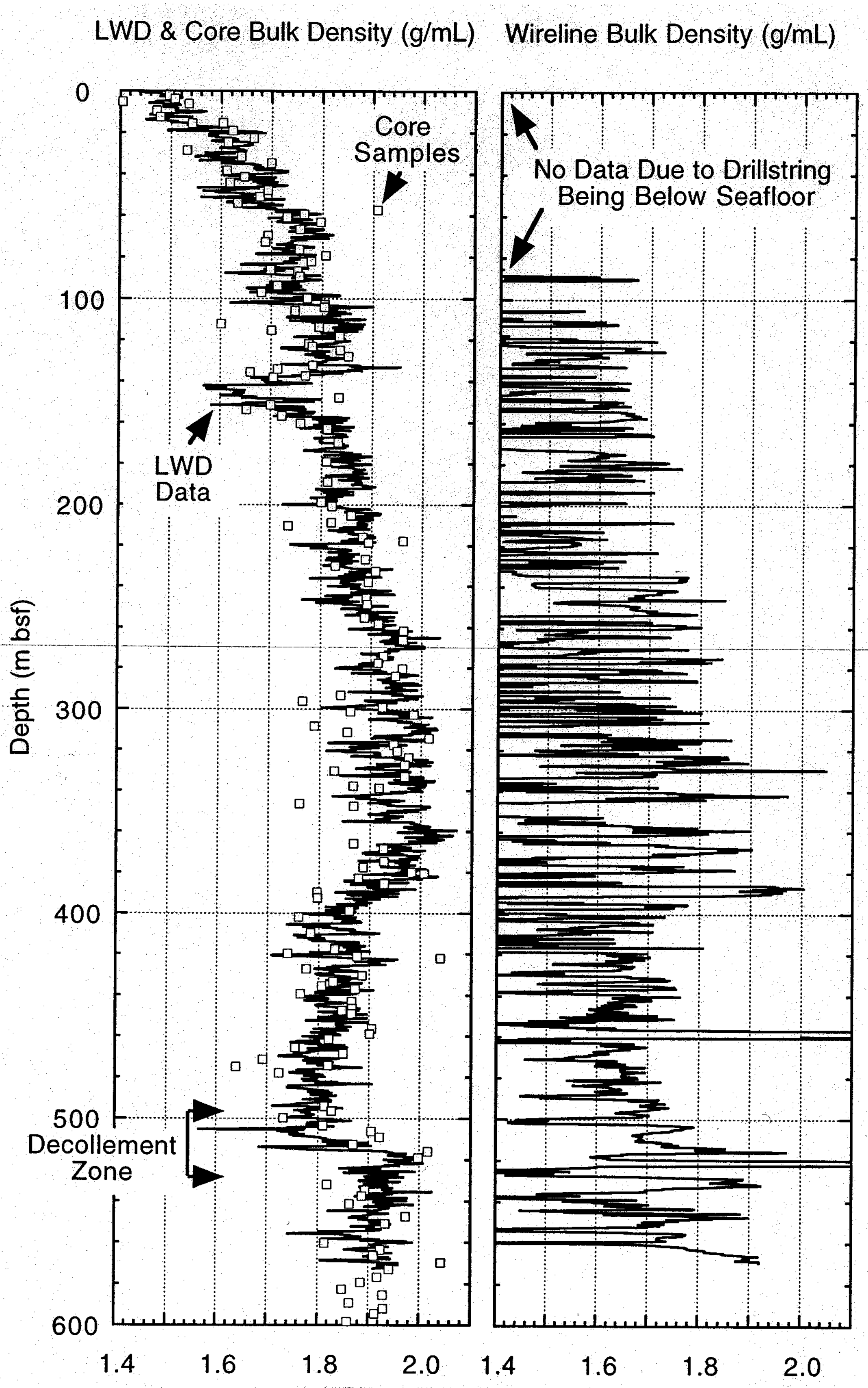


Figure 1. Comparison of density measurements from cores, LWD, and wireline logging at Site 948. Note good correlation of LWD and Core data. Core data average 1.3 percent less than LWD densities probably due to minor elastic rebound of overpressured section. Values deeper than 100 m in wireline data are systematically less dense that those determined by LWD or cores probably due to poor pad contact.

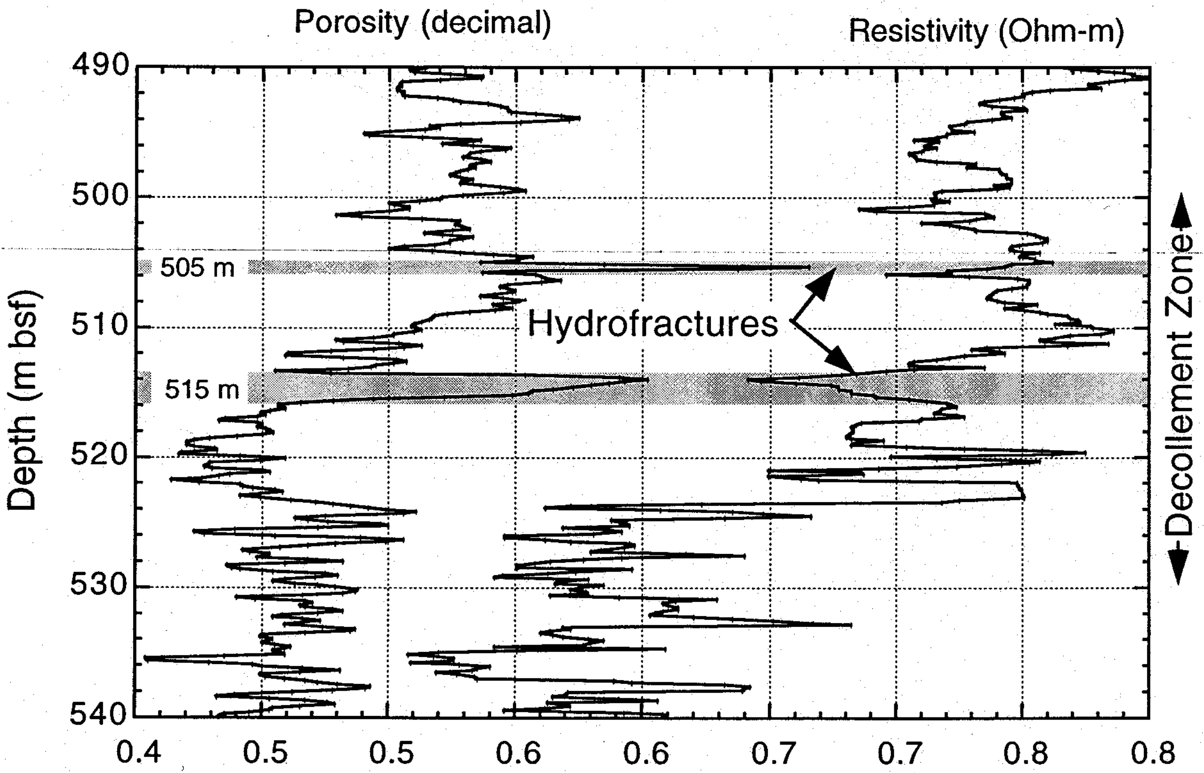


Figure 2, Porosity (derived from density) and resistivity showing evidence for hydrofractures in decollement zone at Site 948 of the Northern Barbados Ridge. Note that the large spikes in porosity that are interpreted as hydrofractures are also apparent in the raw LWD density data in Figure 1. The sharp drops in resistivity correlating with increases in porosity support the presence of fluidized sediment in thin intervals.

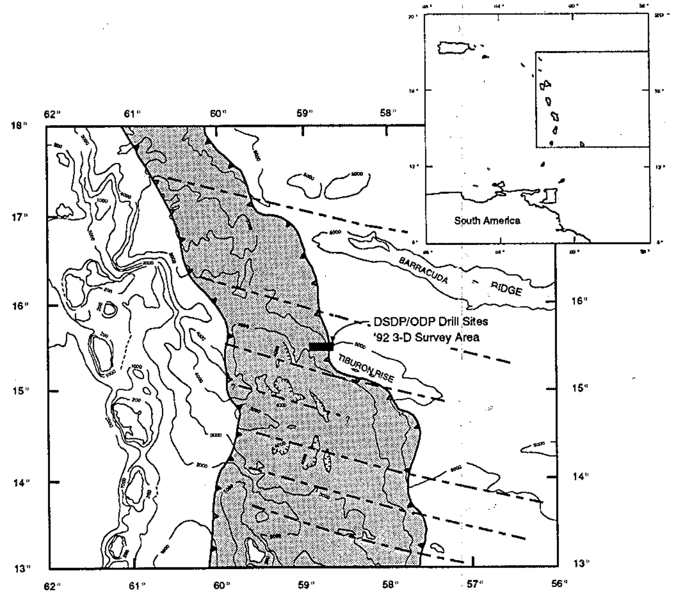
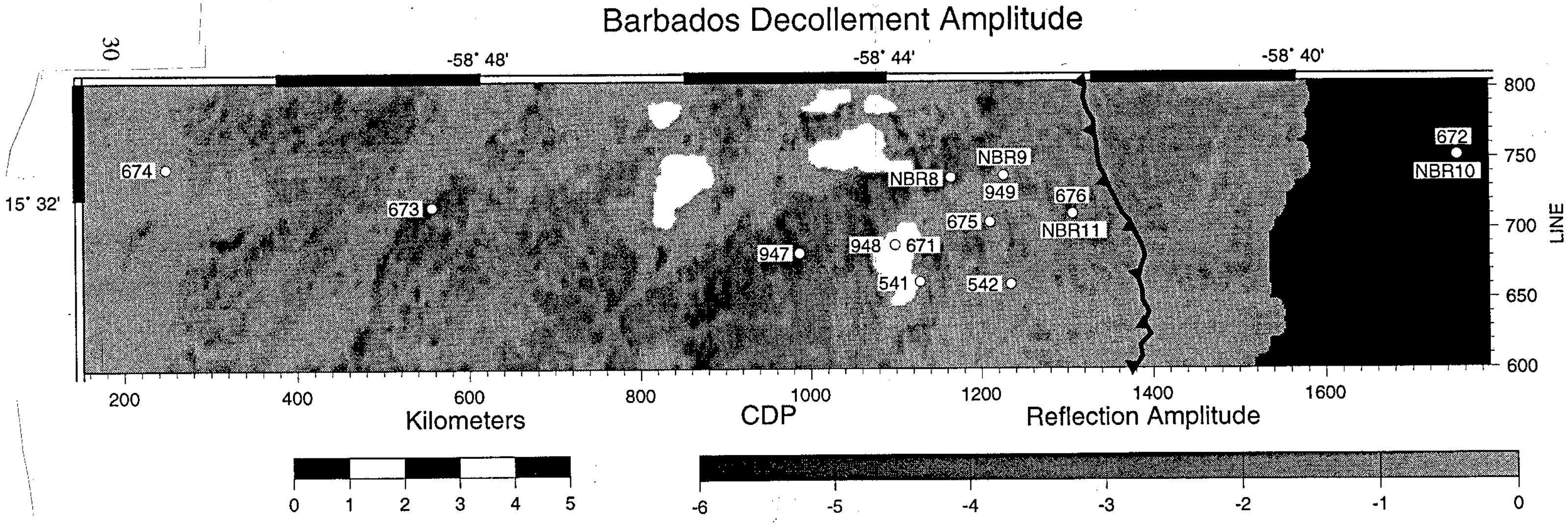


Figure 3. Location map of 3D seismic survey. Locations of past and proposed drilling sites overlay gray tones of map showing seismic reflection amplitude of decollement and proto-decollement. Note that positive reflection polarities are white. Gray shading represents increasing negative reflection amplitudes.



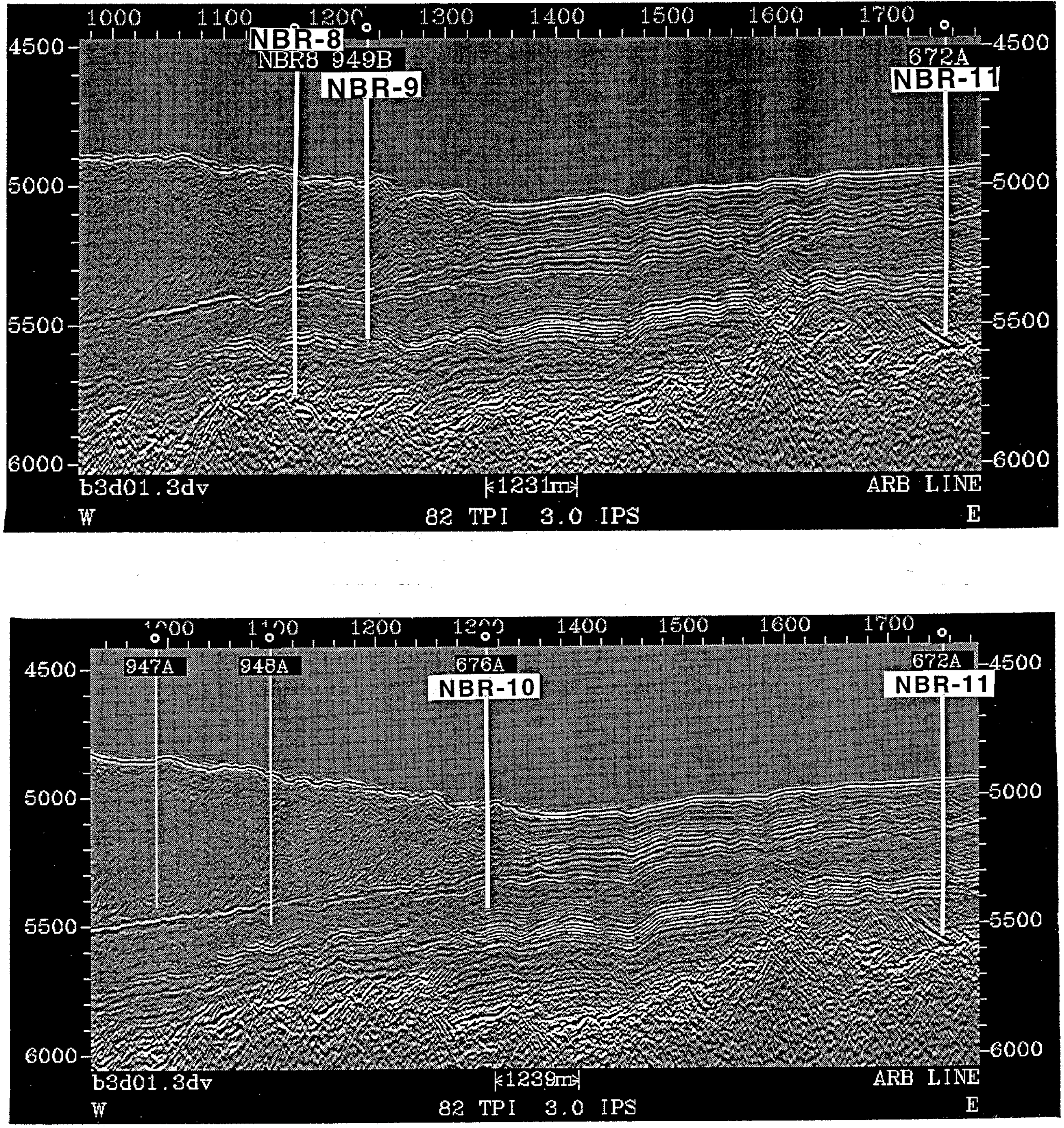


Figure 4. Large-scale cross sections through proposed sites. Depths are in meters. V.E. about 4:1. Black reflections are positive polarity and white reflections are negative polarity. Top: Cross section through NBR-8, NBR-9 (Site 949) to NBR-11 (Site 672). Bottom: Cross section from Site 947 through Site 948 and NBR-10 (Site 676) to NBR-11 (Site 672). LWD data exist for Sites 947 and 948 from Leg 156 ODP.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: NBR-8A	**PRIORITY**: 1	**POSITION**: 15°32.21'N, 58°43.39'W
WATER DEPTH: 4756 m	**SEDIMENT THICKNESS**: 800 m	**TOTAL PENETRATION**: 550 m
SEISMIC COVERAGE: 3-D survey, Line 736		

Objectives: This site will establish the physical properties of the negative polarity reflection at this locality of the Barbados decollement. This site will also completely penetrate the underthrust section to ascertain changes in physical properties during underthrusting.

Drilling Program: No cores

Logging and Downhole Operations: Logging While Drilling

Nature of Rock Anticipated: Pelagic and hemipelagic sediments

SITE: NBR-9A	**PRIORITY**: 1	**POSITION**: 15˚32.16'N, 58˚42.85'W
WATER DEPTH: 4984 m	**SEDIMENT THICKNESS**: 810 m	**TOTAL PENETRATION**: 550 m
SEISMIC COVERAGE: 3D survey, Line 736		

Objectives: NBR-9, located at CORK Site 949 1800 m west of the deformation front, will establish the physical properties of a decollement zone with intermediate reflection polarity characteristics and determine the physical property profile at this instrumented CORK site.

Drilling Program: No cores

Logging and Downhole Operations: Logging While Drilling

Nature of Rock Anticipated: Pelagic and hemipelagic sediments

SITE: NBR-10A	**PRIORITY**:	**POSITION**: 15˚32.85'N, 58˚42.198'W
WATER DEPTH: 5052 m	**SEDIMENT THICKNESS**: 797 m	**TOTAL PENETRATION**: 400 m
SEISMIC COVERAGE: 3D survey, Line 710		

Objectives: This site is located at the position of ODP Site 676A and it will determine the physical properties of the initial deformation zone of the accretionary prism.

Drilling Program: No cores

Logging and Downhole Operations: Logging While Drilling

Nature of Rock Anticipated: Pelagic and hemipelagic sediments

SITE: NBR-11A	**PRIORITY**:	**POSITION**: 15˚32.40'N, 58˚38.46'W
WATER DEPTH: 4938 m	**SEDIMENT THICKNESS**: 605 m	**TOTAL PENETRATION**: 605 m
SEISMIC COVERAGE: 3D survey, Line 751		

Objectives: This site is located at the position of ODP Site 672A and will provide baseline measurements of physical properties for the incoming sedimentary section of the Barbados Ridge. It will both examine the properties of the protodecollement and establish an overall physical property profile.

Drilling Program: No cores

Logging and Downhole Operations: Logging While Drilling

Nature of Rock Anticipated: Pelagic and hemipelagic sediments

LEG 171C

BLAKE NOSE

Paleogene and Cretaceous Intermediate Water History

Modified from Proposal 462 Submitted By

Richard D. Norris

Staff Scientist: Adam Klaus **Co-Chief Scientists:** **Richard D. Norris**
Dick Kroon

ABSTRACT

Sediments on the Blake Plateau and Blake Nose in the western North Atlantic offer an ideal record for reconstructing water mass chemistry and circulation in the Cretaceous and early Cenozoic. The plateau's location in the northern hemisphere, proximal to the western end of the Tethys Seaway, makes the deposited sediments ideal for determining northern sources of deep and intermediate waters. Leg 171C will drill three shallow holes (170-450 m deep) at each of five sites in a transect from the margin of the Blake Plateau to the edge of the Blake Escarpment.

The proposed transect of cores will be used to: (1) interpret the vertical structure of the Paleogene and Cretaceous oceans and test the 'warm saline deep water' hypothesis near the proposed source areas; (2) provide critically needed low latitude sediments for interpreting tropical SST and climate cyclicity in the Cretaceous and Paleogene; (3) provide well preserved planktic microfossils for refinement of low latitude Paleogene and Cretaceous chronologies and evolutionary dynamics; (4) recover a complete Cretaceous/Paleogene boundary along a depth transect to describe the events surrounding the boundary and water depth-related changes in sedimentation of the boundary beds; (5) recover sections suitable for magnetic stratigraphy so that low latitude biochronologies may be tied directly to the magnetic reversal record; (6) interpret the thermocline and intermediate water structure of low latitude, Lower Cretaceous oceans and refine the biochronology of this period.

INTRODUCTION

Leg 171C will drill a transect on the Blake Plateau (Fig. 1) to test current models for Paleogene and Cretaceous history of intermediate and deep waters in the Atlantic Ocean and Tethys Seaway. Presently, deep waters are formed in the North Atlantic and Southern Ocean, and it is the mixture and aging of these water masses that produces the characteristic chemistries of the deep Indian and Pacific oceans. Maps of $\partial^{13}C$ in Paleogene benthic foraminifera suggest that most deep waters of this era have a southern source, but periods of weak latitudinal gradients and short episodes of anomalously-warm deep water indicate that deep or intermediate waters may have formed near the equator or in a northern source area (Miller et al., 1987; Barrera and Huber, 1990; Stott and Kennett, 1990; Pak and Miller, 1992). Another theory is that intermittent production of warm saline deep waters may have continued in the Oligocene to middle Miocene in the remnants of the Tethys Seaway (Woodruff and Savin, 1989). Alternatively, northern component waters may have formed throughout this time, most probably in the North Atlantic (Wright et al., 1992). The absence of a depth transect in the North Atlantic Paleogene prevents resolution of this debate. The northern subtropical location of the Blake Plateau and its position adjacent to the western opening of the Tethys Seaway would place it in the mixing zone between water masses of different origins during the Paleogene and Late Cretaceous.

Presently, most reconstructions of deep-water geometry have focused on the Late Neogene to Holocene record. Paleogene sequences have generally been too deeply buried to be recovered either completely or consistently along depth transects. Yet, the three-dimensional structure of Mesozoic and early Cenozoic oceans is of great interest since these oceans record climates and patterns of water mass development under conditions very different from those of modern seas. As such, an understanding of Paleogene and Cretaceous deep-water structure is necessary to provide boundary conditions on global climate models (GCMs) and to test the assumptions employed in models of the Quaternary oceans.

One of the best existing depth transects through pre-Neogene sections was drilled on Maud Rise during Leg 113. Two sites (Sites 690 and 689) found intriguing evidence for deep-water formation at low latitudes (the 'warm, saline deep water hypothesis'--Kennett and Stott, 1990). However, these sites were located within the region of southern source water formation and so were not well located to detect the chemistry or history of northern source waters, should they exist. A depth transect in the North Atlantic would be well placed to identify northern component water masses. Patterns of mixing between water masses from different sources could be used to reconstruct their three dimensional structure and origins (Corfield and Norris, 1996).

BACKGROUND

Paleogene Climate History and Paleoceanography

High global temperatures in the early Eocene promise a means to test global climate models run under conditions of increased atmospheric CO_2 (Popp et al., 1989; Berner, 1990). Knowledge of low latitude temperatures provides a major constraint on GCMs since equatorial seas play a major role in regulating heat exchange with the atmosphere (Barron and Washington, 1982).

The Eocene had the most equitable climate of the Cenozoic (Dawson et al. 1976; Shackleton and Boersma, 1981; Axelrod, 1984; Rea et al., 1990), and it is possible that these relatively equitable climates were promoted by higher heat transport between latitudes (Covey and Barron, 1988). Isotopic data suggest both surface waters and deep waters reached their maximum temperatures in the early Eocene (Savin, 1977; Miller et al., 1987; Stott and Kennett, 1990). High latitudes were substantially warmer than at present and reached temperatures of 15-17°C (Zachos et al., 1994). This warm interval lasted 3-4 m.y. and marked fundamentally different climate conditions than were present at any other time in the Cenozoic. Latitudinal thermal gradients were probably less than 6-8°C during the Eocene, about half the modern pole-to-equator gradient (Zachos et al., 1994). Yet the interval is poorly known both because low-latitude records are rare and those that do exist are either spot cored or disturbed by drilling through Eocene cherts (Stott and Zachos, 1991). Hence, low latitude temperature data are needed to constrain model runs of Paleocene climate.

The Blake Plateau was located on the western gateway from the relatively restricted Tethys/Atlantic basins to the open Pacific during the early Paleogene. Comparisons between Caribbean and existing equatorial Pacific sites could show whether deep waters aged as they entered the Pacific as expected, if the Tethys was a major source of saline bottom waters. Existing records from the Caribbean (DSDP Site 152) and Central Pacific (DSDP Site 577; ODP Site 865) provide some of the few low latitude temperature estimates for the Eocene. However, more complete temperature records are needed to document surface-water temperatures in the Eocene tropics and subtropics. In addition, the Eocene warm interval provides a test for climate models that integrate latitudinal thermal gradients, atmospheric CO_2 levels, and ocean-atmosphere heat transports.

The Cretaceous-Paleocene Meteorite Event

Recent evidence of the impact of a bolide on the Yucatan Platform has focused debate over the history and consequences of this Cretaceous-Paleogene event. Evidence of an impact in the Caribbean includes discoveries of glass spherules and shocked quartz in boundary sections at Haiti and Mimbral, as well as gravity measurements and drill core data that imply the existence of a 180 km diameter structure of Maastrichtian-earliest Paleocene age beneath the Yucatan (Sigurdsson et al., 1991b; Margolis et al., 1991; Alvarez et al., 1991; Hildebrand and Boynton, 1990). Re-analysis of DSDP Sites 536 and 540 in the Gulf of Mexico has led to the discovery of thick deposits of reworked carbonates of diverse ages. These deposits contain uppermost Maastrichtian nannofossils and occur immediately below lowermost Paleocene sediments. Alvarez et al. (1991) have interpreted these K/P boundary deposits as part of the ejecta blanket. Size distributions of spherules found in boundary beds on Haiti and in the DSDP sites indicate that the impact occurred within the Caribbean (Sigurdsson et al., 1991ba). Finally, geochemical analysis of K/P glasses suggests that the impact occurred in carbonates rich in evaporites—a chemistry consistent with a source similar to rocks beneath the Yucatan structure (Sigurdsson et al., 1991a).

Cretaceous Paleoceanography

A depth transect in Cretaceous strata offers an unparalleled opportunity to study the hydrographic structure of the low latitude Cretaceous oceans. There are five principal issues that may be addressed by recovery of a depth transect of cores from this region:

- determine the response of low latitude SST to the Maastrichtian cooling trend at high latitudes;

- examine the nature of the hydrographic changes in deep and intermediate waters before and after the Cretaceous-Paleocene meteorite event at low latitudes;

- determine the sources of deep waters during the Barremian-Albian, Campanian, and Maastrichtian at times when the North Atlantic was a relatively enclosed basin;

- analyze depth dependency on the formation and expression of carbonate cycles and sediment accumulation rates;

- study the lithology and depositional patterns across an ancient slope.

In addition, the excellent preservation of Cretaceous microfossils in Hole 390A suggests that the Cretaceous record of the Blake Nose may be useful for evolutionary and biostratigraphic studies of the Cretaceous.

Present knowledge of the plateau is based on (1) a series of JOIDES and United States Geological Survey (USGS) boreholes drilled on the shallow parts of the plateau, (2) a COST well drilled on the continental shelf, (3) one rotary cut Deep Sea Drilling Project (DSDP) hole (Site 390) drilled at the edge of the Blake Nose, (4) regional geologic maps of the inner Blake Plateau, (5) low resolution Gloria side scan sonar maps of the exclusive economic zone (EEZ), including the Blake Plateau, (6) regional geologic syntheses of multichannel and single channel seismic lines that focus nearly exclusively on the tectonic development of the Plateau and Early Cretaceous reef sedimentation, (7) manned submersible surveys of the Cretaceous reef deposits along the Blake Escarpment and phosphorite pavements on the inner Blake Plateau. Figure 2 presents some of the existing geophysical survey tracks and core locations for the Blake Plateau. The present core archives are inadequate to construct a depth transect through Paleogene or Cretaceous deposits since all existing cores have low recovery rates or were studied with well cuttings. None of the JOIDES (Holes 1-6) or the USGS Atlantic Slope Project (ASP) holes were drilled at water depths as great as those proposed here although ASP-

3 was drilled just updip of the proposed drilling transect. However, the dense grid of available multichannel lines, single channel lines, and 3.5-kHz echo soundings are ideal for locating future holes in the area.

SCIENTIFIC OBJECTIVES

Cretaceous-Paleogene boundary beds are typically thin in the deep sea yet they contain our best evidence for the geographic distribution and magnitude of the extinctions and the oceanographic history of the earliest Paleocene. There are three major objectives to drilling on the Blake Plateau:

(1) Reconstruct the Paleogene climate history and paleoceanography of this area. Paleogene strata are known to exist at shallow burial depth at all sites along the proposed drilling transect. There are three principle issues that could be addressed by recovery of cores from these areas: a) low latitude surface temperature history during the Paleocene and Eocene, b) nature of the Paleocene-Eocene event at low latitudes, and c) sources of deep waters during the Paleocene and Eocene.

(2) Examine the effects of the Cretaceous-Paleogene meteorite impact on the biostratigraphy and sedimentology of the Atlantic Ocean. Drilling the K/P boundary on the Blake Plateau, will:

- recover a detailed record of events immediately following the impact, including the sequence composed of ejecta fallout and settling of the dust cloud. Site DSDP 390A contains markers for the earliest Paleocene P-alpha zone and the latest Maastrichtian nannofossil zones suggesting the section may be biostratigraphically complete (Gradstein et al., 1978). Unfortunately, rotary drilling of this hole extensively mixed the soft ooze, making a detailed record of K/P boundary events unrecoverable;

- evaluate the recovery of the oceans and biotas following the extinction. Piston cored sections could provide evidence for the magnitude of the extinctions, their duration, and patterns of diversification following the event. Cores containing records of the earliest

Paleocene should also be suitable for studies of the geochemical history of the oceans in the absence of a diverse plankton community;

- determine depth-dependent patterns of sedimentation across the K/P boundary. Our proposed drilling would penetrate the boundary section at present water depths of about 1410-2700 m.

(3) Examine the hydrographic structure of the low latitude Cretaceous oceans. The following problems will be examined:

- the pattern of foraminiferal and nannofossil turnover during the latest Maastrichtian. Is there evidence for heightened turnover prior to the K/P boundary?

- patterns of turnover in middle Maastrichtian nannofossils. Evidence for numerous Southern Ocean sites suggests a major turnover of austral species at about 71 Ma, which coincides with a major carbon isotope excursion and extinction of inoceramid mollusks (Ehrendorfer, 1993). Low latitude sites with good recovery and good preservation through this interval are very rare, so it is still unclear whether the high latitude turnovers are synchronous with a low latitude biotic crisis.

- cyclostratigraphy of the Cretaceous. Can orbital cycles be recognized in low latitude sections, and if so, can they be used to refine Cretaceous time scales? Also, what is the frequency of Cretaceous orbital periodicity and how do patterns of orbital forcing compare with those of the Cenozoic?

DRILLING STRATEGY

Triple APC and XCB coring will be done on five shallow-water (170-450 m deep) sites in a transect from the margin of the Blake Plateau to the edge of the Blake Escarpment. Boreholes will be located along existing, high quality multichannel lines that are crossed by a dense web of single channel and 3.5-kHz lines. Seismic interpretations are supported by a series of JOIDES, USGS, and DSDP boreholes as well as observations from submersibles. The boreholes are intended to penetrate between 170 and 600 m of nannofossil ooze of Eocene, Paleocene, Maastrichtian, Campanian and Aptian-Albian age. All holes extend below Reflector Purple, which is identified as basal Campanian in Hole 390A. All holes should penetrate middle to lower Eocene oozes, Paleocene, and Maastrichtian-Albian strata. Sites BN-2A and BN-3A have a high probability of recovering a complete K/T boundary sequence because these boreholes will penetrate the most stratigraphically complete sequences where the upper Paleocene to Maastrichtian section is about 300 m thick.

The drilling strategy is intended to recover a depth transect in pre-Eocene strata that approaches the depth-resolution possible in upper Pleistocene piston core transects (e.g, Slowey and Curry, 1987; 1992; Lynch-Stieglitz et al., 1994). This will ensure a complete >1300 m depth transect from 1200 mbsl to 2500 mbsl in the Paleocene-middle Eocene and bathyal Barremian-basal Albian. The K/P boundary will be recovered in at least four of the five sites and will permit studies of sedimentation across a depth transect of the boundary beds. Triple coring will ensure nearly 100% recovery of the sedimentary section at each site. Logging will enhance site-to-site correlation, which is critical for reconstructing hydrography.

There is no evidence from previous drilling or from existing seismic records for appreciable hydrocarbons in the slope sediments proposed for drilling. It is unlikely that there are mobile hydrocarbons of Early Cretaceous or younger age on the Blake Nose. The sediments have never been deeply buried to depths sufficient for hydrocarbon maturation. Hydrocarbons may exist in the limestones below the pelagic drape of Barremian to Eocene sediments, but the proposed drilling will not penetrate these limestones except during redrilling of Site 390 (Proposed Site BN-1A). Truncation of the Albian-Barremian clinoforms by the middle Cretaceous unconformity (Reflector Purple) could represent a stratigraphic trap. However, there is no evidence of hydrocarbons below this unconformity in DSDP 390. In addition, there are no obvious cross-strata reflectors that could represent trapped hydrocarbons within the sedimentary section proposed for drilling.

A complication to drilling in this area is the existence of cherts in the lower Eocene and upper Paleocene. Deep Sea Drilling Project Hole (DSDP) 390A encountered seven partly lithified layers of limestone and chert near the edge of the Blake Plateau. The layers are all about 5 cm thick or less and consist of irregularly replaced carbonates in a 30 m thick interval of nannofossil ooze. Once through this section, the lower Paleocene through upper Aptian section is entirely ooze at Site 390.

LOGGING PLAN

The proposed five-site depth transect will span paleowater depths ranging from ~1 to ~3 km across the Blake Plateau. Logging data will be very important to achieve the objectives of this proposed leg. Only holes deeper than 400 m will be logged, and these holes will be logged with standard tools to aid inter-site correlation. Logging would enhance site-to-site correlation, which is critical for reconstructing hydrography. We propose that all but one of the holes be logged with Quad combo, geochemical, Formation MicroScanner (FMS), and Geological High-resolution Magnetometer (GHMT) tool strings. The exception is proposed hole BN-1A where there is too little penetration.

PROPOSED SITES

DSDP Site 390 (location of BN-1A) penetrated five distinctive reflectors (Fig. 3) that are color coded as:

1) Middle Eocene nannofossil ooze (Reflector Orange),
2) Paleocene/lower Eocene nannofossil ooze and chert (Reflector Red),
3) Lower/upper Paleocene nannofossil ooze (Reflector Green),
4) Campanian nannofossil ooze (Reflector Purple), and
5) Barremian strata (Reflector Blue—between Barremian clayey nannofossil ooze and Barremian periplatform limestone).

The proposed sites (Figs. 2 and 3) are located at 1410, 1972, 2264, and 2586 mbsl and are projected to penetrate between 170 and 600 m of nannofossil ooze of Eocene, Paleocene, Maastrichtian, Campanian, and Aptian-Albian age. All holes will extend below Reflector Purple, which is identified as basal Campanian in Hole 390A. All holes should penetrate middle to lower Eocene oozes, and Paleocene and Maastrichtian-Albian strata. By far the most stratigraphically complete sequences should be present at sites BN-2A and BN-3A where the upper Paleocene to Maastrichtian section is about 300 m thick. These sites have a high probability of recovering a complete K/P Boundary sequence, because at least the lower Danian was biostratigraphically complete in the much thinner (20 m) section recovered in Hole 390A.

Site BN-1A

This site is proposed as a reoccupation of Site DSDP 390. The principal objective is to recover a sequence of Eocene though Campanian strata from deep water that can be compared with age-equivalent, but more expanded, sections at shallower water depths. In particular, the middle Eocene, and lower Paleocene-Maastrichtian are thick enough to permit high-resolution studies of Eocene paleoceanography, and the nature of the K/P boundary event.

DSDP Site 390 recovered about 200 m of sediment including 160 m of pelagic sediment that ranges in age from middle Eocene (?) to Barremian, and 40 m of Barremian oolitic limestone. The pelagic sediments were entirely stiff to soupy nannofossil ooze with the exception of seven 5-cm-thick limestone and chert stringers encountered in the 30-m-thick lower Eocene and upper Paleocene sections. Eocene sediments compose about 75 m of the cored section, whereas the Paleocene (35 m), Maastrichtian (28 m), Campanian (2 m), and Barremian to lower Albian pelagic sediments (20 m) make up the remainder. During RCB drilling of DSDP 390A, coring penetrated about 50 m/hour except during drilling through the cherts, where the drilling rate dropped to about 20 m/hour.

Site BN-1A is included mainly to increase the total depth range of the transect (to about 1371 m total water depth range) and recover sediments deposited well within the Paleogene equivalent of modern upper deep water. Further, since DSDP Site 390 was rotary cored, the existing core is useless for paleoceanography. This is a good site for recovering a moderately thick and well-preserved Eocene-Paleocene section and for estimating the chemistry of upper deep water. However, the Cretaceous sequence is too condensed to be of much use for paleoceanography. The Mesozoic section should be of interest to sedimentologists studying the control of water depth on sedimentation at the K/P boundary, and processes of sedimentation (e.g., tying expanded sections (BN-3A) into more condensed intervals (BN-1A)).

Site BN-1B

Site BN-1B would recover a thicker section than Site BN-1A (400 m compared to ~170 m) at a slightly shallower depth (2480 mbsl). Nearly all the increased thickness would be in a more expanded Paleocene-Eocene section. The site is located at shotpoint 2241 on MCS Line TD-5. This site is proposed as an alternate to Site BN-1A.

Site BN-2A

Site BN-2A was previously located in 2265 m water depth at the intersection of SCS line 18 of the *R/V Gloria Farnella* and the profile made by the *Glomar Challenger* during the survey for DSDP 390. This site has been relocated to shotpoint 1291 on Gillis Line 26 at essentially the same water depth as before and with nearly the same stratigraphy and thickness of the stratigraphic section. This move was made entirely because of uncertainties about the correct navigation of the *Glomar Challenger* line.

The site is located immediately NW of MCS line TD-5 to take advantage of an unusually thick sequence of upper Paleocene (?) strata. At this location the depth to Reflector Purple is about 400 m, due primarily to an unusually expanded section above Reflector Green (lower/upper Paleocene) and below Reflector Red (Paleocene/Eocene Boundary). The upper Paleocene is probably about 200 m thick at this site and the lower Paleocene-Campanian section (between reflectors Green and Purple) is about 75 m thick. The sediment packages between the other reflectors have similar thicknesses to their equivalents at Site DSDP 390.

This is a high priority site because it represents an expanded section of Paleocene-Cretaceous sediments that are ideal as a deep-water end member of the depth transect. The expanded section should help considerably in refining Paleocene and Eocene stratigraphy and paleoceanography, since the best available low latitude sites (such as DSDP 577, DSDP 384; and ODP 758) are comparatively condensed. The Aptian and older Cretaceous section is also a good end member for a thermocline-intermediate water depth transect in the Early Cretaceous. In addition, the site is likely to recover a complete K/P boundary with well-preserved microfossils. Drilling is proposed to about 600 m to recover 400 m of middle Cretaceous-Eocene and 200 m of Lower Cretaceous sediments.

Site BN-3A

This site is located at shotpoint 1821 on MCS Line TD-5 and is very similar to BN-2A in terms of the thickness of the sediment packages between all the reflectors. As at Site BN-2A, the middle Eocene is about 75 m thick and overlies a 50-m section of lower Eocene to uppermost Paleocene (Reflector Orange to Reflector Red). The middle Paleocene is nearly 200 m thick (above Reflector Green) and overlies a 100-m-thick drape of lower Paleocene to Campanian strata (above Reflector Purple). The site is located at the intersection of the *Glomar Challenger* SCS line and MCS line TD-5 at about 1972 mbsl.

The section below Reflector Purple consists of 370 m of Lower Cretaceous (?) deposits. The middle Cretaceous represents the distal upper package of clinoforms that overlaps the pre-Barremian (?) reef about 40 km to the southwest and can be traced updip to deposits below Sites BN-4A and BN-5A. Coring is proposed to a depth of about 600 mbsf to recover the Paleogene and part of the Lower Cretaceous sections.

Site BN-3A is about 300 m shallower than Site BN-2A so both add to the resolution of the depth transect. Further, both Sites BN-2A and BN-3A penetrate a thick section of Paleocene sediments, which should provide a fairly high-resolution sequence in well-preserved sediments that is singularly lacking in existing ODP holes. Site BN-3A should recover a well-preserved K/P boundary interval and expanded Aptian to older Cretaceous sequence. The site could be used as an alternate for Site BN-2A, but it would also serve as a site at intermediate depth between Sites BN-4A and BN-2A where it improves the likelihood of correlating accurately between shallower and deeper sites, and increases the probability of recovering a complete section of the Lower Cretaceous strata.

Site BN-4A

This site lies at a water depth of 1410 m and appears to preserve about 200 m of upper

Paleocene to Eocene strata over about 100 m of Campanian to lower Paleocene deposits. Reflector Purple is underlain by about 250 m of deposits that appear to correlate with the seismic package that lies between reflectors Blue and Purple at Site BN-3A. These are likely to be Barremian to pre-lower Albian nannofossil ooze and clay similar to sediments recovered from the equivalent interval at DSDP 390. Coring is propose to about 250 m below Reflector Purple for a total recovery of about 550 m of section.

Site BN-4A is ~560 m shallower than BN-3A and over 800 m shallower than Site BN-2A and should contain a record of the Paleogene equivalent of modern, lower intermediate water. This is a critical site primarily because it provides the best shallow-water end member for the depth transect through Paleocene and Lower Cretaceous strata. In addition, the site should recover a K/P boundary section.

Site BN-4B

Site BN-4B is proposed as an alternate to Site BN-4A. The site is located on shotpoint 1461 at a water depth of 1652 m. The objectives are similar to those described above, but the site would recover a slightly thicker section (~600 m) and so be at a deeper water depth than Site BN-4A. Site BN-4B would recover a more expanded section above Reflector Purple than Site BN-4A but at the expense of about 100 m of section below this reflector.

Site BN-5A

The objectives are to recover the middle Eocene-Maastrichtian (?) and underlying Aptian-Barremian section for correlation with equivalent strata at Sites BN-4A, BN-3A, and BN-1A. Correlation to Site BN-2A will permit a depth transect of about 900 m between Sites BN-5A and BN-2A where the sections are expanded compared to that at Site BN-1A. A total of about 450 m of section will be cored: 200 m of Oligocene-Upper Cretaceous (?) and 250 m of Lower Cretaceous deposits.

Site BN-5A is included since it is the shallowest site that is likely to have a good Cenozoic section. At 1200 m depth, Site BN-5A is well within modern intermediate water and hence is a good end member for paleoceanography. The site probably lacks a K/P boundary section, or it is very condensed relative to Sites BN-2A, 3A, and 4A. However, it should recover an Eocene to upper Paleocene section similar to the deeper sites as well as a shallow-water, end-member Lower Cretaceous section. Hence, this is a desirable site primarily because it expands the total depth range of the transect and increases the probability of being able to reconstruct vertical hydrographic structure during the late Paleocene to middle Eocene, and in the Early Cretaceous.

Site BN-5B

Site BN-5B is proposed as an alternate to Site BN-5A. The site is located on shotpoint 1241 on MCS Line TD-5 at a water depth of 1293 m. The objectives are similar to those described above but the site would recover a more expanded section above Reflector Purple and do so at a deeper water depth than Site BN-5A. Site BN-5B would core about 100 m of Oligocene and younger strata, 200 m of Eocene to Upper Cretaceous (?), and 150 m of Lower Cretaceous deposits for a total penetration of about 450 m.

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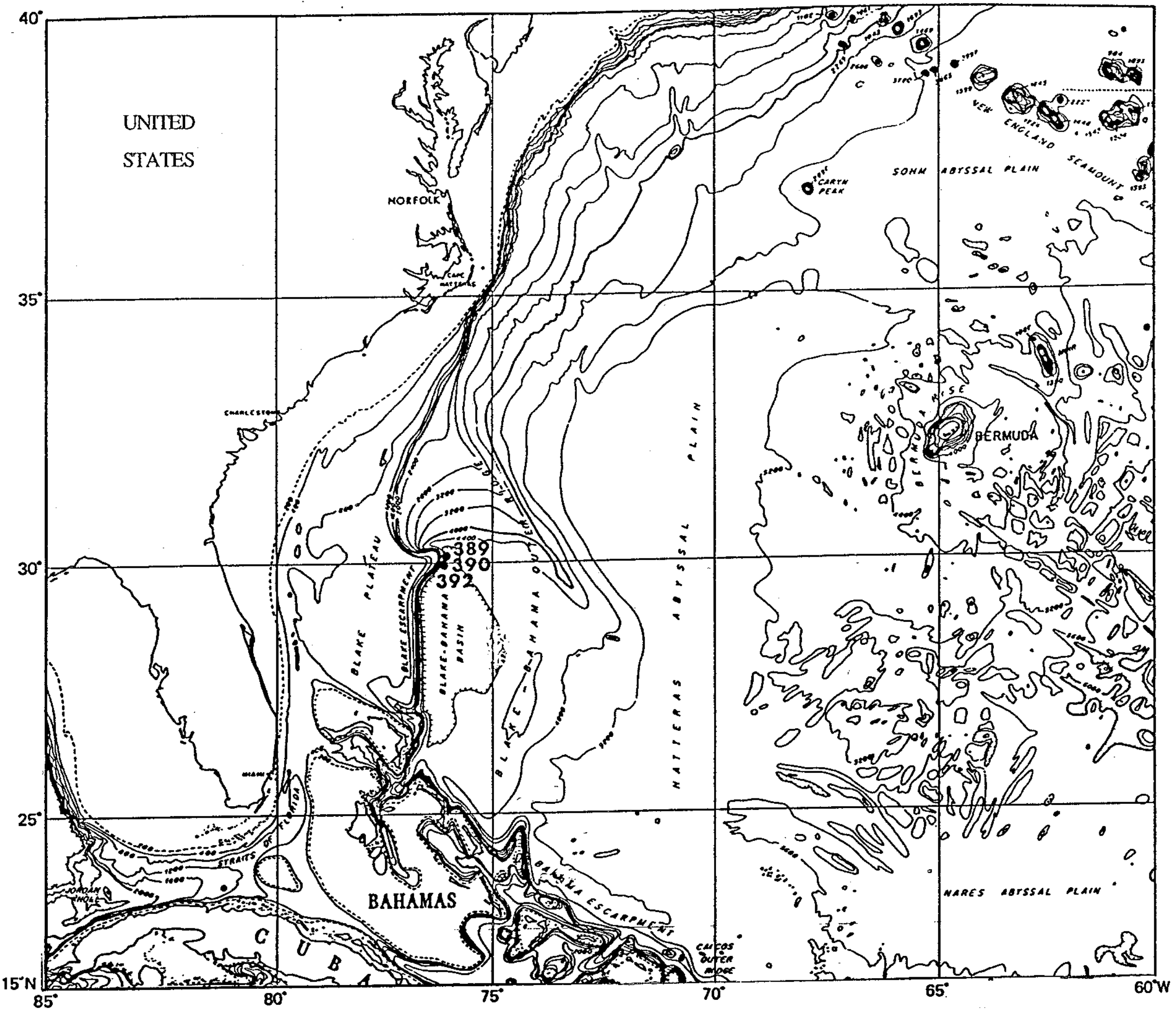

Figure 1. Bathymetric map of part of the western North Atlantic showing the location of Blake Nose next to DSDP Sites 389, 390, and 392. Site BN-1A of Leg 171C will reoccupy Site 390.

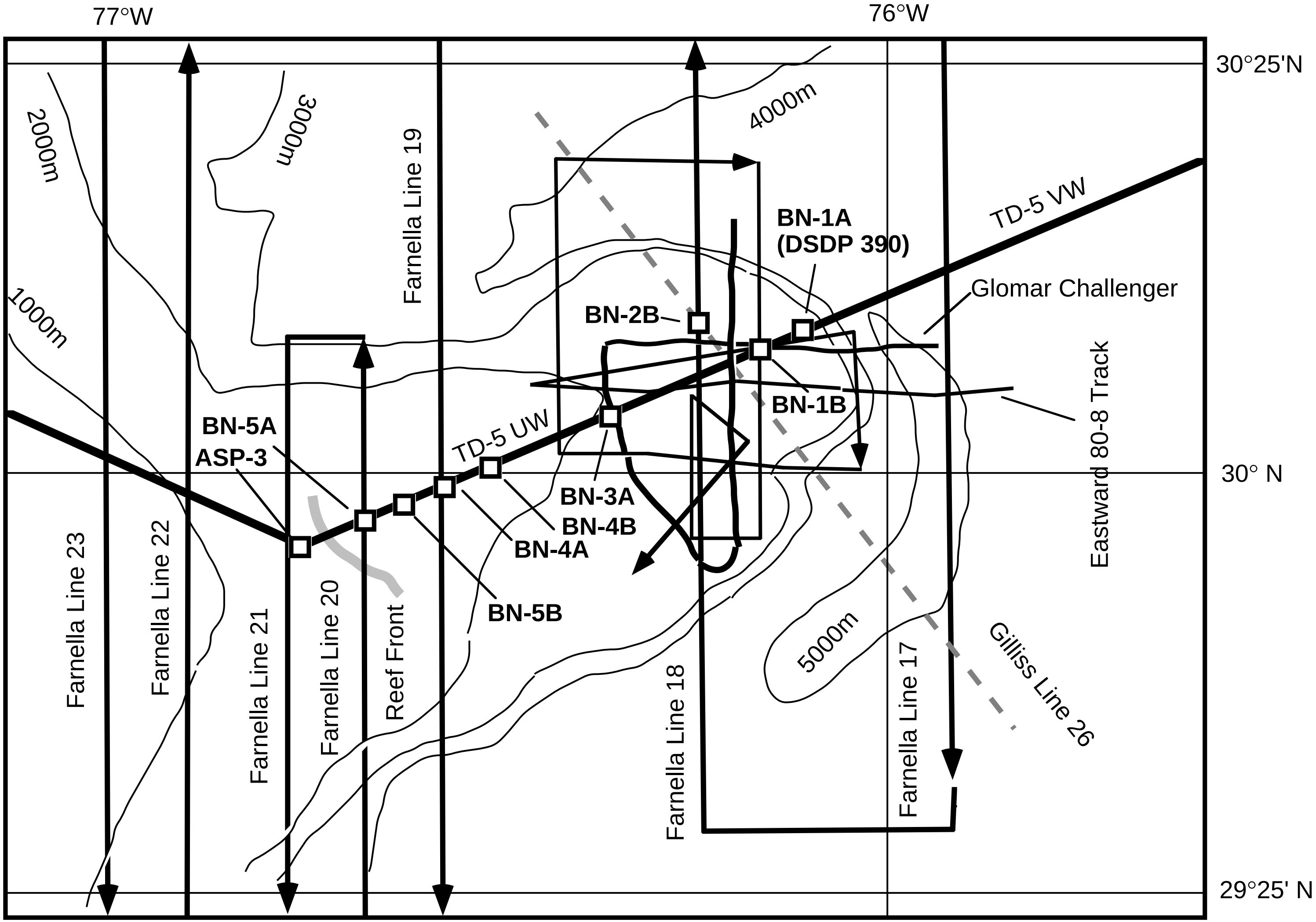

Figure 2. Bathymetric map showing seismic track lines and proposed drill sites on the Blake Nose.

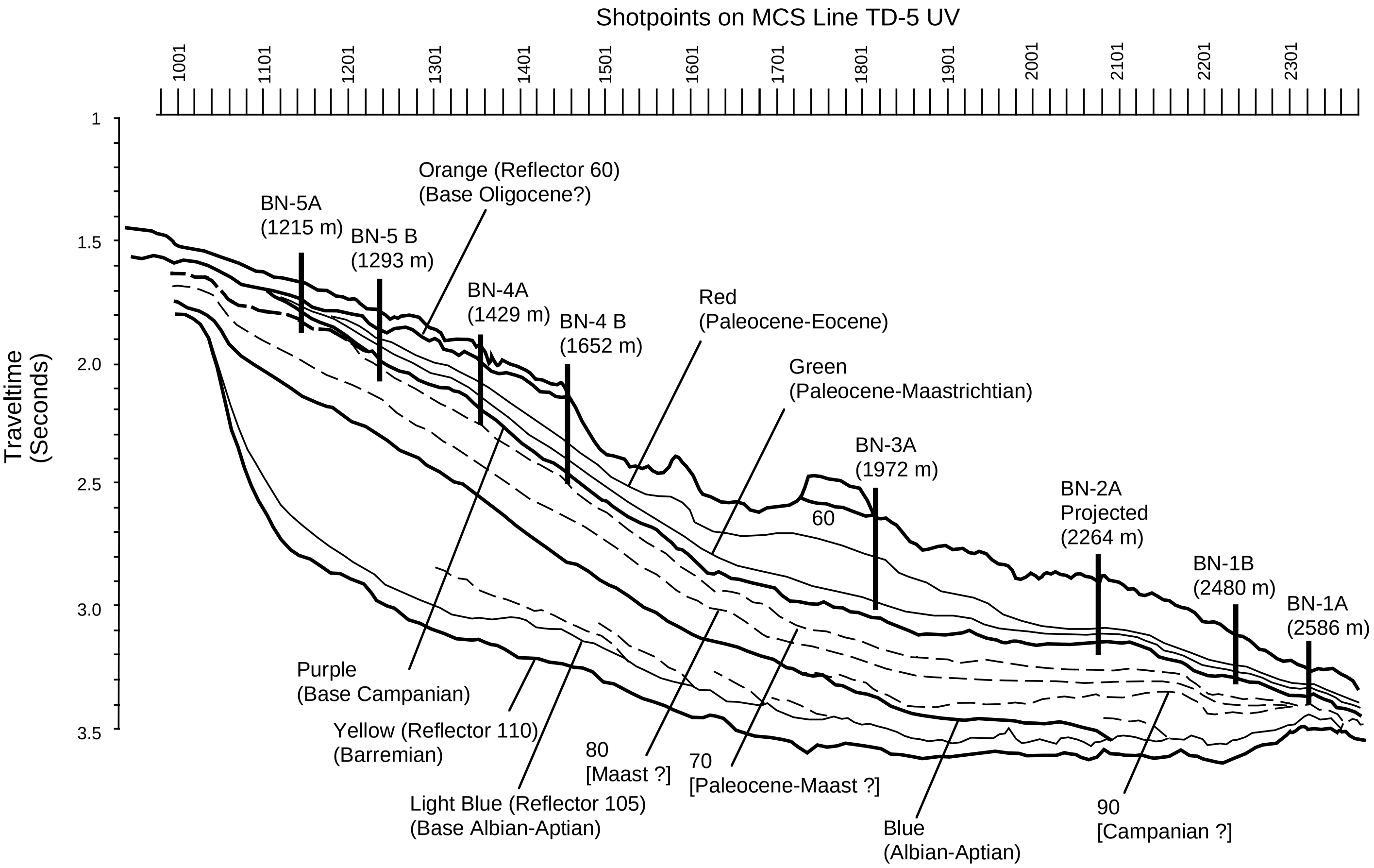

Figure 3. Tracing of MCS Line TD 5UW. Reflectors labeled with numbers are those of Hutchinson et al (in press) as are age estimates given in square brackets (based on W. Poag's interpretation of the seismic line). Ages given in parentheses are those favored here. Maast = Maastrichtian.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: BN-1A (DSDP Site 390) **PRIORITY**: **POSITION**: 30°8.4´N, 76°6.6´W
WATER DEPTH: 2586 m **SEDIMENT THICKNESS**: 3000 m **TOTAL PENETRATION**: 160 m
SEISMIC COVERAGE: TD-5VW

Objectives: Recover Paleogene and Cretaceous ooze to reconstruct the vertical chemistry and origins of deep and intermediate waters. Core Cretaceous/Paleocene and Paleocene/Eocene boundary beds for paleoceanographic, evolutionary, and stratigraphic studies.

Drilling Program: Triple APC, XCB

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs.

Nature of Rock Anticipated: Nannofossil ooze.

SITE: BN-2A **PRIORITY**: **POSITION**: 30°7.8'N, 76°12'W
WATER DEPTH: 2200 m **SEDIMENT THICKNESS**: >3000 m **TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: Gilliss Line 26 & Farnella Line 18

Objectives: Recover Paleogene and Cretaceous ooze to reconstruct the vertical chemistry and origins of deep and intermediate waters. Core Cretaceous/Paleocene and Paleocene/Eocene boundary beds for paleoceanographic, evolutionary, and stratigraphic studies.

Drilling Program: Triple APC, XCB.

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs.

Nature of Rock Anticipated: Nannofossil ooze and chalk.

SITE: BN-3A **PRIORITY**: **POSITION**: 30°6'N, 76°19.8'W
WATER DEPTH: 1972 m **SEDIMENT THICKNESS**: >3000 m **TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: TD-5UW

Objectives: Recover Paleogene and Cretaceous ooze to reconstruct the vertical chemistry and origins of deep and intermediate waters. Core Cretaceous/Paleocene and Paleocene/Eocene boundary beds for paleoceanographic, evolutionary, and stratigraphic studies.

Drilling Program: Triple APC, XCB

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs.

Nature of Rock Anticipated: Nannofossil ooze, calcareous clays, or nannofossil ooze/chalk.

SITE: BN-4A **PRIORITY**: **POSITION**: 29°57.6'N, 76°34.2'W
WATER DEPTH: 1410 m **SEDIMENT THICKNESS**: >3000 m **TOTAL PENETRATION**: 550 m
SEISMIC COVERAGE: TD-5UW and Farnella Line 119

Objectives: Recover Paleogene and Cretaceous ooze to reconstruct the vertical chemistry and origins of deep and intermediate waters. Core Cretaceous/Paleocene and Paleocene/Eocene boundary beds for paleoceanographic, evolutionary, and stratigraphic studies.

Drilling Program: Triple APC, XCB

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs.

Nature of Rock Anticipated: Nannofossil ooze, calcareous clays, or nannofossil ooze/chalk.

SITE: BN-5A **PRIORITY**: **POSITION**: 29°52.8'N, 76°40.2'W
WATER DEPTH: 1215 m **SEDIMENT THICKNESS**: >3000 m **TOTAL PENETRATION**: 450 m
SEISMIC COVERAGE: TD-5UW and Farnella Line 20

Objectives: Recover Paleogene and Cretaceous ooze to reconstruct the vertical chemistry and origins of deep and intermediate waters. Core Cretaceous/Paleocene and Paleocene/Eocene boundary beds for paleoceanographic, evolutionary, and stratigraphic studies.

Drilling Program: Triple APC, XCB

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs.

Nature of Rock Anticipated: Nannofossil ooze, calcareous clays, or nannofossil ooze/chalk.

LEG 172

NW ATLANTIC SEDIMENT DRIFTS

Modified from Proposal 404 Submitted By

L.D. Keigwin, R. Flood, and E.A. Boyle

Staff Scientist: Gary Acton **Co-Chief Scientists:** **Lloyd D. Keigwin**
Domenico Rio

ABSTRACT

The Blake-Bahama Outer Ridge (BBOR) and Carolina Slope are located at the western boundary for deep water circulation in the North Atlantic and the surface waters of the Gulf Stream, which are important as a source of salt and heat to the northern North Atlantic. For this reason, the BBOR is the optimal location to monitor changes in North Atlantic Deep Water (NADW). It is also an excellent location to monitor Antarctic Bottom Water (AABW) because that water mass is recirculated in the subtropics, blending with the exposed NADW. At shallower depths the region is bathed by water from the Labrador Sea, which on geological time scales may be as important a water mass as is the upper NADW. Recently a shallow component to Labrador Sea water has been identified which interacts with the Gulf Stream, probably controlling the distribution of sediment on the Carolina Slope. According to the "Great Ocean Conveyor" paradigm, knowledge of the history of these surface, intermediate, and deep water masses is essential to understanding the world ocean's role in climate change.

Drilling on Leg 172 will provide paleoenvironmental records for late Neogene hemipelagic sediments that are deposited at accelerated rates on western North Atlantic sediment drifts on the BBOR and Carolina Slope. These two areas may represent the only sediment drift locations in the world's oceans where it is possible to conduct high-resolution paleoclimate studies through a 3500-m-range of water depths. Data obtained from the Bermuda Rise site will be compared with data from sites located at deep, high-deposition-rate locations on the BBOR and Carolina Slope to document late Neogene oceanographic changes in the western North Atlantic for millennial as well as Milankovitch times scales over the entire deep and intermediate water column.

INTRODUCTION

Sediment drifts are widespread in the North Atlantic basin and reflect both the abundant sources of sediment and the focusing of the sediments by deep currents (Lonsdale, 1982; McCave and Tucholke, 1986). There is at least one sediment drift associated with every water mass in the North Atlantic, suggesting a potential for tracing the individual components of North Atlantic Deep Water (NADW) on geological time scales using geochemical and sedimentological techniques (Keigwin and Jones, 1989). Leg 172 will core 12 sites: nine on the Blake-Bahama Outer Ridge (BBOR), two on the Carolina Slope, and one on the Bermuda Rise (Figs. 1 and 2) to distinguish between latitudinal changes in the mixing zone between southern- and northern-source waters and changes due to vertical migration of a benthic front. A North Atlantic depth transect at the BBOR is especially important because this feature forms a western boundary for deep currents (Stommel, 1958), which follow depth contours (Heezen et al., 1966). Above ~4000 m these waters are sourced mostly from the north, whereas at greater depths there is a greater proportion of recirculated southern-source water (Hogg, 1983). BBOR coring is essential to document and understand first-order changes in the ocean-climate system such as glacial-interglacial variability in the production and flow of North Atlantic water masses, and changes in terrigenous, authigenic, and biogenic fluxes. In addition, coring on sediment drifts with high deposition rates is especially important in order to understand North Atlantic climate on orbital time scales.

BACKGROUND

Paleoceanography and Paleoclimatology

One of the most intensively studied sediment drifts in the North Atlantic lies on the northeast Bermuda Rise, where the overlying deep water is the most turbid in the basin (Biscaye and Eittreim, 1977) due to advection of clays and silts by the deep Gulf Stream return flow (Laine and Hollister, 1981; see also Hogg, 1983). The ultimate source of this terrigenous sediment is probably eastern Canada. During glaciation, deposition rates were as high as 200 cm/k.y. on the Bermuda Rise (Keigwin and Jones, 1989). Geochemical studies of cores from the Bermuda Rise have revealed the coupling of the ocean, the atmosphere, and ice sheets on the sub-millennial scale. For example, deep ocean circulation at the depth of the Bermuda Rise

(~4500 m) responded to the Younger Dryas cooling episode (Boyle and Keigwin, 1987), as well as earlier oscillations in the climate system (Keigwin et al., 1991). Results from isotope stages 3-5 (23-80 k.y.) at the bottom of Giant Piston Core (GPC)-5 show similar climate oscillations. Unfortunately, the price for high resolution sedimentology is a short temporal record, even in a core 28 m long. Thus, it is important to core the much longer record on the Bermuda Rise (BR) using the Advanced Hydraulic Piston Corer (APC).

The most heavily studied core from the BBOR region, GPC-9, was taken in 1973 from the northwest flank of the Bahama Outer Ridge at a depth of 4758 m (Fig. 3). Initial stratigraphy of that core was discussed by Flood (1978), followed by unpublished benthic foraminiferal (Lohmann, unpublished) and stable isotope studies (Curry and Lohmann). Keigwin and Jones (1989) documented the planktonic, stable isotope stratigraphy and presented accelerator mass spectrometer (AMS) radiocarbon results. Using AMS and $\partial^{18}O$ stratigraphy (Fig. 4A), we have plotted percent carbonate results at 4 cm spacing from the upper 2200 cm of GPC-9 vs. age (Fig. 4B). A core at 4935 m (GPC-7; Figure 3) has too little carbonate to determine a useful stratigraphy (Keigwin and Jones, 1989), making the depth of GPC-9 (~4800 m) a lower limit for cores in the depth transect.

Results from about six conventional diameter piston cores have been reported from the crest of the Blake Outer Ridge between water depths of 2600 m and 4400 m on cruises of the *Cape Hatteras* (Fig. 3). Most of these cores have lower rates of deposition than GPC-9, based on the available low-resolution (20-cm spacing) percent carbonate curves and $\partial^{18}O$ curves on planktonic foraminifera (Johnson et al., 1988, and Haskell et al., 1991). The major emphasis on these cores was to study grain-size variations as a measure of Western Boundary Undercurrent velocity and position. Grain size results were consistent with nutrient proxy results (Keigwin et al., 1991) as monitors of deglaciation changes in deep-ocean circulation, indicating there have been important changes in the intensity and position of the Deep Western Boundary Current on the Blake Outer Ridge (Haskell et al., 1991). A summary of percent carbonate in the Blake Outer Ridge piston cores (Fig. 5; Haskell, 1991) shows that had they been sampled closely enough, they might reveal variability similar to that of GPC-9 (Fig. 4B).

Although the Blake Outer Ridge has the potential for benthic paleochemical reconstructions with resolution similar to that on the Bermuda Rise and Bahama Outer Ridge, it has not yet been demonstrated.

Large vertical gradients can be expected in the Tertiary and Quaternary oceans. Using benthic foram chemistry, the BBOR region will monitor southern-source waters entering the North Atlantic basin as well as northern-source deep and intermediate waters exported in the depth range 2000 to 4800 m. We also can expect to monitor important basin-wide changes in the position of the lysocline, which may have an additional influence at this location by the position of the Deep Western Boundary current (Balsam, 1982). Sedimentological studies also indicate considerable depth-related variability, which may reflect changes in sediment provenance and current speed (Haskell et al., 1991).

On the Bermuda Rise we found evidence for oscillations in surface and deep water properties which appear to be related to millennial-scale variability in carbonate content characteristic of the past 80 k.y. By comparison with the core from the Bahama Outer Ridge, we speculate that similar oceanographic change is typical of the deep western basin of the North Atlantic in general. Specific questions to be answered include:

- How far up the water column do these oscillations persist?
- How many water masses are involved?
- Could lower NADW alone account for this variability and the (apparently) associated climate oscillations in northern Europe (Lehman and Keigwin, 1992)?
- Was nutrient-depleted intermediate water produced in the Atlantic each time there was a decrease in NADW production? What is the depth of the "hinge" between glacial intermediate and deep waters?

For a bathymetric reconstruction to be most useful it should range from the deepest waters (the location of GPC-9, ~4800 m) to intermediate depths. For this part of the western North Atlantic we have good intermediate coverage to 1500 m from the thesis transect of Slowey (1990) at Little Bahama Bank (Fig. 6). Slowey's glacial-interglacial ∂^{13}C comparisons clearly show that the glacial thermocline was better ventilated (more nutrient-depleted) than today. Other results on widely distributed Atlantic Ocean cores show that the nutrient depletion extended as deep as ~2400 m (Boyle and Keigwin, 1987; Oppo and Fairbanks, 1987), but there has been no concentrated transect of cores to make detailed reconstruction for the western North Atlantic. Because the Blake Outer Ridge first detaches from the continental margin at ~2000 m (Fig. 7), the proposed coring transect for this leg will begin there, making a patch with Slowey's nearby results. Coring will extend deeper than the deepest *Cape Hatteras* core, onto the Bahama Outer Ridge where we will fill in the depth range between the Bermuda Rise (~4500 m) and core GPC-9 (~4800 m). Data obtained from Site BR-1 on the Bermuda Rise will be compared with data from sites located at deep, high-deposition rate locations on the BBOR and Carolina Slope to document late Neogene oceanographic change in the western North Atlantic for millennial as well as Milankovitch time scales over the entire deep- and intermediate-water column.

Mud Wave Dynamics

Recent studies of mud wave dynamics suggest that mud waves migrate because there are cross-wave changes in bed shear stress (Flood, 1988; Blumsack and Weatherly, 1989). In the case of fine-grained cohesive sediment, accumulation rate decreases as shear stress increases (McCave and Swift, 1976), thus less sediment accumulates on the wave flank with the higher flow speed. In the case of a lee-wave flow pattern, flows on the upcurrent, upslope wave flank are weaker than those on the downcurrent wave flank, leading to upslope and upcurrent wave migration. Enhanced wave migration is expected at higher flow speeds because currents on the downcurrent flank approach the critical shear stress for deposition before those on the upcurrent flank (Flood, 1988).

Wave migration can be measured by determining the ratio of sediment thickness deposited on each wave flank during a time interval or between two correlated layers, and a model-dependent flow speed can be estimated (Flood, 1988). This approach has been used with success in the Argentine Basin where a mud wave appears to have become inactive during the last 20-30 k.y. (Manley and Flood, 1992). Although our present understanding suggests that only two core sites are required to make this comparison (one on each wave flank), this needs to be explicitly tested by sampling at least four places across the wave profile (crest, trough, each flank) in order to choose the best locations for ODP cores. Independent evidence of changes in flow speed will supplement interpretations of circulation change made on the basis of ocean paleochemistry.

Wave migration on sediment drifts has been a long-standing interest of the drilling program, but it has not yet been successfully studied by ODP. As the Sedimentary and Geochemical Processes Panel (SGPP) White Paper (JOIDES Journal, 1990) states:

> “The history of thermohaline bottom current processes is preserved in sediment drifts and sediment waves molded under relatively steady currents. Drilling transects will test sedimentation models for sediment structure and bottom current depositional processes and use these models to determine past variations in the bottom flow regime of the ocean.”

Waveforms observed at DSDP Sites 610 and 611 were found to be surprisingly stable, migrating on the million year time scale (Kidd and Hill, 1986). However, that study sampled wave crests and troughs, not wave flanks. Evidence from the Bahama Outer Ridge (Flood, 1978) and the Argentine Basin (Manley and Flood, 1992) as well as models suggests that the largest difference in sedimentation rates is to be expected on the flanks. The Bahama Outer Ridge wavefield (Fig. 8) is mapped with much greater precision than those on Gardar and Feni Drifts and carbonate content in small free-fall cores indicates that sedimentation rates did indeed change between upstream and downstream wave flanks during the latest Quaternary (Flood, 1978).

SCIENTIFIC OBJECTIVES

The major objectives of this program are to obtain a detailed history of Late Neogene paleoceanography and paleoclimate in the North Atlantic by investigating: 1) millennial scale oscillations of stable isotopes (C, O), carbonate, and trace metals in drift deposits; 2) the nature of cyclicity of these oscillations; and 3) how these cycles are related to the history of Northern Hemisphere glaciations during the Late Neogene.

In addition, this proposal seeks to investigate:

- sediment wave migration and drift sedimentation processes

- detailed variations of the Earth's magnetic field (secular variations, reversals)
- geotechnical/acoustic properties of the deep-sea sediments
- structure of stable isotope Milankovitch cycles during the Pleistocene/Pliocene

DRILLING STRATEGY

The goals of Leg 172 can best be achieved by APC/XCB coring of one site on the Bermuda Rise (BR), coring a depth transect on the Blake-Bahama Outer Ridge (BBOR, nine sites) and the Carolina Slope (CS, two sites), the first such ODP transect in the North Atlantic. The original drilling plan called for APC/XCB coring at all the sites given in the table below. At the annual Planning Committee (PCOM) meeting in December 1995, PCOM considered this proposal in the light of results from North Atlantic-Arctic Gateways II Leg 162 and decided that ODP's long-term planning for climate and ocean circulation studies would be best served by extending the objectives of some of the sites in the transect (see Site Table).

LOGGING PLAN*

Most of the proposed holes in the depth transect will not exceed 350 m penetration and will not be logged, although deeper holes may be logged. The primary objectives of Leg 172 will depend on good core recovery of material for stable isotope measurements, as well as other paleoclimate proxies. Downhole logging may help achieve the primary goals of this proposal by ensuring that full stratigraphic coverage is achieved through the integration of core and log measurements. Where core recovery is incomplete or core disturbance is high, usually in XCB cored sections, downhole logs will provide continuously sampled physical properties that can serve as proxies for paleoclimatic indicators.

Geophysical logs (sonic, porosity density, and resistivity) may also provide the acoustic characterization of the sediments and further quantification of gas and gas hydrate present in the sediments. In addition, Formation MicroScanner (FMS) images may provide detailed characterization of sedimentary structures (particularly difficult to obtain in XCB cores) for interpretation of sedimentary processes in the drift deposits, help orient XCB cores for magnetic

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*Tentative logging plan

studies, as well as provide a very high-resolution record of resistivity (although not in absolute values) for cyclicity studies. In summary, the total number of logged holes will depend on penetration, core recovery and quality, available time, and the specific objectives at the site.

PROPOSED SITES**

BBOR-1

This site is in the well-known deep mud wave field just northwest of the Bahama Outer Ridge (~4700 m). The waters there are ~20% AABW that has mixed with the southward-flowing NADW and follows the bathymetric contours. The deposition rates are very high, which we know from the site survey and other cores. For example, for the latest Quaternary a typical wave accumulates at an average of 262 m/m.y. At this site we plan to core six holes to 200 m, three on the high-depositional rate east flank, and three on the lower rate western flank. These sites will be the deepest high-resolution paleoceanography sites in the North Atlantic (and perhaps the deepest anywhere), and will be useful for monitoring the evolution of the blend of NADW and AABW in the North Atlantic, for studying magnetic reversals in high resolution and for directly measuring paleocurrent speed through ratios of sedimentation rates on either flank of the wave. As these holes are the last to be cored in the CS/BBOR region and will not be affected by gas hydrate, this hole may be cored as deep as 350 mbsf if problems are experienced at shallower sites or if we do not core as deep as 200 m at the lower-sedimentation -ate side of the wave.

BBOR-1A

No information at this time.

BBOR-1B

No information at this time.

BBOR-1C

No information at this time.

**Sites were not finalized at time of publication.

BBOR-3

This site will be triple APC cored to 200 m at the tip of the Blake Outer Ridge at ~4250 m. Sediments there should be free of gas hydrate, so we are requesting clearance to extend holes as deep as 350 m, if the situation permits. This location has the highest late Quaternary sedimentation rate of the entire BBOR region (~339 m/m.y.). It should make a useful complement to the Bermuda Rise site (BR1) far to the northeast in the Sargasso Sea.

BBOR-4A

No information at this time.

BBOR-5

This site will be triple APC cored to refusal and double XCB cored to 350 m. It is located at the position of DSDP Site 102 (3430 m), a high sedimentation rate location in the heart of the lower NADW. From Site 102 we know that the sedimentation rates are nearly constant, with the ~3 Ma level at 350 m (based on the LA of *Sphaeroidinellopsis* and *G. altispira*). Significant gas expansion was noted at Site 102 beginning at ~100 m, but carbonate diagenesis like that which interfered with APC operations on Leg 164 was not noted.

BBOR-6 and -9

Like the deeper mud wave field, this pair of sites reveals striking physical evidence of current-controlled sedimentation. At present, the plan calls for three APC cores to 150 m at a high deposition-rate location where the boundary current at ~3000 m has expanded the section, and three comparison holes to the same depth at a relatively lower sedimentation-rate location less than a mile away. These two pairs of triple-core locations will allow us to directly observe the history of boundary current movement by comparing sedimentation rates for short-time intervals. Such a comparison might reveal, for example, that the boundary current is only active at this location in interglacial time. Sediment flux studies at these sites will test some fundamental assumptions in sediment drift paleoceanography. If the only difference between the two groups of holes is the lateral flux of sediment brought by the boundary current, and if the foraminifera are not subject to traction transport, then the foram fluxes should be identical regardless of sedimentation rate. We are considering extending the penetration of the relatively low sedimentation-rate holes at the expense of the higher sedimentation-rate holes to get farther into the Pliocene.

BBOR-7

This Blake Ridge site was chosen for its high sedimentation rate and its modern day location between the upper and lower limbs of the NADW. BBOR-7 will be triple APC cored to 100 m.

BBOR-8B

As a result of a Detailed Planning Group (DPG) study, this site has been moved slightly to a location with better seismic coverage. In addition, this site will be extended to 200 m by XCB which may be necessary judging from the experiences of Leg 164. That should give a bottom age well within the Pliocene, which is important considering that at 2164 m this site lies close to a bathymetric front during late Quaternary time.

CS-2 and CS-3

These sites will complete the depth transect in the BBOR region by providing high-resolution sections from water depths of 1790 m and 1203 m, respectively. CS-3 has been moved slightly by the DPG (now CS-3B) to lie on an existing seismic line. Because of the prevalence of slumps and slides on the Carolina Slope, it is recommended that these sites receive a quick seismic survey by the drillship before coring.

BR-1

This is the last site to be cored by Leg 172, on the way to port in Lisbon, Spain. The location is very well surveyed, and the facies should be the same as those cored by DSDP Site 9. Goals at that site were to date the bottom of the prominent acoustic reflectors at ~300 mbsf and to date sediment overlying basalt as a test of seafloor spreading. Neither objective was achieved because of spot coring, core catcher failure, and generally unfossiliferous sediments at great depth. It is expected that the acoustically stratified facies began with Northern Hemisphere glaciation.

BR-1A

No information at this time.

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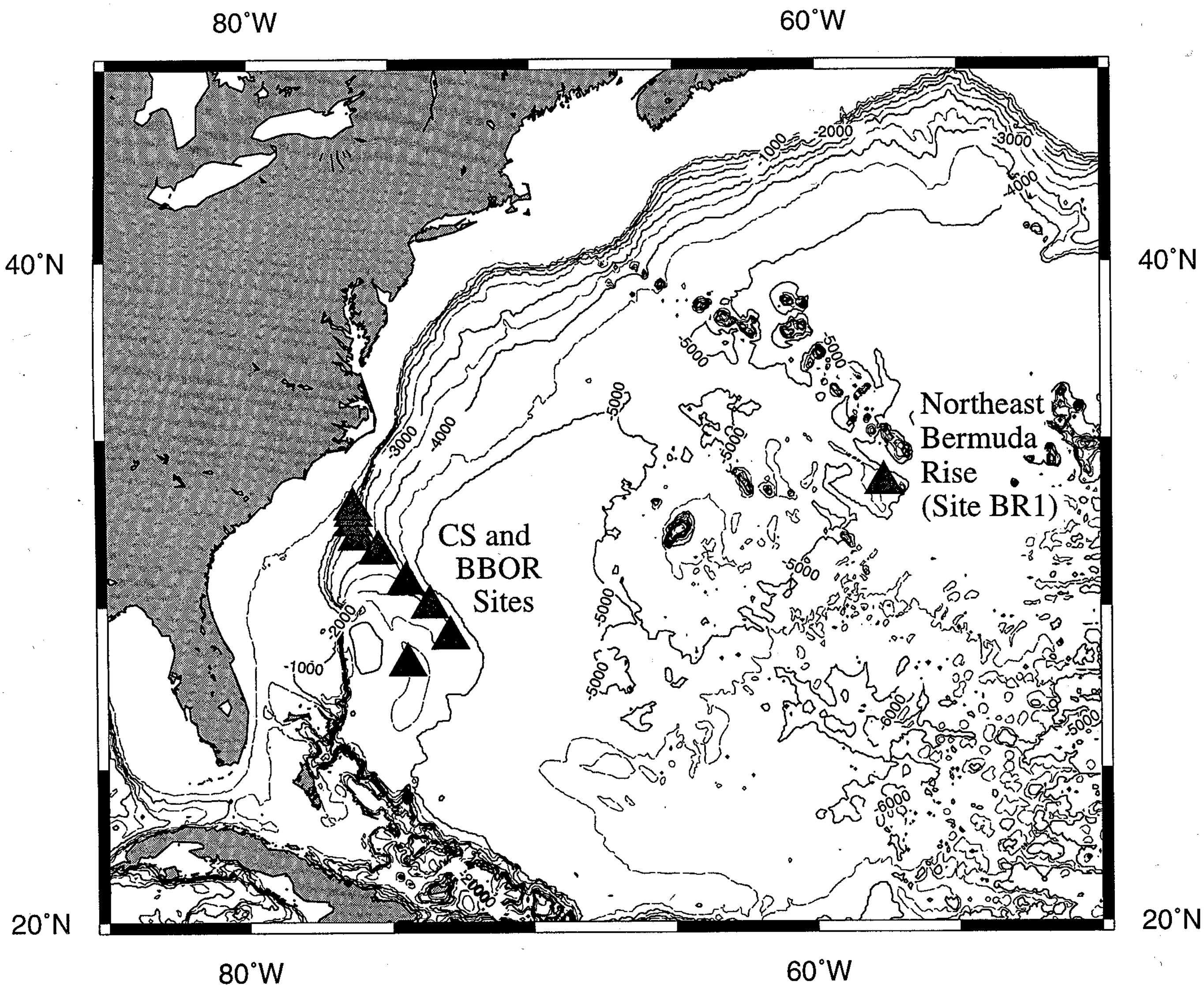


Figure 1. Map of the western North Atlantic Ocean showing the locations of proposed Leg 172 sites on the northeast Bermuda Rise (Site BR-1), the Carolina Slope (CS), and Blake-Bahama Outer Ridge (BBOR). Note: Site BR-1A (alternate to BR-1) is very near Site BR-1 and is not shown.

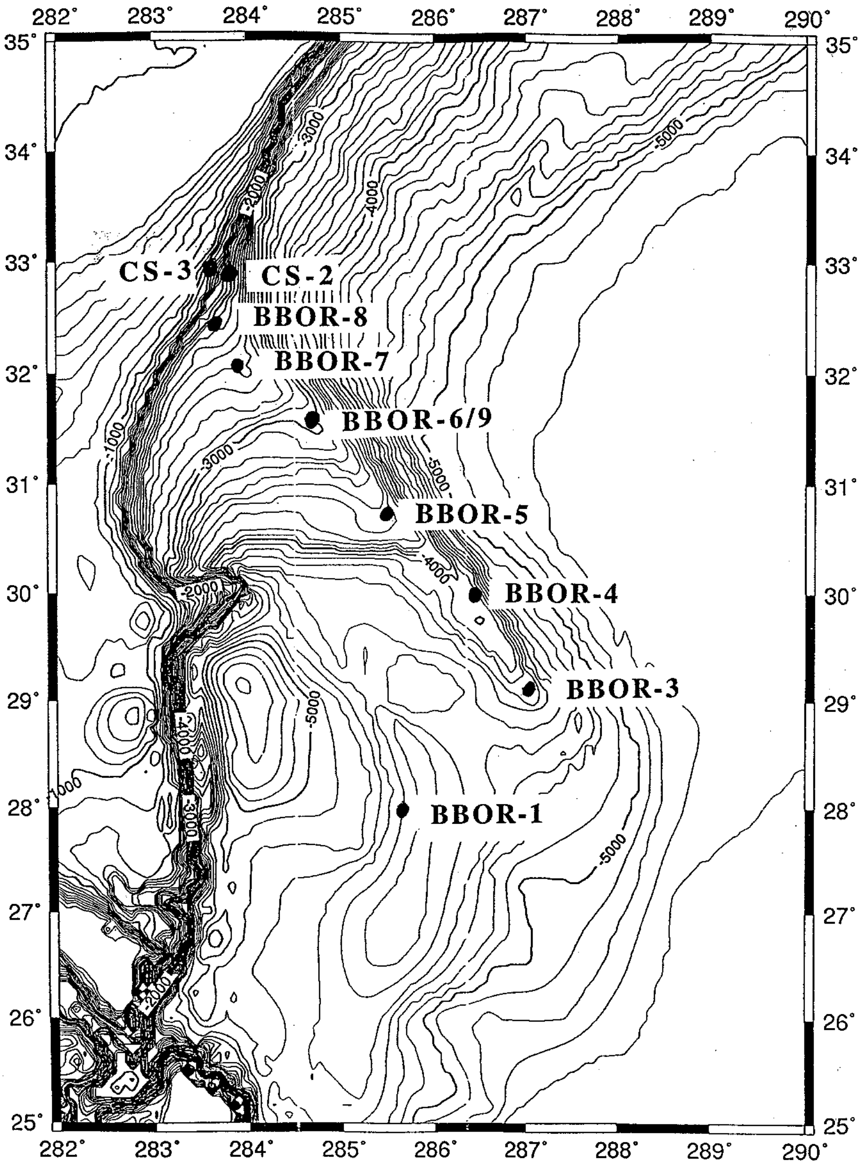


Figure 2. Map showing the location of the Carolina Slope (CS) and Blake-Bahama Outer Ridge (BBOR) sites. These sites form a depth transect from about 1200 to 4800 m water depths. Sites BBOR-6 and BBOR-9 (~2 km apart) span an abrupt change in terrigenous sediment flux, and Site BBOR-1/2 will sample across a mud wave. Note: alternate sites are not shown because they are near the primary sites.

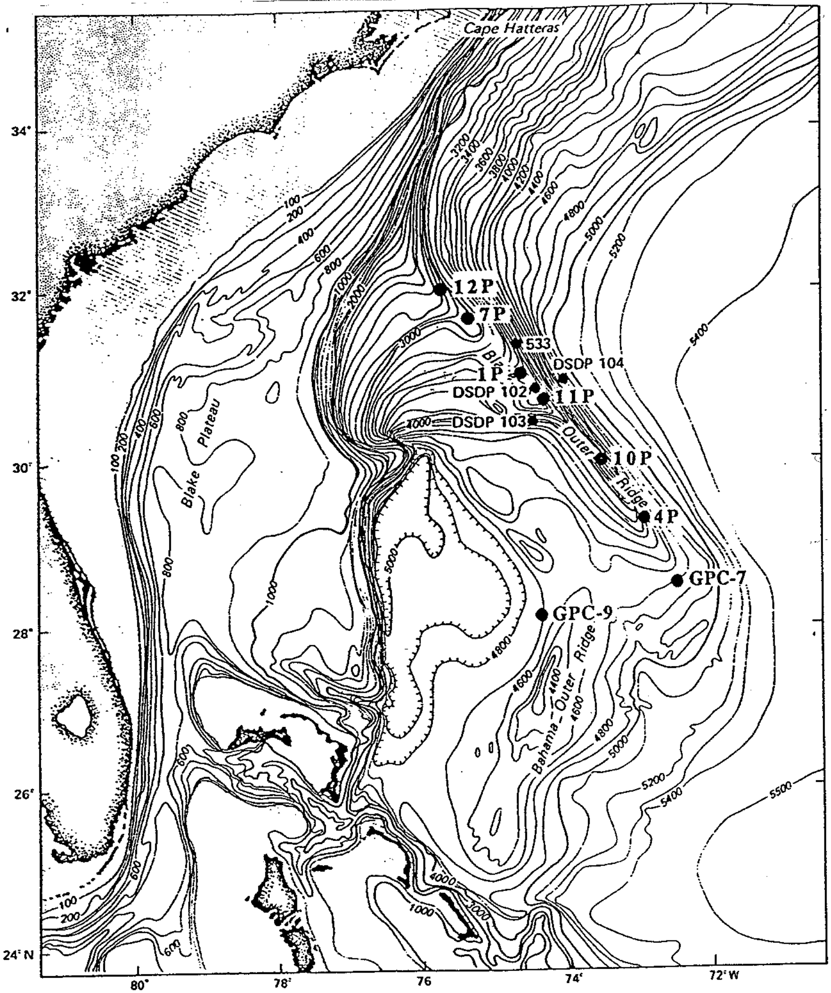


Figure 3. Piston cores (e.g., 11P) and DSDP sites in the Blake-Bahama Outer Ridge region. Description of most cores ending in "P" can be found in Johnson et al. (1988) and Haskell et al. (1991). GPCs were described by Flood (1978) and Keigwin and Jones (1989).

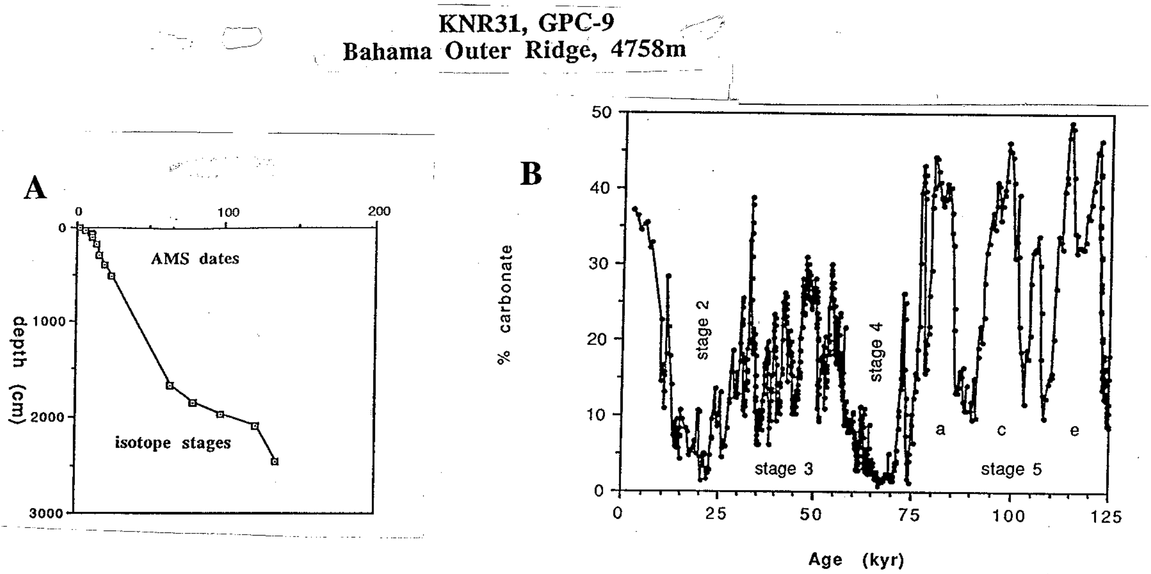
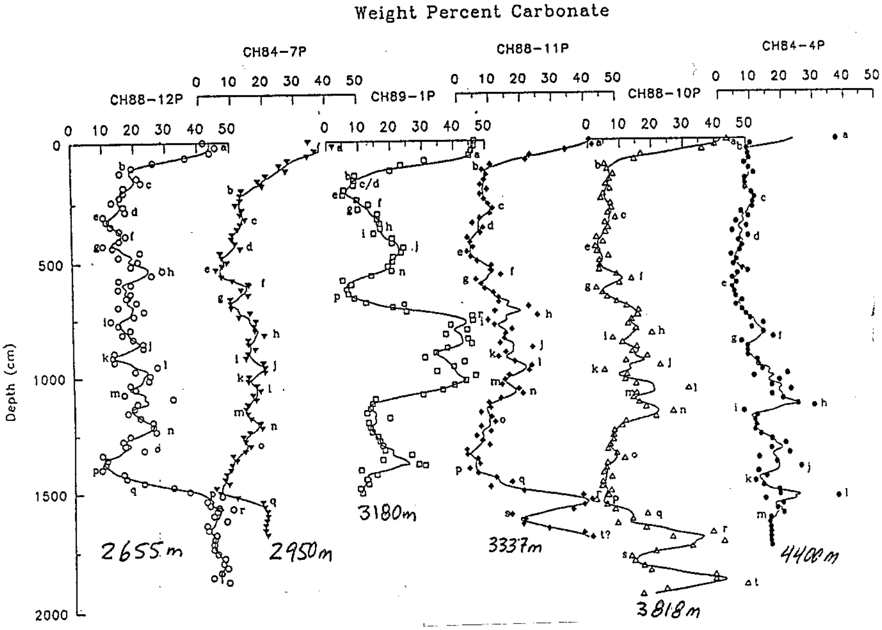


Figure 4. GPC-9 age-depth relationship (A) and percent carbonate vs. age (B).

Figure 5. Percent carbonate analyses at 20-cm spacing from six Cape Hatteras cores (Haskell, 1991).



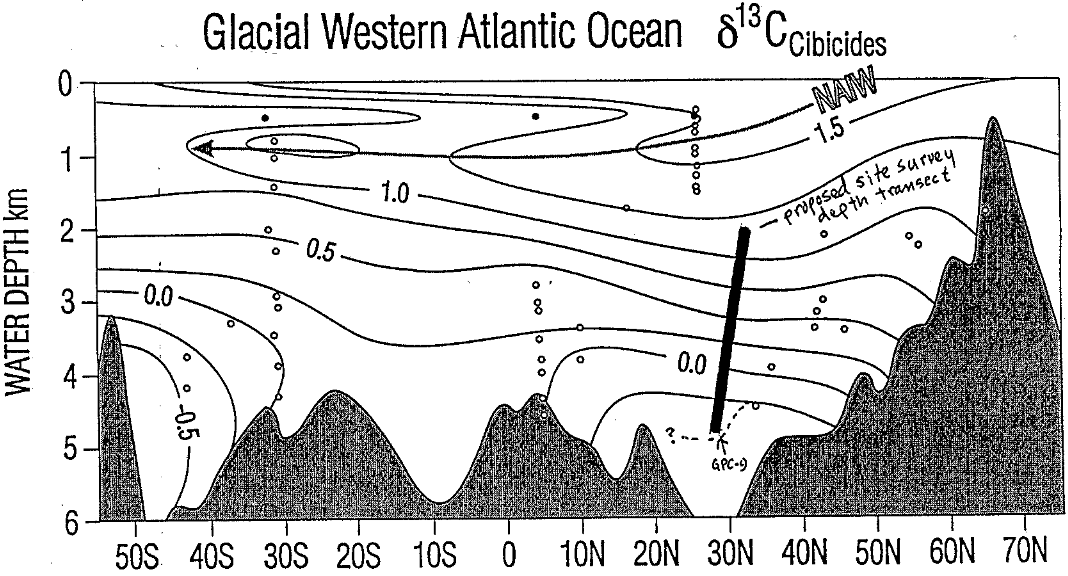


Figure 6. Reconstruction of glacial ∂13C for the western Atlantic (Lohmann et al., unpublished) showing location of proposed depth transect of cores in BBOR region. Together with nearby data from 500 to 1500 m at Little Bahama Bank (Slowey, 1990), we will have nearly complete coverage of intermediate and deep water mass distribution in the North Atlantic. Combined with transects to the south at Ceara (5°N) and Rio Grande Rises (30°S), it will be possible to monitor latitudinal changes in benthic fronts through time. Using piston cores in reconstructions such as this establishes important baseline conditions for ODP hydrographic reconstructions on longer time scales with fewer sites.

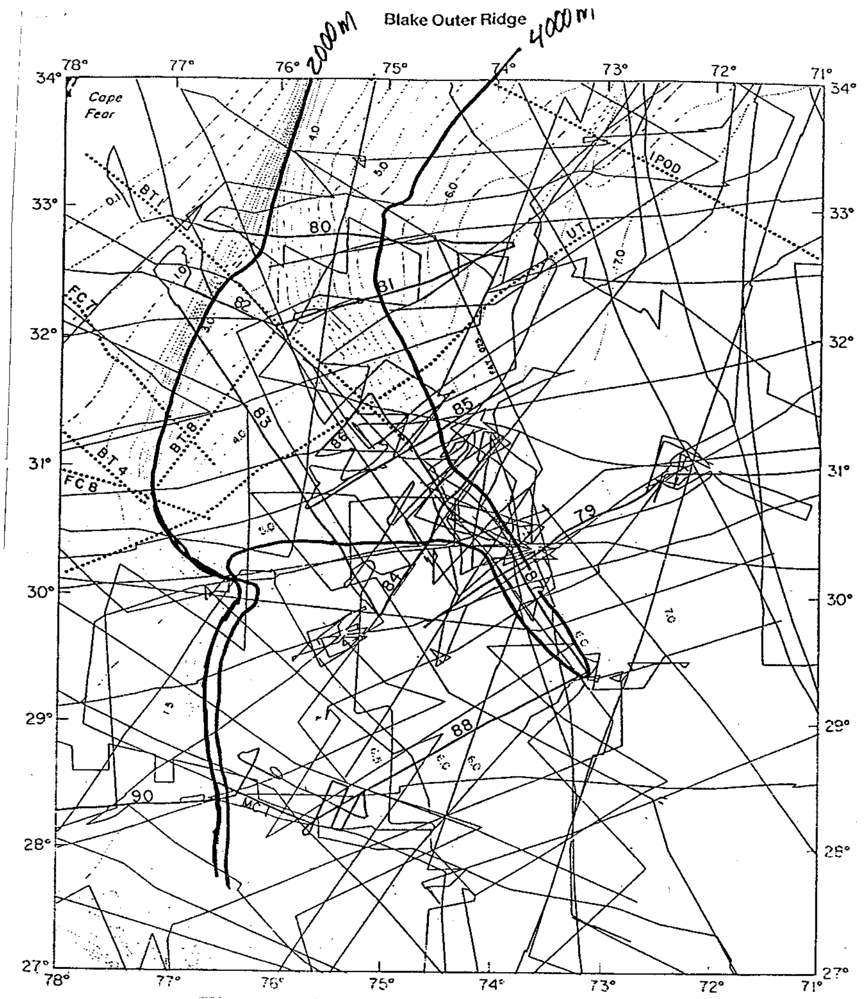


Figure 7. Coverage by single and multichannel seismic lines 79-90 at Blake-Bahama Outer Ridge (Markl and Bryan, 1983). Approximate location of 2000 and 4000 m contours is drawn for reference. USGS line BT-1 and LDGO line 87 run down the axis of the Blake Outer Ridge. BT & FC=USGS lines, UT=Univ. of Texas lines

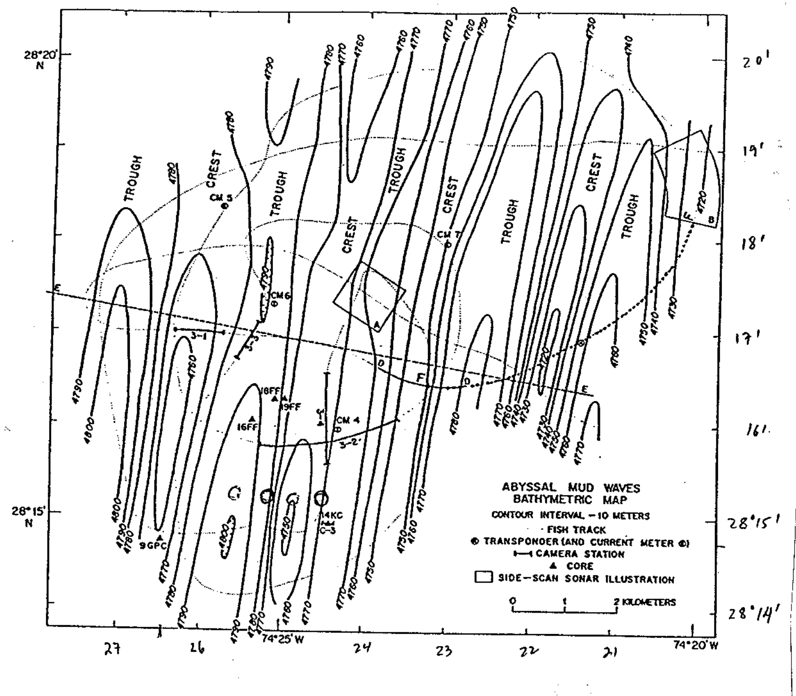


Figure 8. Map of mud wave field on northwestern flank of Bahama Outer Ridge, based on Scripps Deep tow with 4 kHz profiler, sidescan sonar, etc. (Flood, 1978). Note location of core GPC-9 in southwest corner. We will core flanks of a wave from a shallower field, to the south of this figure.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY***

SITE: BBOR-1 **PRIORITY**: **POSITION**: 28˚15'N, 74˚24.6'W
WATER DEPTH: 4715 m **SEDIMENT THICKNESS**: 1000 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE: Single channel seisimc Vema 2114; Vema 2401; 3.5kHz seismic KNR 31 and 140

Objectives: High resolution paleoclimate/paleoceanography; study of sediment wave migration & paleocurrents

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: BBOR-1A **PRIORITY**: **POSITION**: 28˚15'N, 74˚26.4'W
WATER DEPTH: 4700 m **SEDIMENT THICKNESS**: 1000 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE:

Objectives: High resolution paleoclimate/paleoceanography; study of sediment wave migration & paleocurrents

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: BBOR-1B **PRIORITY**: **POSITION**: 28˚14.4'N, 74˚24.6'W
WATER DEPTH: 4700 m **SEDIMENT THICKNESS**: 1000 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE:

Objectives: High resolution paleoclimate/paleoceanography; study of sediment wave migration & paleocurrents

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Silty clays and silty marls

***Proposed site and logging data were not finalized at time of publication

SITE: BBOR-1C **PRIORITY**: **POSITION**: 28˚14.7'N, 74˚24.6'W
WATER DEPTH: 4700 m **SEDIMENT THICKNESS**: 1000 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE:

Objectives: High resolution paleoclimate/paleoceanography; study of sediment wave migration & paleocurrents

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: BBOR-2 **REPLACED BY BBOR-1A, 1B, & 1C** **POSITION**:
WATER DEPTH: m **SEDIMENT THICKNESS**: **TOTAL PENETRATION**:
SEISMIC COVERAGE:

Objectives: REPLACED

Drilling Program: REPLACED

Logging and Downhole Operations: REPLACED

Nature of Rock Anticipated: REPLACED

SITE: BBOR-3 **PRIORITY**: **POSITION**: 29˚4.2'N, 72˚54'W
WATER DEPTH: 4250 m **SEDIMENT THICKNESS**: >300 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE: V2807, KNR140

Objectives: High resolution paleoclimate and study of sediment wave migration

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: BBOR-4 **WITHDRAWN AT PPSP** **POSITION**:
WATER DEPTH: **SEDIMENT THICKNESS**: **TOTAL PENETRATION**:
SEISMIC COVERAGE:

Objectives: WITHDRAWN

Drilling Program: WITHDRAWN

Logging and Downhole Operations: WITHDRAWN

Nature of Rock Anticipated: WITHDRAWN

SITE: BBOR-4A **PRIORITY**: **POSITION**: 28°58.8'N, 73°34.8'W
WATER DEPTH: 3975 m **SEDIMENT THICKNESS**: - m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE:

Objectives: High resolution paleoclimate; Pliocene objectives

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: BBOR-5 **PRIORITY**: **POSITION**: 30°43.8'N, 74°28.2'W
WATER DEPTH: 3430 m **SEDIMENT THICKNESS**: >300 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE: V2807, C2102, KNR140

Objectives: High resolution paleoclimate

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Foram, nanno marls, or silty clays and marls

SITE: BBOR-6 **PRIORITY**: **POSITION**: 31˚40.2'N, 75˚25.2'W
WATER DEPTH: 2975 m **SEDIMENT THICKNESS**: >1000 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE: CH1292 line 16, KNR140

Objectives: High resolution paleoclimate and study of current controlled deposits

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Foram, nanno marls, or silty clays and marls

SITE: BBOR-7A **PRIORITY**: **POSITION**: 32˚4.8'N, 76˚10.2'W
WATER DEPTH: 2585 m **SEDIMENT THICKNESS**: >1000 m **TOTAL PENETRATION**: 100 m
SEISMIC COVERAGE: Farnella 17, 18; KNR140

Objectives: High resolution paleoclimate

Drilling Program: APC/XCB

Logging and Downhole Operations: None***

Nature of Rock Anticipated: Foram, nanno marls

SITE: BBOR-8B **PRIORITY**: **POSITION**: 32˚28.8'N, 76˚20.4'W
WATER DEPTH: 2164 m **SEDIMENT THICKNESS**: >150 m **TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE:

Objectives: High resolution paleoclimate and study of continental slope processes

Drilling Program: APC/XCB

Logging and Downhole Operations: None***

Nature of Rock Anticipated: Foram, nanno marls

SITE: BBOR-9 **PRIORITY**: **POSITION**: 31˚41.4'N, 75˚25.8'W
WATER DEPTH: 2975 m **SEDIMENT THICKNESS**: >1000 m **TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE: CH1292-16, KNR140

Objectives: High resolution paleoclimate and study of current controlled deposits

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, and FMS logs***

Nature of Rock Anticipated: Foram, nanno marls, or silty clays and silty marls

SITE: BR-1 **PRIORITY**: **POSITION**: 33˚41.4'N, 57˚37.2'W
WATER DEPTH: 4500 m **SEDIMENT THICKNESS**: >1000 m **TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: KNR31, IFP line BER 1

Objectives: High resolution paleoclimate and study of underconsolidation; Pliocene reference section

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, FMS, and dipole sonic logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: BR-1A **PRIORITY**: **POSITION**: 33˚41.4'N, 57˚38.4'W
WATER DEPTH: 4469 m **SEDIMENT THICKNESS**: >1000 m **TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE:

Objectives: High resolution paleoclimate and study of underconsolidation; Pliocene reference section

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, geochemical, GHMT, FMS, and dipole sonic logs***

Nature of Rock Anticipated: Silty clays and silty marls

SITE: CS-2 **PRIORITY**: **POSITION**: 32˚46.8'N, 76˚17.4'W
WATER DEPTH: 1790 m **SEDIMENT THICKNESS**: >300 m **TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: CH0692-41; Farnella 8, 16; CH9115-8, 9; CH0790; KNR140

Objectives: High resolution paleoclimate and study of continental slope processes

Drilling Program: APC/XCB

Logging and Downhole Operations: No logging planned at this time***

Nature of Rock Anticipated: Foram, nanno marls

SITE: CS-3B **PRIORITY**: **POSITION**: 33˚00'N, 76˚16.2'W
WATER DEPTH: 1292 m **SEDIMENT THICKNESS**: >300 m **TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: Farnella 7, CH0692-43; KNR140

Objectives: High resolution paleoclimate and study of continental slope processes.

Drilling Program: APC/XCB

Logging and Downhole Operations: No logging planned at this time***

Nature of Rock Anticipated: Foram, nanno marls

LEG 173

RETURN TO IBERIA

Rift-to-Drift Processes Within the Ocean-Continent Transition West of Iberia

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Modified from Manuscript by Bob Whitmarsh Based on Proposal 461

Submitted By

T.J. Reston, M-O Beslier, G. Boillot, D.S. Sawyer, and R.B. Whitmarsh

Staff Scientist: Paul Wallace **Co-Chief Scientists:** **Marie-Odile Beslier**
R.B. Whitmarsh

ABSTRACT

The Galicia Bank and Iberia Abyssal Plain segments of this margin were drilled during ODP Legs 103 and 149 and have been extensively studied geophysically. Leg 149 determined landward and oceanward limits to the ocean-continent transition (OCT) off western Iberia by drilling an east-west transect of holes. However, only one of these holes penetrated basement in a region that is probably typical of the OCT, at the latitude of the southern Iberia Abyssal Plain. This site, Site 900, cored 56 m of fine- to coarse-grained gabbro that experienced synrift dynamic crystallization under granulite facies conditions at 136.4±0.3 Ma, according to $^{40}Ar/^{39}Ar$ dating. Geophysical data clearly show that the OCT has magnetic and seismic velocity properties that are in some sense transitional between continental and oceanic crust. Multichannel seismic reflection profiles, one of which has been recently reprocessed, strongly indicate that, although the eastern (landward) part of the OCT is dissected by deep-cutting normal faults and low-angle detachments these die out westward (oceanward) into a region of smoother basement that lacks significant intrabasement reflectors and is of uncertain origin. A sequel to Leg 149, Leg 173 will drill a small number of holes to basement on basement highs, mainly within the ocean-continent transition (OCT), to characterize the OCT, to test the simple-shear lithospheric extension hypothesis for the lower-plate (?) margin, to determine the extent of synrift magmatism, and to determine the existence and nature of the first-formed oceanic crust.

INTRODUCTION

Ocean Drilling Program (ODP) Leg 149 defined landward and oceanward limits to the ocean-continent transition (OCT) in the Iberia Abyssal Plain; however, only one hole penetrated basement in a region probably typical of such a transition. Leg 173 (Fig. 1) is a sequel to Leg 149, and it will enable (1) drilling of a well-imaged major detachment fault (an analogue to the S-reflector), (2) recovery of more rift-related igneous material (e.g., gabbro) and its host rock (continental or slow spreading crust?), (3) testing of the nature of the high between the rift-gabbros and the most landward known serpentinite complex (detached continental outlier, a volcanic mound, or serpentinite?), and finally (4) sampling the oldest oceanic crust that seems to have a continuous volcanic cover ("normal" crust). These kinds of observations, together with the improved quality and quantity of seismic images, will allow us to address the timing and nature of melt generation from the mantle during breakup and to determine the earliest generation of "normal" oceanic crust. The planned drilling will also add to our knowledge of the early sedimentary history of the rifted margin.

BACKGROUND

Rifted margins contain the principal record of the break up that follows continental rifting and the onset of seafloor spreading, both of which are first-order plate tectonic processes. Such margins exhibit a wide spectrum of characteristics, far greater than the characteristics observed in continental rifts, probably in response to different combinations of asthenospheric temperature, lithospheric rheology, strain rate, and stress. The rifting process, through the indirect effects of concurrent subaerial volcanism as well as greater sedimentation and heat flow, can also have important environmental and resource implications. Drilling commonly affords the only means of directly characterizing the nature, age, and emplacement conditions of igneous, metamorphic, and/or sedimentary rocks formed, deposited, or tectonically exposed during margin formation.

Nonvolcanic margins in particular provide opportunities to investigate and understand the tectonic aspects of rifting for two reasons. First, faults that penetrate deep into the crust and uppermost mantle are often evident on seismic profiles and, as was demonstrated by Leg 149, allow rocks from deeper lithospheric levels to be exposed at the top of acoustic basement. Second, voluminous intrusives/extrusives, which can obscure crustal tectonics, are limited and commonly appear to be absent. Conjugate rifted margins often exhibit some asymmetry in structural style. This asymmetry may be related to the mode of lithospheric rifting, e.g., pure or simple shear, or simply to the location of the original break in the continental crust. The west Iberia margin is an excellent example of a nonvolcanic rifted margin. The Galicia Bank and Iberia Abyssal Plain segments of the margin were cored during ODP Legs 103 and 149, and have been studied extensively by geophysical methods.

Iberia separated from the Newfoundland margin of the Grand Banks in the Early Cretaceous after prolonged rifting that began in the late Triassic and is well documented on both sides of the Atlantic (Wilson et al., 1989; Welsink et al., 1989). The subsequent plate tectonic and seafloor-spreading history of this part of the North Atlantic is well constrained by seafloor-spreading magnetic anomalies and demonstrates that Iberia drifted away from North America along roughly E-W fracture zones (e.g., Klitgord and Schouten, 1986).

During the short-lived Late Cretaceous opening of the Bay of Biscay a ridge-ridge-ridge triple-point existed off NW Spain (Sibuet and Collette, 1991). However, throughout its post-rift history the west Iberia margin has remained an essentially undisturbed rifted margin that has experienced only minor compression in the north in Eocene time (Pyrenean phase, short-lived subduction of Bay of Biscay crust under northern Spain) and in the south and center in the middle Miocene (Rif-Betic phase, gentle folding of abyssal plain sediments).

Offshore, the west Iberia continental margin has been studied extensively by geophysical techniques and to a lesser extent by geological sampling (e.g., Beslier et al., 1993; Boillot et al., 1987, 1988; Hoffman and Reston, 1992; Sawyer et al., 1994; Whitmarsh et al., 1990, 1993; Whitmarsh and Miles, 1995; Whitmarsh et al., in press). It exhibits tilted continental fault blocks and an apparent lack of synrift volcanism, which are characteristic of a nonvolcanic rifted margin. Significant syn-rift volcanism is equally absent on shore.

The first drilling of the OCT off the west Iberia margin was carried out by ODP Leg 103 in 1985 (Boillot, Winterer, Meyer, et al., 1987); this leg drilled a short transect of holes west of

Galicia Bank (Sites 637-641, Fig. 1). In 1991 the recommendations of the North Atlantic Rifted Margin Detailed Planning Group were accepted by JOIDES Planning Committee, which programmed two drilling legs in the North Atlantic during 1993. One of these, Leg 149, drilled a transect of holes into acoustic basement across the ocean-continent transition in the southern Iberia Abyssal Plain (Sawyer, Whitmarsh, Klaus, et al., 1994; Whitmarsh, Sawyer, Klaus, and Masson, in press; Sites 897-901, Fig. 1).

Results of Leg 149

Leg 149 drilled a west-to-east transect of five sites. Three sites (Sites 897, 899, and 900) reached acoustic basement (Figs. 1 and 2). A fourth site (Site 901) enabled a firm prediction to be made that the underlying basement is continental crust. The sites were chosen in the context of a conceptual model of the location of the OCT previously defined by gravity, magnetic, and seismic velocity modelling and by seismic reflection profiles. The results obtained during the leg broadly confirmed this model but also produced some surprises.

The results of Leg 149 proved the existence of a peridotite ridge at the inferred landward edge of the oceanic crust formed by seafloor spreading. They also showed that between this ridge and Site 901, which is situated on a fault block of almost unequivocal continental crust, there exists a 130-km-wide region that is probably underlain mostly by a heterogeneous transitional crust. One indication of the transitional nature of this crust may be the MORB-like gabbro at Site 900. Other indications are the transitional to alkaline mafic clasts in mass-wasting deposits at Sites 897 and 899. The magnetic and seismic reflection character and velocity structure of the crust provide additional evidence. Whether the Site 900 gabbro formed by pre- or synrift metamorphism, the original granulite metamorphic grade and the ^{40}Ar/^{39}Ar age of the cores imply that the gabbro was exhumed by important synrift faulting that accompanied lithospheric extension. Although Site 899 sampled a serpentinite breccia and an underlying serpentinized peridotite mass-flow deposit, magnetic evidence suggests that the basement of this site may be atypical of the rest of the Iberia Abyssal Plain OCT, and it may not be correct to infer continuity of peridotite basement between Sites 897 and 899. Leg 149 succeeded in defining the western boundary of the OCT precisely, and it also limited the eastern boundary without providing more than a single site that sampled the basement itself at a typical location within the transitional zone. Models that explain these observations are presented below. To test these models, drilling is planned to focus on the nature of the basement itself within this zone and on the possible detachment faults identified there.

Review of the Galicia Bank and Iberia Abyssal Plain Transects

The transects of Legs 103 and 149 and their associated research contributed to a number of aspects of the rifted west Iberia margin. These are lithospheric detachment faults, block faulting of the crust, the emplacement and exposure of mantle rocks, synrift magmatism, and the characterization of the OCT. The two margin segments, about 200 km apart, exhibit both similarities and differences. The Galicia Bank margin has a narrow OCT (~30 km), an unusually clear subhorizontal detachment fault (the S reflector), clear crustal fault blocks and extensive margin-parallel peridotite outcrops (possibly accentuated by post-rift uplift), and possible synrift magmatism (Schärer et al., 1995). The southern Iberia Abyssal Plain (IAP) margin has an unusually wide OCT (up to 130 km), clear crustal block faults, peridotite basement (exposed both along a narrow ridge and on an isolated high) and, at present, tentative evidence of syn-rift magmatism. Here too, there is apparently no obvious deep and extensive sub-horizontal detachment like S, although a possible detachment, dissected by higher-angle normal faulting, has been recognized. The results of Leg 149 have highlighted the need for more basement drilling, principally within the OCT, in order to understand the rift-to-drift tectonic and magmatic processes at this excellent example of a non-volcanic rifted margin. Further, independent geophysical work since Leg 149 has led to revised tectonic and magmatic models for the rifting and initial seafloor spreading at this margin (Whitmarsh and Miles, 1995; Krawczyk et al., in press; Whitmarsh and Sawyer, in press), which can now be tested by further drilling to basement.

Problems that need further investigation and can be resolved by drilling along the southern IAP transect include:

- Characterization of the OCT (the petrology, original level in the lithosphere, and age of the basement rocks). Is there unequivocal continental crust? What is the extent, if any, of a region of serpentinized peridotite within the OCT?

- Characterization of a low-angle detachment fault by drilling through the fault zone

- Testing of pure-shear and simple-shear lithospheric extension models

- Determining the nature, extent and depth of emplacement of synrift magmatism

- Determining the nature of the early-formed oceanic crust

Southern Iberia Abyssal Plain OCT Models

A series of preliminary tectonic and magmatic models for lithospheric rifting of the west Iberia margin has been produced (Whitmarsh and Miles, 1995; Krawcyzk et al., in press; Whitmarsh and Sawyer, in press), based on (1) earlier geophysical observations, (2) the Leg 149 results, (3) an interpretation of a new magnetic anomaly chart (Fig. 3) and (4) the latest time-migrated seismic reflection profiles in the southern Iberia Abyssal Plain (only one is included, Fig. 4). The models differ in the relative importance attributed to the nature of the basement cores, with respect to the geophysical observations, in the significance attributed to the peridotite ridge, and in whether the east-west distribution of different basement rocks within the OCT is considered to be systematic or just random. Such variety of approaches was valid after Leg 149 because of the small number of drill sites that reached basement.

The above data provide evidence both for emplacement of gabbro in the transition zone, possibly immediately prior to break up, and for detachment tectonics west of Site 901, at least as far as Site 900. An integrated, relatively detailed model incorporating all available data is shown in Figure 5. Here, extension at crustal levels was originally controlled by simple-shear detachment faulting, which may have exhumed lower crust at Site 900 and even peridotite to the west in the broad northwest-southeast basement low east of Site 898. Lithospheric extension at depth, possibly by a pure-shear necking mechanism, and accompanying asthenospheric upwelling led to adiabatic decompression melting and intrusion of the lower crust. Intrusion may have occurred both during detachment faulting and during the subsequent block-faulting (in which the fault geometry was probably controlled by pre-existing fabric landward of about Site 901), which led to final break up. The model predicts the occurrence of a detachment fault, dissected by subsequent block faults, the exposure of progressively deeper lithospheric levels to the west of Site 901 and synrift intrusion into the lower crust or uppermost mantle west of Site 901. Additional drilling during this leg will determine if the model in Figure 5 is correct by testing the detachment hypothesis, by investigating the nature of the basement in the transition zone, and by seeking evidence of synrift magmatism.

SCIENTIFIC OBJECTIVES

As outlined above, Leg 149 largely succeeded in determining the oceanward and landward bounds of the OCT in the southern Iberia Abyssal Plain. The principal problem now is to investigate the nature of the basement within the OCT itself to determine its intrinsic relevance to the general problem of rift-to-drift processes and to test aspects of our best models for these tectonic and igneous processes at the west Iberia nonvolcanic margin. Leg 173 will attempt to achieve the following objectives:

- Sample acoustic basement, principally within the OCT, to characterize the tectonic and magmatic processes that dominate the transition from continental to oceanic crust in space and time (see Sites 901, Iberia-7A, Iberia-8A/8B, Iberia-9A/9B, Iberia-10A).

- Determine the role of detachment tectonics in the evolution of the margin. This will be done by drilling through a detachment on the east side of the high on which Site 900 has already been drilled. This new site (two alternative sites, Iberia-9A/9B have been proposed) will also enable determination of the sense of motion on the fault and assessment of the lateral extent of the Site 900 mafic rocks. Another site (Iberia-7A) will be drilled on the westernmost basement high associated with a westward-dipping normal fault, to test the prediction that simple-shear detachment faulting of the upper lithosphere exposed low-level continental crust (or even uppermost mantle) at this point on the lower plate.

- Determine the role and extent of synrift magmatism in the OCT crust, which is inferred to exist from the new magnetic anomaly chart and other data. Use isotope data to determine petrogenetic origin and dates of original crystallization and subsequent metamorphism of igneous rocks (see Sites 901, Iberia-7A, Iberia-8A/8B, Iberia-9A/9B).

- Sample acoustic basement beneath Site 901 or Site Iberia-8A/8B to confirm predictions of the existence of continental crust there and to determine the approximate level it came from in the crust, thereby setting an unequivocal landward limit to the OCT (see Sites 901, Iberia-8A/8B).

- Sample the early-formed oceanic crust, as this remains unsampled over the whole west Iberia margin. Its presence is inferred only by geophysical observations. Samples from this site are expected to provide definitive evidence of the oceanic nature of the crust immediately (20 km) west of the peridotite ridge and may enable the seafloor-spreading model to be verified. They will also yield the, possibly unusual, chemistry of the thin crust formed by the earliest magma-starved seafloor spreading and provide valuable petrological information about initial melt production (c.f. Site 900 gabbro) following continental break up at a nonvolcanic margin (see Site Iberia-10A).

DRILLING STRATEGY

There will be time on Leg 173 to drill no more than three sites. The first priority sites are Iberia-7A (to test the simple-shear-extension model for the upper lithosphere); Iberia-9A **or** -9B (to test the simple-shear-extension model and assess the lateral extent of the possibly synrift gabbro basement rocks sampled at Site 900); and Sites 901 **or** Iberia-8A (to confirm the continental nature of the basement, and its approximate original level in the crust, to thereby limit the landward edge of the OCT).

LOGGING PLAN

Leg 173 proposes to (1) drill a small number of holes to basement in order to characterize the OCT and a low-angle detachment fault, (2) test the pure and simple shear lithospheric extension models, (3) determine the extent of synrift magmatism and the nature of the earliest oceanic crust, and (4) investigate the mechanisms of mantle unroofing (related to the presence of a peridotite ridge).

The tectonic and petrologic objectives of this rifted-margin study should particularly benefit from logging data. We recommend that standard geophysical, geochemical, and Formation MicroScanner (FMS) logs be run on each hole. Downhole measurements will contribute to (1) acoustic characterization of penetrated structures, (2) site-to-site comparison of chemical signature in basement rocks within the OCT, and (3) detailed description of tectonic features. Standard geophysical and geochemical logs should be run in each of the proposed holes to meet the first two objectives. While the recording of physical properties data is essential to core-log integration studies, electric images allow a clear identification and centimeter-scale description of the succession of basement units. The FMS electrical images will give the necessary high resolution for accurate description of tectonic features, in terms of lithologic boundaries, bedding attitude (dip and strike), presence of fractures and faults and their spatial orientation, and degree of alteration of basement features. In summary, geochemical and geophysical logs and FMS high-resolution electrical images should be acquired in all holes.

PROPOSED SITES AND SITE PRIORITIES

Site Iberia-7A

The seismic crossing line confirms the N-S trend of the basement high on which the site is situated. Further processing will probably be required to image the possible detachment fault below the high seen on adjacent profile LG-12. No shift in the site is suggested on the basis of the new data.

Site Iberia-8A

The N-S crossing of this site plus a further E-W crossing of the broad high on which it lies reveal that the high has a trend somewhat west of north and shoals quite rapidly northward; the high could conceivably represent the southward continuation of the Vasco da Gama Seamount below the Iberia Abyssal Plain. There is a strong suggestion of tilted reflectors (pre-rift sediments?) on the east side of the high and of a diffractive ‘ledge’ on the west side (at CDP 3100) which may represent the top of the basement that underlies the prerift sediment. This reinforces the view that the site has features that make it an attractive alternative to re-drilling Site 901, also situated on a tilted fault block. The shallower basement on the E-W profile might, with further processing, suggest a better location more easily reached with the drill (possible new site here called Iberia-8B).

Sites Iberia-9A and Iberia-9B

The N-S seismic data crossing of Site Iberia-9B confirms the weak N-S trend of the basement high. The profile does not image the east-dipping detachment fault underlying the site that is visible on a prestack depth migrated profile; the new profile will require further processing. No shift in the site is suggested on the basis of the new data.

The following priorities have been assigned to the sites.

Priority 1. Site Iberia-7A, the most oceanward site within the OCT, will sample basement on a topographic high, which is apparently bounded to the west by a major normal fault. This will test the simple-shear extension model for the upper lithosphere and may even reveal an upper mantle exposure.

Sites Iberia-9A/9B (either 9A or 9B, but not both, will be drilled) will transect a crustal detachment fault, and thereby test the simple-shear lithospheric extension model, and assess the lateral extent of the possibly synrift gabbro basement rocks sampled at Site 900.

Site 901 or Site Iberia-8A/8B (one site only) will be drilled to confirm the continental nature of the basement, and its approximate original level in the crust, to thereby limit the landward edge of the OCT. Final choice of site will depend on results of further seismic processing and estimated drill times. All the above sites will potentially provide evidence to assess the contribution and lateral extent of synrift magmatism.

Priority 2. Site Iberia-10A will be drilled to demonstrate the existence, age, and chemical nature of the early-formed oceanic crust 20 km oceanward of the peridotite ridge.

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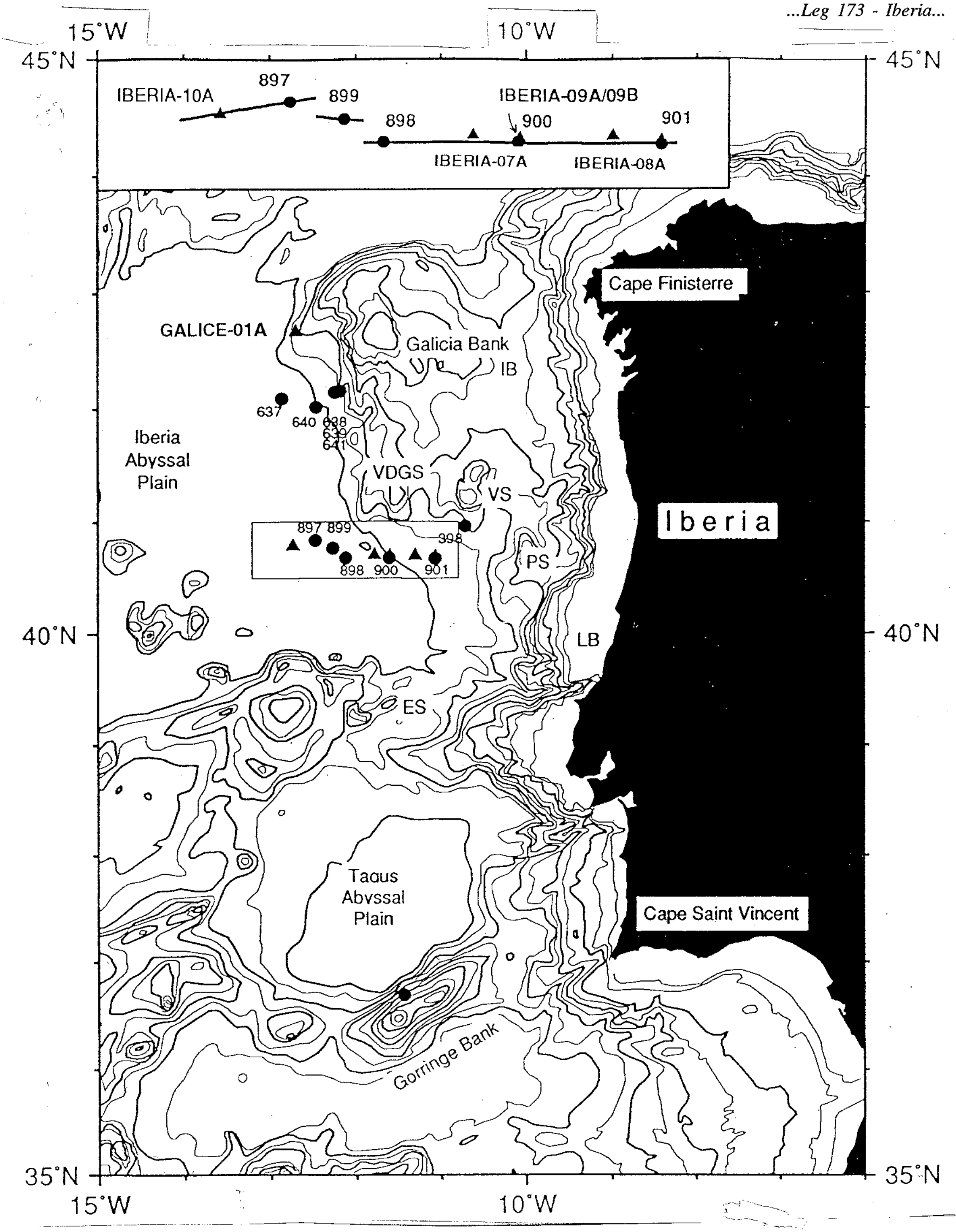

Figure 1. Bathymetric chart of the west Iberia margin; contours at 200, 500, 1000 m etc. Existing DSDP/ODP sites are shown by black dots. Sites proposed here are shown by black triangles. Inset is expanded plot of the boxed area at 40°40'N showing old (circles) and proposed (triangles) drill sites and tracks of seismic reflection profiles used to create the composite cross-section in Fig. 2.

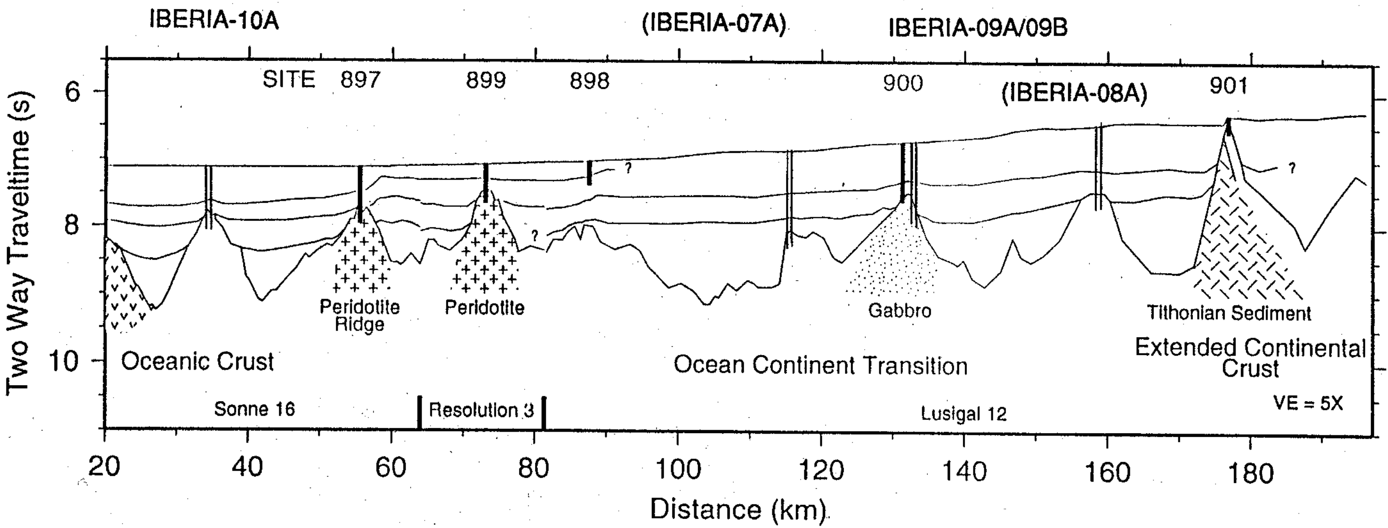

Figure 2. Composite seismic time section created from the track segments of, from west to east, the Sonne, JOIDES Resolution and Lusigal profiles shown in Fig. 1. The irregular surface is the top of the acoustic basement. Basement was sampled at Sites 897, 899, and 900 during Leg 149. The nature of basement (oceanic, transitional, extended continental) is indicated; at Site 901 it is inferred. Proposed Sites Iberia 7A, Iberia 8A/8B, Iberia 9A/9B and Iberia 10A are also indicated. Iberia 7A lies slightly to the north of this profile.

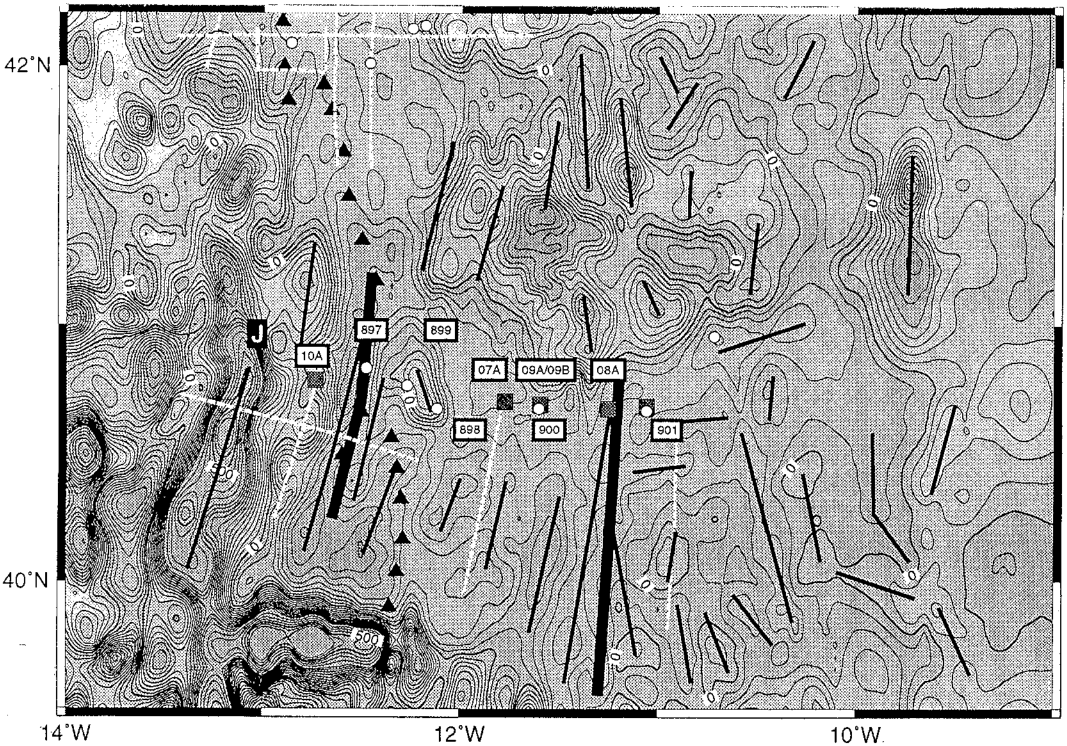

Figure 3. Part of a new reduced-to-the-pole magnetic anomaly chart of the whole west Iberia margin produced in collaboration with the Atlantic Geoscience Centre, Dartmouth, Nova Scotia, Canada (Miles et al., in press). The chart was made from a 5-km gridded data set and is contoured at 25 nT. The main chart is based on over 400,000 sea-surface observations which were corrected to remove the effects of secular variation, high geomagnetic activity, spurious tracks, and systematic cross-over errors. Greater confidence in the quality of the resulting data set allowed the use of the small contour interval. ODP Leg 149 drilled to basement in this area (white dots); proposed sites are shown by squares. The data were reduced to the pole to clarify many features. Major linear trends in the anomalies are picked out by bold lines. The chart clearly shows the strong positive J anomaly which appears just west of 13°W and south of 41°30´N. Between anomaly J and the continental shelf (~9°15´W) other less strong positive anomalies are associated with the shallow region south of Galicia Bank. South of ~41°N the chart can be divided into three distinct zones (bounded by the two broad N-S black bands) based on the character of the anomalies.

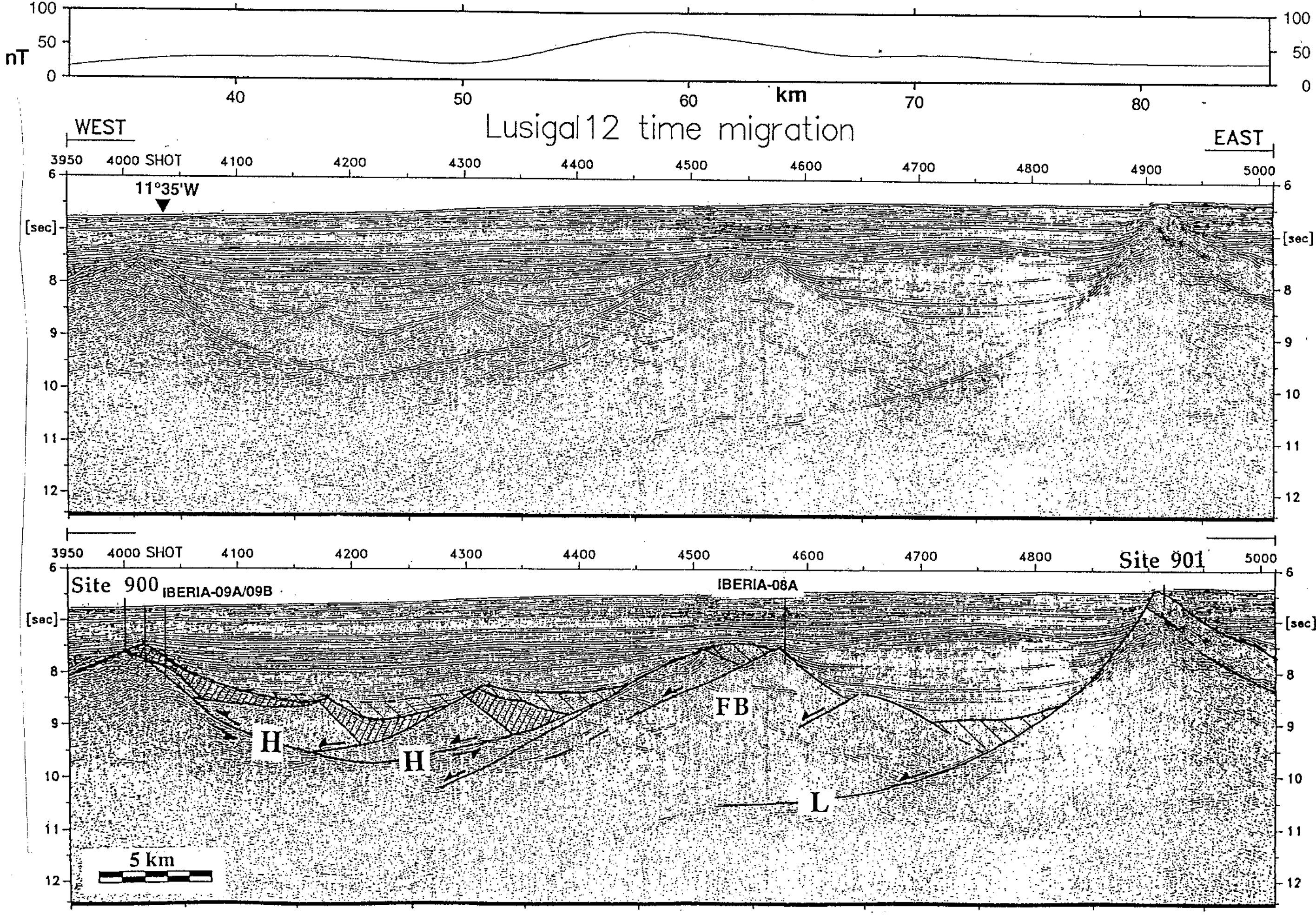

Figure 4. East-west migrated multichannel seismic reflection profile Lusigal-12 through Sites Iberia 8A, Iberia 9A/9B, 900, and 901 (Fig. 1). The lower profile is an interpretation of basement reflections seen in the upper profile. Syn-rift I sediments are marked by close diagonal ruling; syn-rift II sediments are marked by coarser ruling. H is a detachment fault controlling extension during syn-rift I phase; L is a listric fault active during syn-rift II phase. Pre-rift units are probably present in fault block FB, but are not identified. The magnetic anomaly profile (top) was computed from the data set used to produce the magnetic anomaly chart in Fig. 3.

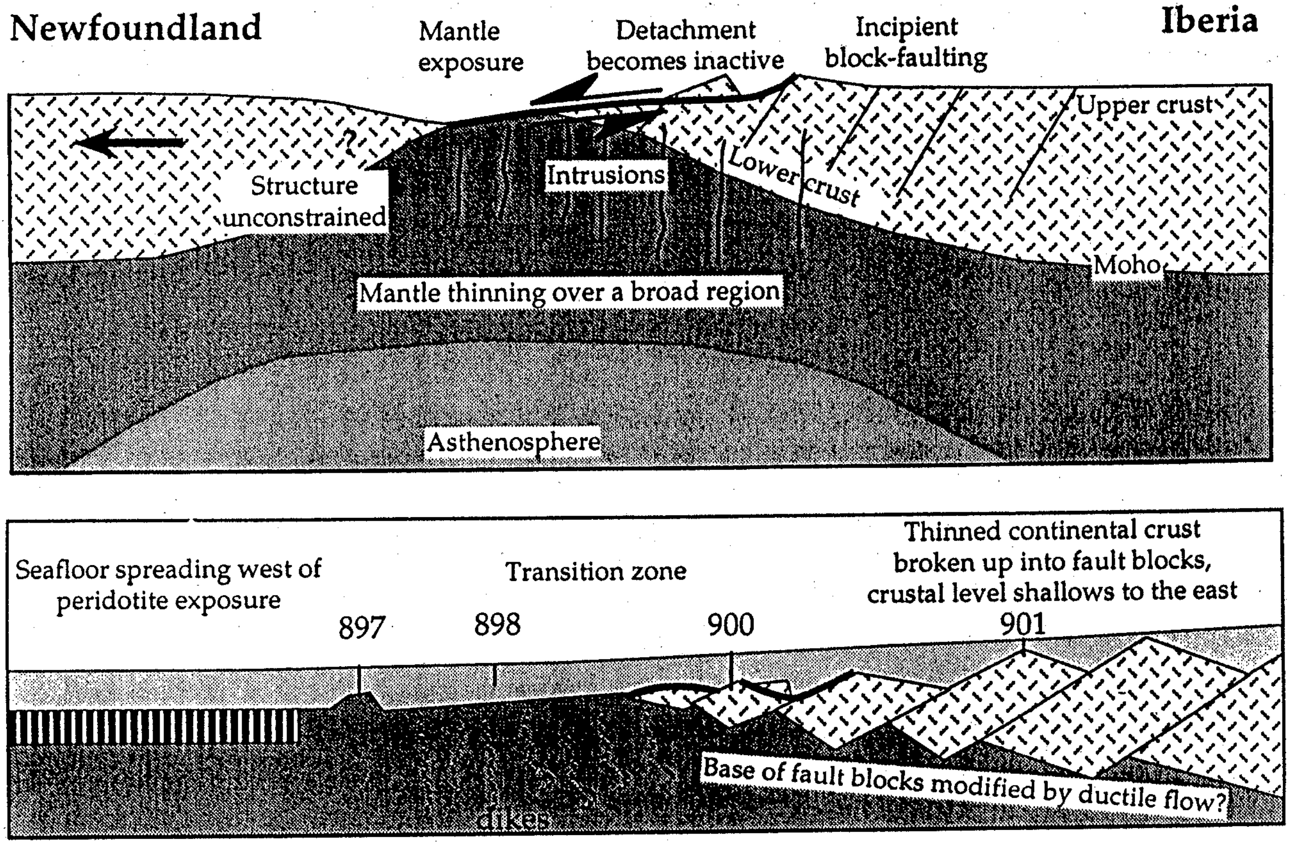

Figure 5. Cartoon incorporating available drill core and geophysical evidence into a single integrated model for the evolution of the Iberia Abyssal Plain margin. As high level extension was accommodated along a detachment fault, upwelling of asthenosphere in response to "pure-shear" extension at depth caused melting and intrusion of lower crust in the transition zone. Intrusion probably continued during subsequent block-faulting which dissected the lower plate to the detachment fault. Drilling during Leg 174A will test this model by investigating the nature of crust in the transition zone and testing the detachment hypothesis.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: Iberia-7A	**PRIORITY**: 1	**POSITION**: 40°42'N, 11°48'W
WATER DEPTH: 5150 m	**SEDIMENT THICKNESS**: 920 m	**TOTAL PENETRATION**: 1020 m
SEISMIC COVERAGE: Sonne-75 Line 2, CDP730; Line CAM 134		

Objectives: Sample acoustic basement high on westernmost fault block; refine history of turbidite/contourite sedimentation; measure heat flow

Drilling Program: Wash down and RCB

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Nannofossil clay, clay, claystone, siltstone and fine sandstone, ooze and chalk; mid/lower continental crust or serpentinized peridotite

SITE: Iberia-8A*	**PRIORITY**: 1	**POSITION**: 40°42'N, 11°18'W
WATER DEPTH: 4830 m	**SEDIMENT THICKNESS**: 1050 m	**TOTAL PENETRATION**: 1150 m
SEISMIC COVERAGE: Lusigal-12, SP4580; Line CAM 145		

Objectives: Sample acoustic basement high (continental crust overlain by syn-rift sediments); refine history of turbidite/contourite sedimentation; measure heat flow

Drilling Program: Wash down and RCB

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Nannofossil clay, clay, claystone, siltstone and fine sandstone, ooze and chalk; mid/lower continental crust possibly overlain by tilted syn-rift sediments

OR

SITE: Site 901*	**PRIORITY**: 1	**POSITION**: 40°42'N, 11°3.6'W
WATER DEPTH: 4720 m	**SEDIMENT THICKNESS**: 600 m	**TOTAL PENETRATION**: 700 m
SEISMIC COVERAGE: Lusigal Line 12 SP4938		

Objectives: Continue Site 901 to basement at east end of OCT to sample and date the pre-rift sediments; refine lithospheric extension rift model; determine sedimentation and subsidence history, measure heat flow

Drilling Program: Wash down and RCB to 100 m or bit destruction

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Nannofossil clay, silt, sandstone, shallow-water sandstones and carbonates; continental crust

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*First Priority Sites

SITE: Iberia-9A*	**PRIORITY**: 1	**POSITION**: 40˚42'N, 11˚36'W
WATER DEPTH: 5150 m	**SEDIMENT THICKNESS**: 1100 m	**TOTAL PENETRATION**: 1150 m
SEISMIC COVERAGE: Sonne-75 Line 21; Lusigal Line 12, SP4020 (-9A), SP4035 (-9B)		

Objectives: Drill through the detachment fault

Drilling Program: Wash down and RCB

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Nannofossil clay, clay, claystone, siltstone and fine sandstone, ooze and chalk; continental crust or gabbro

OR

SITE: Iberia-9B	**PRIORITY**: 1	**POSITION**: 40˚42'N, 11˚33'W
WATER DEPTH: 5040 m	**SEDIMENT THICKNESS**: 1500 m	**TOTAL PENETRATION**: 1550 m
SEISMIC COVERAGE: Sonne-75 Line 21; Lusigal Line 12, SP4020 (-9A), SP4035 (-9B); Line CAM 136		

Objectives: Drill through detachment fault

Drilling Program: Wash down and RCB

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Nannofossil clay, clay, claystone, siltstone and fine sandstone, ooze and chalk; continental crust or gabbro

SITE: Galice-1A	**PRIORITY**: 2	**POSITION**: 42˚42'N, 12˚48'W
WATER DEPTH: 4500 m	**SEDIMENT THICKNESS**: 600 m	**TOTAL PENETRATION**: 700 m
SEISMIC COVERAGE: Lusigal 6, GP03		

Objectives: Exploratory hole above S´ reflector

Drilling Program: Wash down through 600 m of sediment and RCB 100 m of basement

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Pelagic clay, sand, silt, clay turbidites, chalk, continental crust

SITE: Iberia-10A	**PRIORITY**: 2	**POSITION**: 40˚48'N, 12˚42'W
WATER DEPTH: 5500 m	**SEDIMENT THICKNESS**: 830 m	**TOTAL PENETRATION**: 930 m
SEISMIC COVERAGE: Sonne-75 Line 16 SP310; Discovery-161 day 234		

Objectives: Sample oceanic basement west of known peridotite; refine history of turbidite sedimentation; measure heat flow.

Drilling Program: Was down and RCB to 100 m or bit destruction

Logging and Downhole Operations: Quad, GLT, FMS

Nature of Rock Anticipated: Nannofossil clay, clay, claystone, fine sand, silt, claystone turbidites, basalt

LEG 174A

New Jersey Shelf

Modified from Proposal 348A Submitted By

K.G. Miller, G.S. Mountain, N. Christie-Blick, and J.A. Austin, Jr.

Staff Scientist: Mitch Malone **Co-Chief Scientists:** **James Austin, Jr.**
Nicholas Christie-Blick

ABSTRACT

Sea-level changes have direct consequences to mankind. Understanding the ages, amplitudes, and causal mechanisms of sea-level changes, as well as the resulting stratigraphic changes, continues to be a fundamental goal of the Ocean Drilling Program. Leg 174A will core four holes in the New Jersey shelf margin to investigate the Oligocene-Holocene history of sea-level changes and add to the existing data of the New Jersey Mid-Atlantic Transect (MAT). One goal of MAT is to determine the geometry and age of Oligocene to Miocene sediments and to evaluate the role of sea-level changes in developing the sediment sequences deposited during that time period. Another major goal of MAT is to evaluate the possible causal links between glacioeustatic changes inferred from the deep-sea $\partial^{18}O$ record and depositional sequences from this "Icehouse World." Secondary goals include evaluating Paleocene to Eocene sequences, because of debate over the existence of ice sheets (the "Doubthouse World") during this time.

INTRODUCTION

Leg 174A will core four holes off the coast of New Jersey to investigate the Oligocene-Holocene history of sea-level change. The New Jersey shelf margin is an ideal location for this research for several reasons: rapid sedimentation, tectonic stability, good chronostratigraphic control, and abundant reconnaissance-quality seismic, well log, and borehole data (Miller and Mountain, 1994). The general goals of the New Jersey Mid-Atlantic Transect (MAT) are to determine the geometry and age of Oligocene to Miocene depositional sequences, and to evaluate the role of relative sea-level changes in developing this record. When completed, the New Jersey Mid-Atlantic Transect will evaluate possible causal links between glacioeustatic changes inferred from the deep-sea $\partial^{18}O$ record and depositional sequences from this "Icehouse World."

BACKGROUND

The Leg 174A transect (Fig. 1) is designed to sample several Oligocene to Holocene shelf sequences (unconformity-bounded depositional units) in three locations: (1) immediately landward of each clinoform inflection point; (2) at the toe of each clinoform; and (3) at a distal setting well seaward of the clinoforms (Fig. 2). The first location provides facies and paleodepths of the toplapping portion of a target sequence as well as the thickest record of the underlying sequence. The second location at the clinoform toe establishes the paleodepth and facies of the lowstand systems tract. Drilling both locations allows estimation of the amplitude of relative sea-level change associated with each sequence boundary using methods similar to Greenlee et al. (1988). Oligocene to Holocene clinoforms are beneath the modern New Jersey shelf and none of these shelf boreholes have been drilled to date (Fig. 3). The third, distal location for transect boreholes can be reached beneath the modern continental slope where samples have more pelagic microfossils and provide optimal conditions for dating the age of sequence boundaries. Furthermore, properly chosen slope sites promise a more continuous record than can be expected on the adjacent shelf. Leg 150 drilled four slope sites that provide the age control needed for most of the Oligocene-Holocene sequences (e.g., Miller et al., in press). Only one additional slope site (proposed and previously approved Site MAT-13) is needed to complete this task.

Two primary goals of Leg 150 were to date major Oligocene to Holocene sequences on the New Jersey slope and rise and to evaluate their correlation with glacioeustatic-age estimates obtained from the ∂^{18}O record. Multichannel and single channel seismic grids allow the tracing of seismic sequences from the shelf (e.g., the Tuscan, Yellow, Blue, Pink, and Green sequences of Greenlee et al., 1992) to the slope (Miller and Mountain, 1994). To evaluate sequence ages, Leg 150 drilled four sites on the New Jersey continental slope that allow direct dating of seismic reflectors traced from the continental shelf (the Greenlee et al. [1992]) shelf reflector nomenclature has been superseded by names developed by the Leg 150 party and will be used from here on). Leg 150 met its major goal by integrating Sr-isotopic stratigraphy (Miller et al., in press) with planktonic foraminifer biostratigraphy (Snyder et al., in press), nannofossil biostratigraphy, and magnetostratigraphy (Van Fossen and Urbat, in press); this provided a chronology of Oligocene to middle Miocene sequences (Miller et al., in press). In addition, Leg 150 evaluated the response of slope deposition to changes in sea level. For example, Mountain et al. (in press) evaluated the incision, maintenance, and demise of a buried middle Miocene slope canyon.

Primary objectives of the New Jersey onshore boreholes (Leg 150X, Fig. 1) were to date Cenozoic sequences (including Paleocene-Eocene Doubthouse sequences) and to evaluate facies models in an updip setting. Drilling at Island Beach, Atlantic City, and Cape May, NJ, exceeded expectations (Miller et al., 1994, in press). In particular, Oligocene to middle Miocene sections at Atlantic City and Cape May represent two of the best-dated sections for sea-level studies (Miller and Sugarman, in press), whereas the Paleocene-Eocene at Island Beach provides a remarkably complete and well-dated section (Browning et al., in prep.). Oligocene to middle Miocene sequence boundaries on shore correlate well with major ∂^{18}O increases, suggesting that these unconformities were cut by global sea-level lowerings. In addition, these unconformities correlate with the slope sequence boundaries drilled during Leg 150, suggesting a causal link between onshore and slope sequences (Mountain, Miller, Blum, et al., 1994; Miller et al., in press). Facies successions (systems tracts) are generally well developed for the Paleocene through middle Miocene onshore sequences, with a shell bed or glauconite sand at the base (=transgressive systems tract) and quartz sand at the top (=highstand systems tract; Miller et al., 1994). Thus, onshore drilling provided sections needed to evaluate systems tracts successions, although the boreholes are updip of the Oligocene to Miocene clinoforms and do not provide information on clinoform facies or constraints on the amplitudes of relative sea-level variations.

SCIENTIFIC OBJECTIVES

The Oligocene to Holocene is an interval in which continental margin sequences may be directly compared with eustatic estimates obtained from ∂^{18}O studies (e.g., Miller et al., 1991). The Leg 174A transect will evaluate possible causal links between ice-volume (glacioeustatic) changes inferred from the deep sea ∂^{18}O record and depositional sequences from this "Icehouse World.” The goals of this leg are to:

- date major Oligocene to Holocene sequences on the New Jersey margin;
- evaluate their correlation with glacioeustatic age estimates obtained from the ∂^{18}O record;
- estimate the amplitudes and rates of sea-level change independent of ∂^{18}O estimates; and
- assess the stratigraphic response of sequence architecture and facies successions to glacioeustatic forcing.

Secondary goals include evaluating Paleocene to Eocene sequences. Much debate continues over the existence of ice sheets (the "Doubthouse World") during this time.

DRILLING STRATEGY AND PROPOSED SITES

Site MAT-7B

Proposed Site MAT-7B (Fig. 4) will focus on recovering Paleocene-Eocene strata for two important reasons: (1) to calculate amplitudes of Oligocene-Holocene sea-level changes, and (2) to examine mechanisms of sea-level change in the Paleocene-Eocene.

1) Amplitudes

Accurate knowledge of basin subsidence is an essential element in modeling the amplitude of sea-level change. Sediment compaction is a major component of total subsidence history, and to measure it accurately, one must have porosity information as far into the sub-bottom as possible, ideally well below the actual clinoform that is used to measure sea-level change. Equivalent strata without the concerns of drilling in water depths less than 75 m can be reached at reasonable depths on Ew9009 MCS Line 1002 where we propose Site MAT-7B. We have preserved the "7" designation in this site to emphasize that this location is the equivalent of Site MAT-7 in determining the facies across the m3 sequence boundary.

2) Paleocene-Eocene “Doubthouse”

Penetration below the Icehouse interval at MAT-7B will also address a secondary goal of the transect by providing valuable information about the Paleocene-Eocene "Doubthouse." This is a time for which glacioeustatic forcing is a questionable factor in sequence development. This aspect of sequence stratigraphic studies has been highlighted by results from the onshore Island Beach borehole that obtained an excellent record of Paleocene-Eocene sequences (Miller et al., 1994; Browning et al., in prep.) and by recent onshore drilling of an Eocene-Oligocene dip transect on shore in Alabama and Mississippi (Miller et al., 1993; Baum et al., 1994; Dockery et al., 1994). Additional sites are needed to evaluate Paleocene-Eocene sequences on this and other margins; Site MAT-7B will be the only site that recovers this section off the shore of New Jersey.

Sites MAT-8B and MAT-9B

Proposed Sites MAT-8B and -9B will focus on upper Miocene clinoforms m1 and younger (Tuscan of Greenlee and Moore, 1988; Greenlee et al., 1992). LWD at both sites is proposed.

Site MAT-13B

Proposed Site MAT-13B (Fig. 5) is a slope site designed to date Miocene to Pleistocene sequence boundaries (particularly m1 that is still poorly dated) and to evaluate Pleistocene sequence stratigraphy. We propose LWD at this site.

Available Data

The New Jersey margin is one of two study areas recently selected by the U.S. Office of Naval Research for a multi-year initiative that it has termed "Stratal Formation" (STRATAFORM). Together with studies of the contrasting margin off Northern California, the goal is to understand the range of factors affecting shelf and slope sedimentation (Nittrouer and Kravitz, 1995). Modern processes will be linked to the seismically imaged and sampled (preserved) record through an evolution of increasingly sophisticated models. The key will be the collection of "nested" geophysical and geological data using a variety of tools whose individual temporal and spatial scales overlap to form a wide-ranging continuum of measurements. Clearly, the missions of STRATAFORM and the Sea Level Transect coincide offshore New Jersey.

Consequently, both ONR and JOI are supporting investigators from LDEO, UTIG, and Rutgers to collect and interpret high-resolution MCS data on the New Jersey shelf and upper slope in June-July, 1995. The new data will build on a substantial set of regional geophysical and geological data that includes: (1) 60-fold MCS profiles collected by the *Maurice Ewing* (Figs. 1, 3-5) from the inner shelf to the rise; (2) Huntec 2D and 3D seismic grids and associated vibra-cores collected by UTIG in 1989 and 1993; and (3) commercial MCS profiles collected during the 1970's in a dense grid (~2.5 km line spacing) across the outer shelf and upper slope that are now undergoing analysis and interpretation at UTIG.

A survey in 1995 consisted of two interwoven track plans and missions: (1) hazards-type survey grids at proposed shelf sites (to meet Transect goals, funded by JOI and by ONR); and (2) a regional grid across the outer shelf and upper slope (to meet STRATAFORM goals funded by ONR, and to meet ODP goals by tying the shallow stratigraphy together).

Together these profiles will: (1) determine the nature of buried stratal surfaces and their accompanying acoustic characteristics across a wide range of depositional environments; (2) provide links among the various elements of the STRATAFORM initiative; (3) tie well-dated ODP Leg 150 sequences and other upper slope data to coeval shelf and onshore sections; and (4) pave the way for ODP to drill a number of shelf sites off the shore of New Jersey.

The aforementioned data should assess the degree of safety of New Jersey shelf drilling with respect to trapped "shallow" gas and migration of thermogenic hydrocarbons upward along faults. Still to be resolved is the issue of seafloor hazards (e.g., pipelines, shipwrecks, etc.). Proponents have already coordinated the proposed site locations with cable location services at AT&T, and there are no cable hazards at any site. The ONR/STRATAFORM schedule calls for swath mapping and associated backscatter coverage to be collected during the spring-summer of 1996 (by Larry Mayer and his group at the University of New Brunswick). These data will be incorporated into the overall hazards assessment prior to drilling.

LOGGING WHILE DRILLING

The very good to excellent core recovery at slope sites on Leg 150 (88% mean) was due largely to the abundance of fine-grained sediments; however, problems arose whenever sands were encountered. Sand is likely to be much more prevalent at the shelf sites, and logging will consequently take on a particularly important role in meeting the objectives of facies characterization. Even in mudstones, Leg 150 operations relied exclusively on the Side-Entry Sub (SES) technique of wireline logging, which left the pumps online during the logging operation so that fluid circulation was available to clear downhole obstructions. Unfortunately, SES cannot be used at sub-bottom depths greater than the water depth, and hence will not be available at any of the proposed Sites MAT-7 through 9. Logging While Drilling is a cutting-edge technology still on a steep development curve in the oil industry. It was used successfully on Leg 156 on the Barbados accretionary wedge, and it will be used again on the Costa Rica and Barbados accretionary prisms on Legs 170 and 171B, respectively. Although LWD has drawbacks (cost; lack of sonic, FMS, and geochemical log data), it is rich in positives: (1) in borehole conditions typical of ODP operations, it is likely to provide the best gamma-ray, density, porosity, and caliper logs possible by measuring these data within minutes of being drilled (the sensors are a few meters above the bit); (2) it is nearly certain to save time over wireline logging, which requires drilling to TD, and then logging a potentially unstable hole from there back up to ~100 mbsf; and (3) LWD provides log data right up to the mudline. LWD will provide logging details of 0-100 mbsf that will be crucial to tying the Pleistocene of Site MAT-13 to that of Sites MAT-9 and -8B (Fig. 6). In lieu of missing sonic, FMS, and geochemical data, and as a "log-log integration" plan, we propose to conduct standard wireline logging and LWD at the deepest site drilled (MAT-7B). We are confident that the velocity data provided by this one "sonic calibration hole" will yield sufficient detail for extrapolating to the other shelf sites, provided each of them have LWD porosity and density logs.

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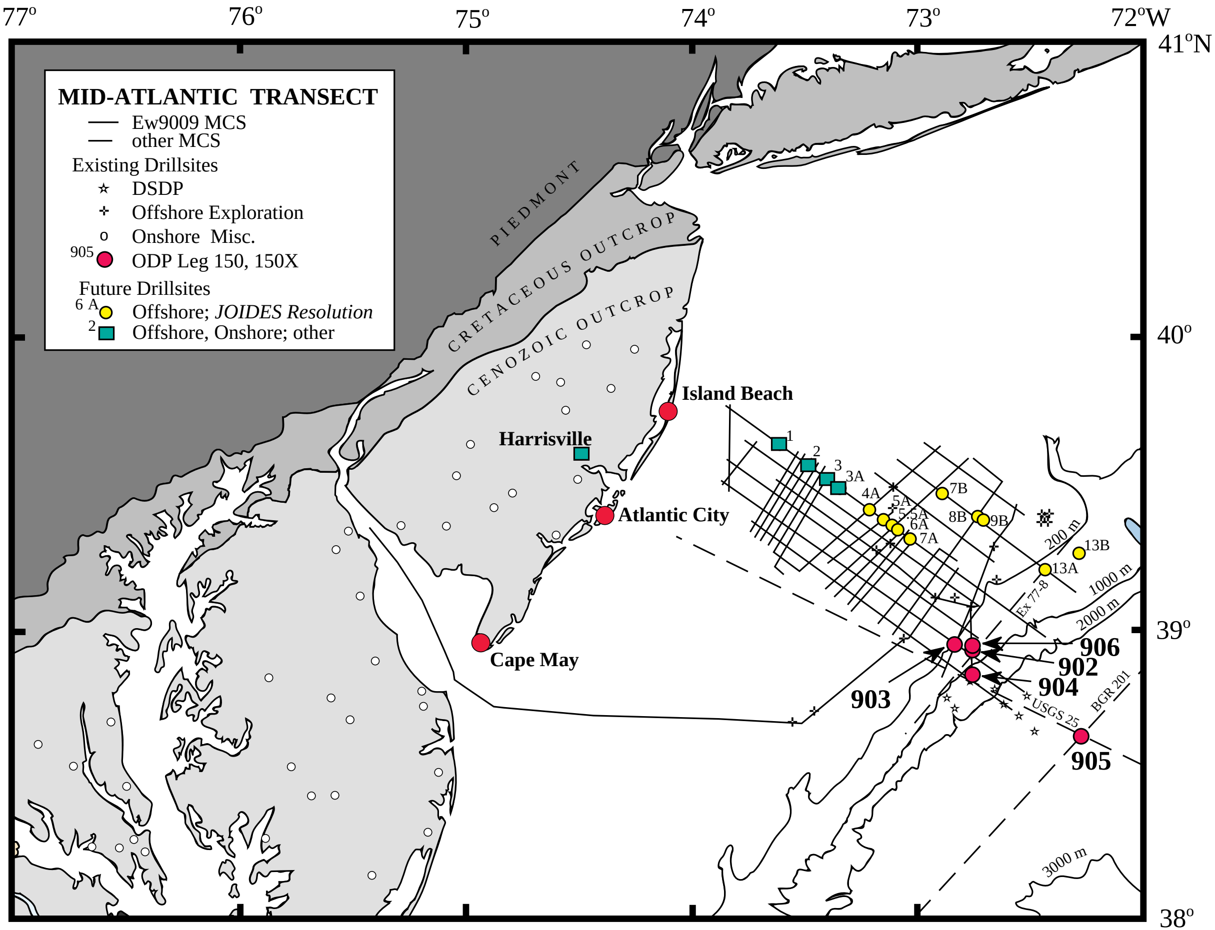

Figure 1. Map showing the locations of Ew9009 MCS (heavy) and SCS (light) profiles, proposed sites MAT 1-9, ODP Leg 150 slope and rise sites, and Leg 150X onshore boreholes.

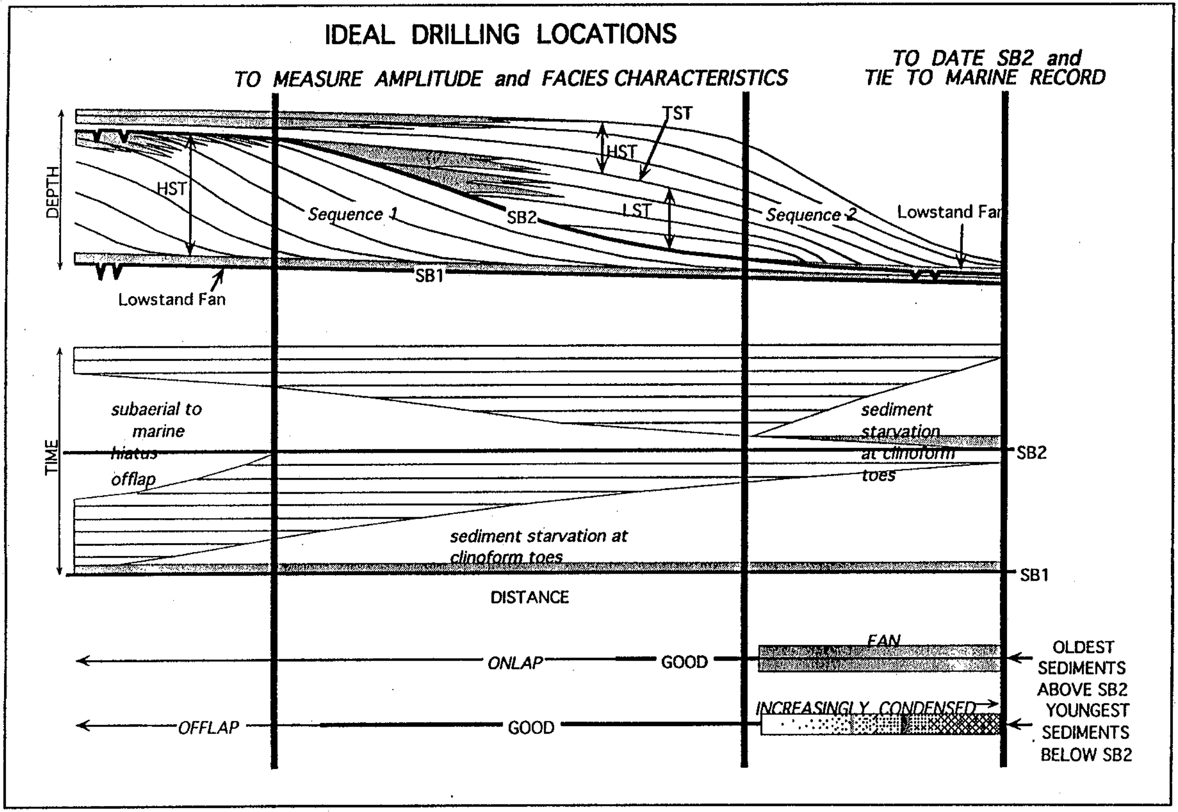

Figure 2. Drilling strategy across an ideal clinoform. Stratal geometry (upper panel), time-distance diagram (middle panel) and facies (lower) of two idealized sequences typical of the Oligocene through Miocene section offshore New Jersey. The optimal drillsite location shown here minimizes the hiatus across the younger sequence boundary (SB2) and provides an opportunity to estimate relative sea-level changes associated with SB2.

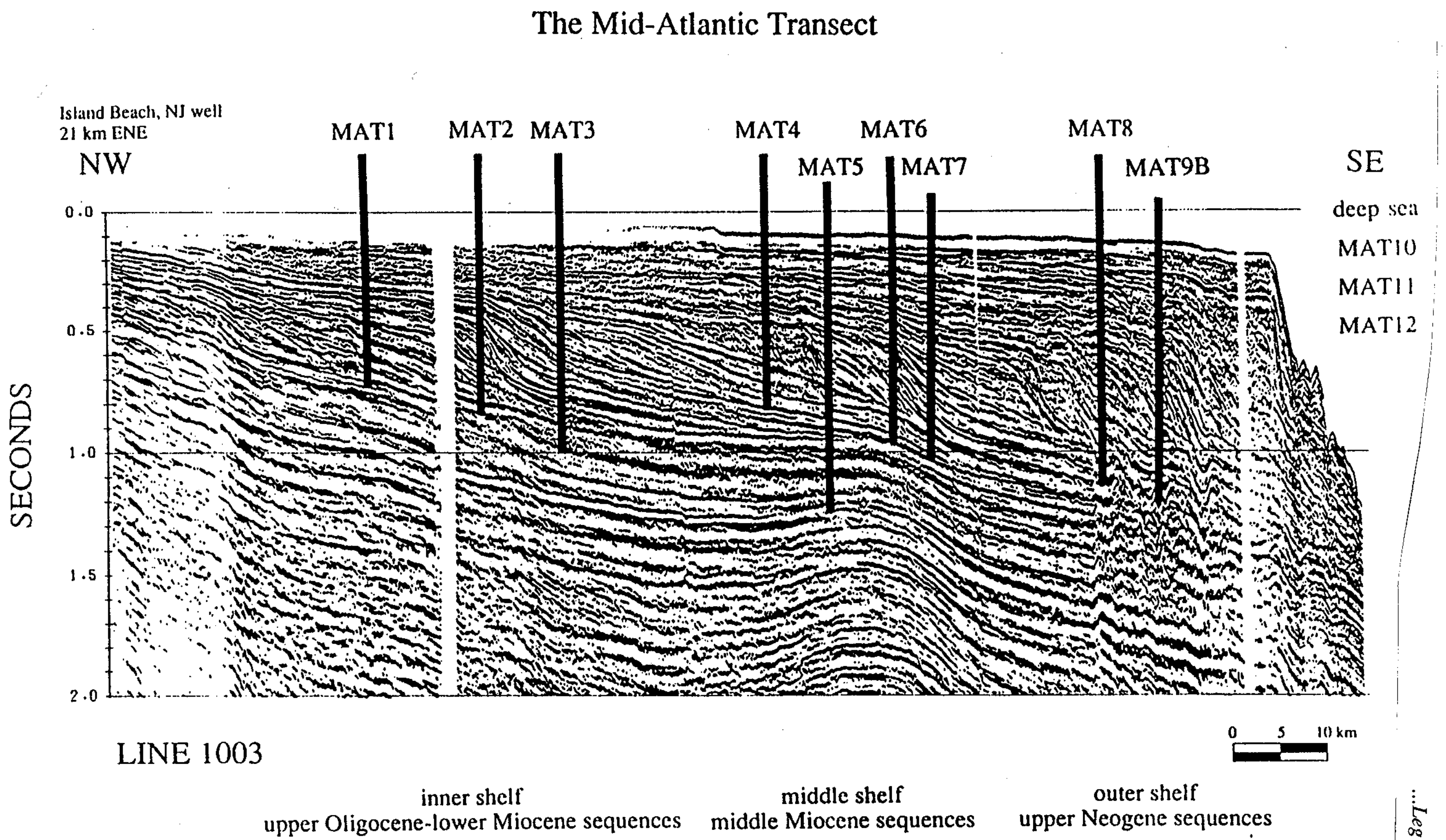

Figure 3. Highly compressed Ew9009 Line 1003 showing locations of proposed ODP boreholes MAT 4-9 and supplementary platform boreholes MAT1-3.

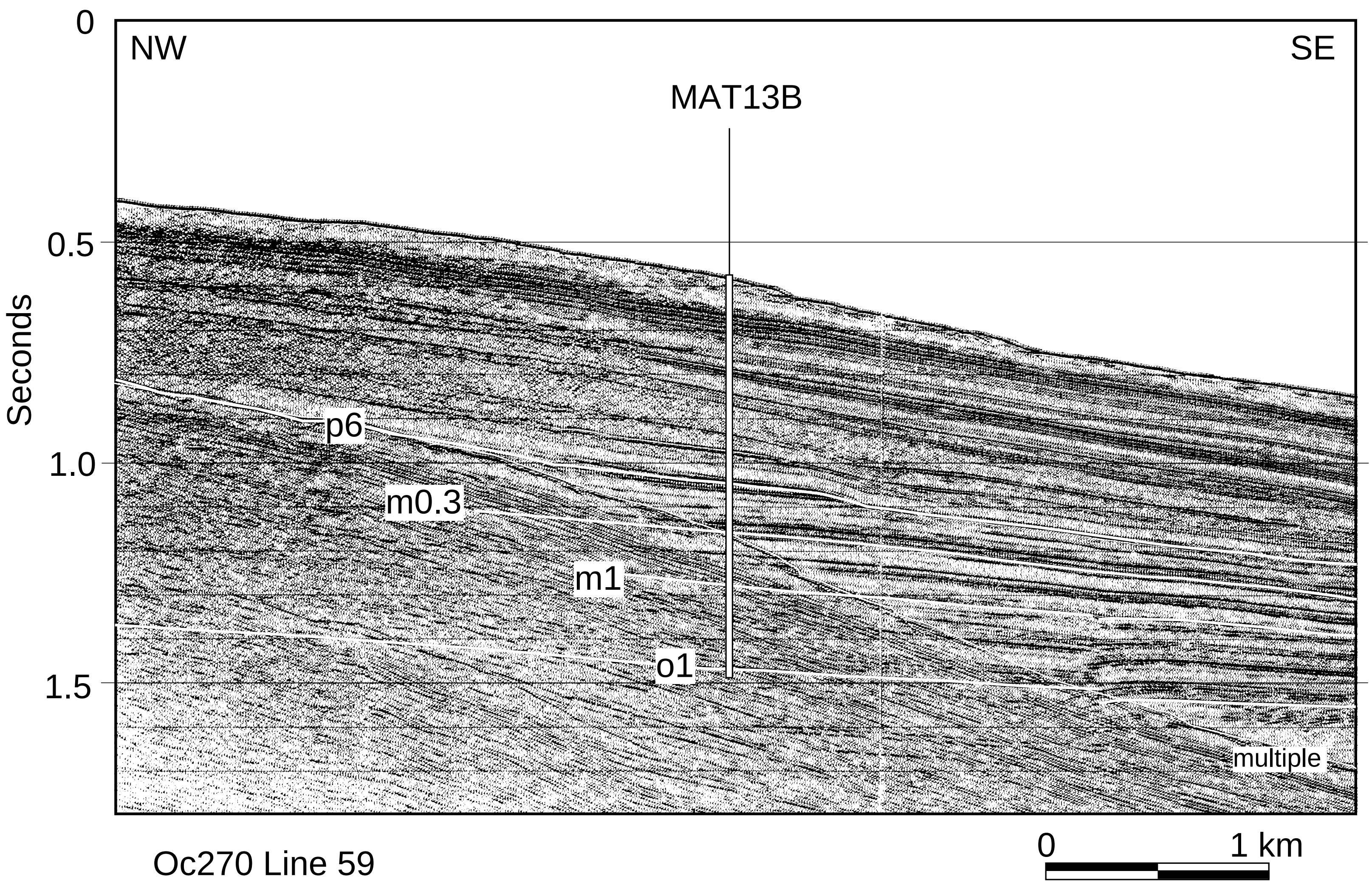

Figure 4. Close up of a near-trace display of Oceanus Line 59 showing MAT 13B in 427 m of water on the slope offshore New Jersey. We anticipate that 420 m of Pleistocene section above p6 contains an especially complete history of glacioeustatic control on the stratigraphic record back to at least Stage 12, and will be compared with the equivalent shelf sequences at Sites MAT 7B, 8B and 9B. In addition, drilling to TD will yield valuable age control on the as-yet poorly defined middle and upper Miocene sequences above m1.

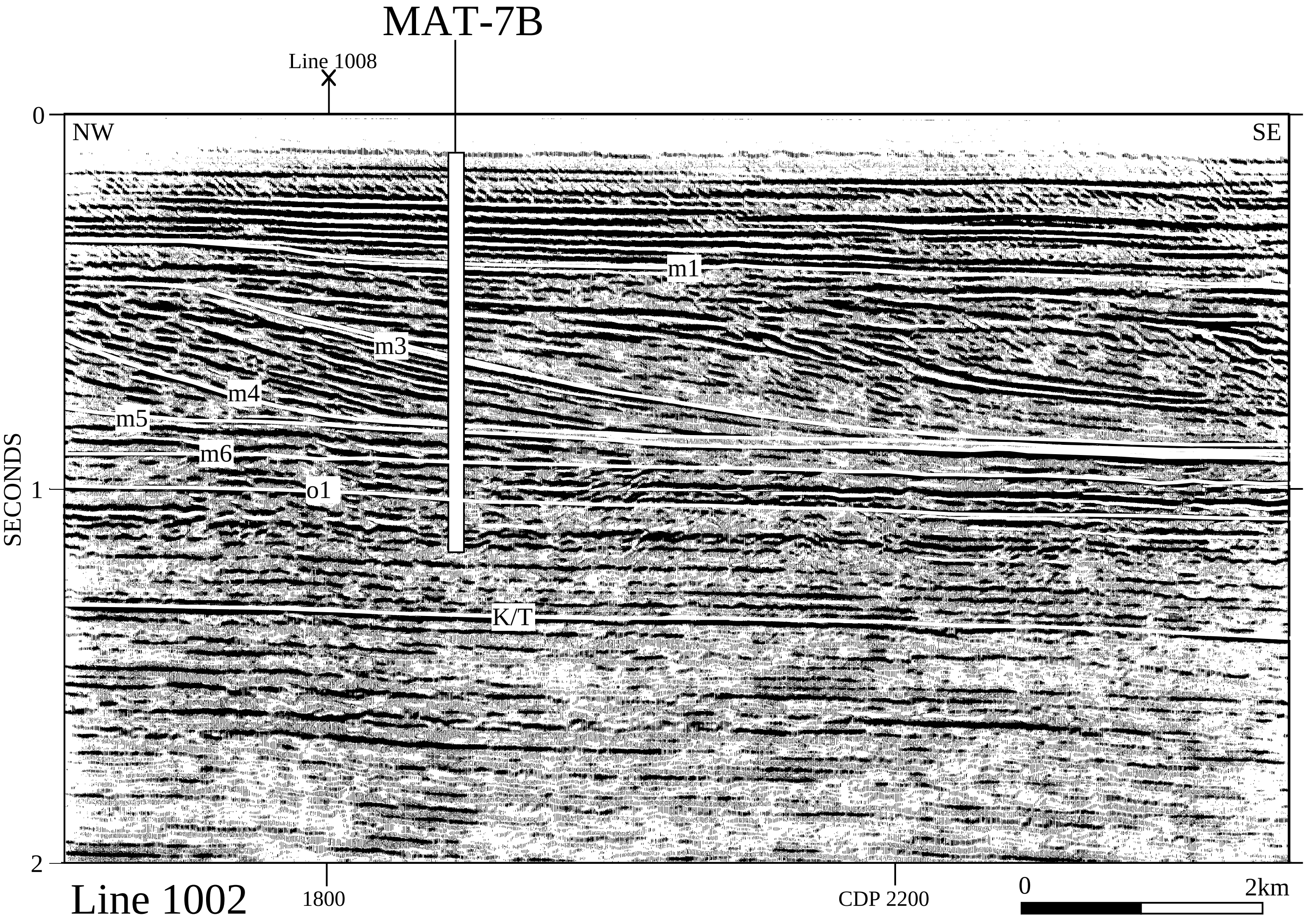

Figure 5. Close-up of Line 1002 showing MAT-7B. Carbonate sequences below o1 are targeted to yield information about the non-glacial "Doubthouse" world, to provide valuable sediment compaction history for the overlying Icehouse strata. This site is also designed to focus on the post m4 interval.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: MAT-8B **PRIORITY**: 1 **POSITION**: 39˚22.8'N, 73˚43.8'W
WATER DEPTH: 88 m **SEDIMENT THICKNESS**: – **TOTAL PENETRATION**: 829 m
SEISMIC COVERAGE: Ew9009 MCS, Line 1002, Line 1007

Objectives: Determine the age and facies of the middle Miocene

Drilling Program: Double APC/XCB

Logging and Downhole Operations: Logging While Drilling*

Nature of Rock Anticipated: Sands, silts, and clays

SITE: MAT-9 **PRIORITY**: 1 **POSITION**: 39˚21.6'N, 72˚41.4'W
WATER DEPTH: 90 m **SEDIMENT THICKNESS**: – **TOTAL PENETRATION**: 1065 m
SEISMIC COVERAGE: Ew9009 MCS, Line 1014

Objectives: Determine the age and facies of the middle Miocene

Drilling Program: Double APC/XCB

Logging and Downhole Operations: Logging While Drilling*

Nature of Rock Anticipated: Sands, silts, and clays

SITE: MAT 13B **PRIORITY**: 1 **POSITION**: 39˚15'N, 72˚8.4'W
WATER DEPTH: 427 m **SEDIMENT THICKNESS**: – **TOTAL PENETRATION**: 818 m
SEISMIC COVERAGE: MCS Oc270 Line 59

Objectives: Determine age and facies of deep sea correlative conformities of the upper Miocene m1 sequence boundary and provide a thick, high resolution middle to upper Miocene slope section

Drilling Program: Double APC/XCB

Logging and Downhole Operations: Quad, GHMT, Logging While Drilling*

Nature of Rock Anticipated: Sands, silts, and clays

*LWD tools: CDR - resistivity, gamma-ray, CDN - neutron, density, ISONIC - sonic velocity, RAB - resistivity at bit, MWD - weight on bit and real-time transmission

SITE: MAT-7B‡	**PRIORITY**: 1	**POSITION**: 39°28.2´N, 72°54.6´W
WATER DEPTH: 75 m	**SEDIMENT THICKNESS**: –	**TOTAL PENETRATION**: 1080 m
SEISMIC COVERAGE: Ew9009 MCS Line 1002, Line 1003		

Objectives: Determine age facies of Paleocene-Eocene sediments

Drilling Program: Double APC/XCB

Logging and Downhole Operations: Quad, Logging While Drilling*

Nature of Rock Anticipated: Sands, silts, and clays

SITE: MAT-13A‡	**PRIORITY**: 1	**POSITION**: 39˚12.6'N, 72˚26.4'W
WATER DEPTH: 427 m	**SEDIMENT THICKNESS**: –	**TOTAL PENETRATION**: 818 m
SEISMIC COVERAGE: Ew9009 MCS		

Objectives: Determine age and facies of deep sea correlative conformities of the upper Miocene m1 sequence boundary and provide a thick, high resolution middle to upper Miocene slope section

Drilling Program: Double APC/XCB

Logging and Downhole Operations: Quad, GHMT, Logging While Drilling*

Nature of Rock Anticipated: Sands, silts, and clays

‡Alternates sites

LEG 174B

CORK Hole 395A/Offset Drilling Engineering

CORK Leg Section Modified from Proposal 424 Submitted By

K. Becker and E. Davis

Engineering Leg Section Proposed by Tom Pettigrew

Staff Scientist: Mitch Malone **Chief Scientist: Keir Becker**

ABSTRACT

Leg 174B is a two-part leg. The first half of the leg will perform downhole experiments and then CORK Hole 395A located in the Mid-Atlantic Ocean. The second half of the leg will perform field tests on the hammer drill-in casing system at the Mid-Atlantic Ridge at the Kane Transform. The primary purpose of the CORK experiments at Hole 395A is to monitor how the hydrologic system varies with time as natural hydrogeological conditions are re-established after sealing the hole. Returning to the natural thermal regime will allow us to determine if the downhole flow observed at this site is dynamically maintained due to active circulation occurring in the basement, with or without the presence of a borehole, or due to flow induced by the geothermal gradient. The downhole experiements will provide essential information about the formation pressure and permeability structure to understand the crustal hydrogeology of the active off-axis hydrologic system at Hole 395A. The purpose of testing the hammer drill-in casing system is to determine the viability of the hammer drill, as well as the complete casing system, and determine the maximum slope that can be spudded by the tool.

PART I: CORK HOLE 395A LEG

INTRODUCTION

Leg 174B will conduct a selected suite of downhole experiments in Hole 395A (Fig. 1) and then emplace an instrumented borehole seal or CORK with pressure sensor and a 600-m-long, 10-thermistor cable for subsequent data acquisition to test a model developed from the observations obtained since the hole was drilled 20 years ago. The observations from Hole 395A generally support a model of lateral circulation in the upper basement beneath the sediment pond in which the site is located. The primary purpose of the CORK experiment at Hole 395A is to monitor how the hydrological system varies with time as natural hydrogeological conditions are re-established when the hole is sealed. The experiment will provide essential information about the formation pressure and permeability structure, which are the real keys to understanding the crustal hydrogeology, and which control the apparently more active off-axis hydrologic system at Hole 395A.

Extensive downhole measurements and heat flow surveys were obtained on both holes since they were originally drilled (Fig. 2). Despite the data collected to date which suggest that young, upper oceanic crust under a sediment cover is easily permeable enough to support considerable flow of seawater, the details of off-axis circulation and its control by the pressure distribution and fine-scale permeability structure are as yet poorly understood. Hole 395A is an excellent place for this experiment because returning to the natural thermal regime will allow determination of whether the observed downhole flow is dynamically maintained due to active circulation occurring in the basement, whether or not a borehole is present, or is due to flow induced by the geothermal gradient.

BACKGROUND

DSDP/ODP Holes 395A (mid-Atlantic Ocean, Fig. 1) and 504B (Pacific Ocean, Fig. 1) penetrate more than 500 m into the "normal" oceanic crust formed at a mid-ocean ridge and, thus, form a key pair of reference sites for young upper oceanic crust formed at slow and medium spreading rates, respectively. They are especially important for understanding the hydrogeology of young oceanic crust. When time has been taken to carefully log holes drilled into young oceanic crust, a large proportion of these holes have proven to be drawing ocean bottom water down into permeable levels of basement (e.g., Erickson et al., 1975; Hyndman et al., 1976; Anderson and Zoback, 1982; Becker et al., 1983a, 1984; Davis, Mottle et al., 1992). Such downhole flow requires both sufficient permeability and a differential pressure between the fluids in the borehole and the formation fluids. In general, we surmise that the necessary differential pressures may arise because of some combination of two possibly independent effects:

(1) the differential pressure (which should **not** be termed an "underpressure") between the cold hydrostatic pressure in a borehole drilled with cold seawater and the warmer hydrostatic formation pressure, and

(2) true, dynamically maintained underpressures due to active circulation in the basement that would occur whether or not a borehole were present.

In cases of downhole flow in holes drilled into formations with high geothermal gradients, e.g., the strong downhole flow observed during Leg 139 drilling at Middle Valley, the driving force is dominated by the former effect (Davis, Mottl et al., 1992). In the case of other holes that were drilled into crust with low geothermal gradients, e.g., Hole 395A, the latter effect may be predominant.

Hole 395A is one of the best-documented examples to date. The strong and consistent downhole flow requires both a significant pressure differential and long-lived formation permeability. The hole was sited where heat flow is very low, so there is very little differential between cold hydrostatic drilling fluids and formation temperatures to induce downhole flow. The fact that the downhole flow in Hole 395A has continued so strongly and for so long suggests that the dynamic pressure differentials due to an active circulation system are the predominant cause (and in fact these hydrologic processes may also be the cause of the low heat flow at the site).

Hole 395A is located in 7-m.y.-old crust in an isolated sediment pond (Hussong et al., 1979) that might be considered somewhat typical of the structure and hydrogeological setting for thinly sedimented crust formed at slow spreading rates. The hole has been revisited three times since it was drilled in 1975-1976 (Melson, Rabinowitz, et al., 1979): during DSDP Leg 78B in 1981 (Hyndman, Salisbury, et al., 1984), during ODP Leg 109 in 1986 (Bryan, Juteau, et al., 1988), and during the French wireline reentry campaign DIANAUT in 1990 (Gable et al., 1992). On each of these visits, the first order of business was temperature logging, because that measurement requires an undisturbed hole. Each of the three temperature logs showed strongly depressed borehole temperatures, essentially isothermal to a depth of about 300 m into basement (Fig. 2) (Becker et al., 1984; Kopietz et al., 1990; Gable et al., 1992). This indicates a strong downhole flow of ocean bottom water, at rates of thousands of liters/hr into the permeable upper oceanic crust, virtually unabated over the 20 years that the hole has been open (Fig. 3).

In comparison, temperatures measured during the multiple visits to Hole 504B were initially strongly depressed to a depth of about 100 m into basement, but then rebounded non-monotonically towards a conductive profile, indicating that the rate of downhole flow has decayed since the hole was first drilled and that the downhole flow is directed into a more restricted section of upper basement (Becker et al., 1983, 1985, 1989; Gable et al., 1989; Dick et al., 1992). This comparison indicates that Hole 504B penetrates a more passive hydrothermal regime, while Hole 395A provides a man-made shunt into a significantly more active circulation system. The various observations at Site 395 generally support a model of lateral circulation in the upper basement beneath the sediment pond in which the site is located (Fig. 4) (Langseth et al., 1984, 1992), but we have little resolution on the details of such circulation.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

By leaving Hole 395A open for 20 years, with revisits for discrete data sampling roughly every five years, we have learned only that the downhole flow has apparently continued at a significant rate. We have no resolution as to possible variations in downhole flow rates with time (as has been documented in Hole 504B), let alone the constancy or variability of (a) the driving forces responsible for the downhole flow or (b) the formation hydrologic properties that may limit it. Furthermore, we still do not understand exactly where in the formation the downhole flow is directed, other than the general statement that it is directed into the upper 300 m or so of basement.

The proposed program is intended to address these important issues by providing essential information about the formation pressure and permeability structure, which are real keys to understanding the crustal hydrogeology. Logging will begin with three logs designed first to provide a fourth estimate of the downhole flow at a single time point and to assess the fine-scale distribution of permeability in the hole. The hole will then be CORKed with pressure sensor and thermistor cable, for a long-term record of the pressure and temperature variations in the sealed hole as the natural hydrologic system re-establishes itself. In more detail, we propose the following sequence of experiments:

(1) After initial reentry, a temperature log will be run followed by Formation MicroScanner (FMS) and flowmeter logs to delineate the fine-scale permeability structure of the section penetrated by Hole 395A. The upper 300 m of basement is known to be quite permeable on average from the downhole flow, packer measurements, and an incomplete flowmeter experiment during the DIANAUT program (Becker et al., 1984; Hickman et al., 1984; Becker, 1990; Kopietz et al., 1990; Gable et al., 1992; Morin et al., 1992). Detailed permeability information will be required to allow interpretation of the data collected from the CORKed hole (individual thermistor readings plus an integrated pressure) in terms of active hydrogeological processes in discrete zones of the formation. The FMS will provide a detailed log of fracturing (filled and unfilled), and a full flowmeter experiment will allow the integration of the fracture information with a detailed permeability distribution (given the strong downhole flow already occurring, the flowmeter experiment can be conducted without using a packer). This sequence would require a pipe trip, plus about 36 hours logging time, for a total of 48-60 hours.

(2) Deployment of a fully configured CORK to seal the hole, plus a thermistor string and pressure sensor in the sealed section (an actual mechanical latch to hold the CORK in the cone would not be necessary, as the differential pressure that has driven downhole flow will hold the seal in place). Such an installation would allow a long-term record of (a) the rebound of temperatures towards formation conditions after the emplacement

of the seal, (b) possible temporal variations in temperatures due to lateral flow in discrete zones, and (c) pressure variations, which would be the primary manifestation in a sealed hole of changes in the forces that drive the natural circulation system. We would deploy a 600-m-long cable, with 10 thermistors spaced relatively equally below 100 m, to span the lowermost sediments, permeable extrusives and breccias, and the lowermost, relatively impermeable section of open hole (although the hole was originally drilled to 664 mbsf, during Legs 78B and 109 the deepest 55 m was found to be filled with cave-ins). The data logger and sensor string could probably be pulled out of the hole without the drillship, if necessary, but the CORK hardware would require the drillship for future removal. The deployment sequence would be similar to that required for deployment of the CORK already emplaced during Legs 139 and 146. A separate pipe trip would be required, plus about 6-8 hours to run in the cable and release the installation from the bottom of the pipe. Based on the Leg 139 experience, we estimate that a deployment in Hole 395A (nearly 2 km deeper than the Leg 139 sites) would probably require about 36 hours total.

The primary purpose of the CORK experiment would not necessarily be to assess the equilibrium pre-drilling thermal regime (which we can estimate from detailed heat flow surveys as in Fig. 2), but instead would be to monitor how the hydrologic system varies with time as natural hydrogeological conditions are re-established. Full thermal re-equilibration could require many tens or hundreds of years if it occurs by conductive processes only, but could also occur in much less time if the Langseth et al. (1984, 1992) model of active lateral circulation is correct. We are interested primarily in exploring the causes of the hydrogeological state and any possible temporal variations, with the simplest goal being to determine how these are associated with and controlled by formation pressure and/or permeability structure. It is impossible to model or predict all of the possible outcomes of the experiment, but considering two possible end-member results might be instructive:

(1) If the model of active lateral circulation is basically incorrect, and downhole flow is indeed simply an artifact of drilling, then sealing the hole should remove the driving force for the downhole flow, and temperatures and pressures will slowly and smoothly trend towards values consistent with conductive, hydrostatic processes.

(2) If there is some element of truth to the model of active lateral circulation in basement, with this circulation providing the driving pressure differential for the downhole flow, then sealing the hole will not change the driving force, and lateral circulation should continue even though the seal has stopped the downhole flow. Pressures in the sealed hole should approach a nonhydrostatic value in an irregular fashion that reflects variability in the natural hydrogeologic processes. Similarly, temperatures will rebound towards values consistent with the circulation system, also in an irregular fashion that reflects natural hydrogeologic variability. In addition, differences in the behavior of the temperature sensors should reflect vertical variations in the lateral flow regime due to fine-scale permeability variations. We understand so little about crustal hydrogeology that simply defining the natural time- and space-scales of such variability will be a very important result.

DRILLING/LOGGING STRATEGY

After initial reentry at Hole 395A, temperature logs, followed by FMS and flowmeter logs, will be run to delineate the fine-scale permeability structure of the section penetrated by the hole. Detailed permeability information will be required to allow interpretation of the data collected from the CORKed hole in terms of the hydrogeological processes in discrete zones of the formation. The FMS will provide a detailed log of fracturing. A fully configured CORK with a thermistor string and pressure sensor will then be installed to seal the hole. The cable will be 600 m with 10 thermistors spaced relatively equally below 100 m to span the lowermost sediments, permeable intrusives and breccias, and the lowermost, relatively impermeable section of the hole with pressure sensor and a 10-thermistor sensor cable 600 m long.

Hole 395A, drilled during DSDP Leg 45 (1975), together with 504B and other holes has been used for a long-term effort to determine the in situ petrophysical, geophysical, and geochemical properties of oceanic crust and toward the understanding of its formation and evolution. Comparative studies of in situ oceanic structures and hydrothermal circulation systems at oceanic ridges demand high quality and high resolution logging data. The logging data acquired before 1986 in Hole 395A at the Mid-Atlantic Ridge are poor compared with the high quality and high resolution logging data acquired in Hole 504B in 1993. In particular, the dual laterolog (DLL), critical to estimating porosity in high-resistivity formations, was not run in Hole 395A. A borehole televiewer (BHTV) downhole tool run was acquired by Morin et al. (1992) by wireline re-entry. With the recent advances in ODP logging capabilities, it is recommended that Hole 395A be logged again with the Quad combination with the array sonic tool, as well as the DLL, temperature, FMS, BHTV, and flowmeter tools. Time permitting with the limited number of logging runs, additional logs such as the dipole sonic and vertical seismic profile (VSP) would be extremely valuable for log integration with seismic data and for comparative studies of large-scale porosity, anisotropy, and hydrothermal properties in the ridge crest environment.

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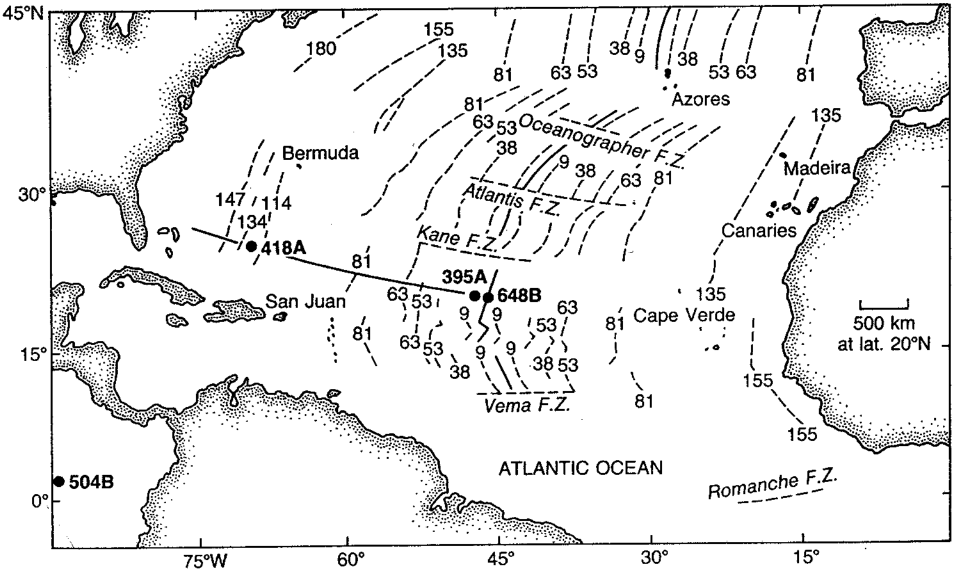


Figure 1. Location of Holes 395A, 418A, 504B, and 648B. Dashed lines show age of crust in Ma, deduced from magnetic anomalies (after Salisbury and Hyndman, 1984)

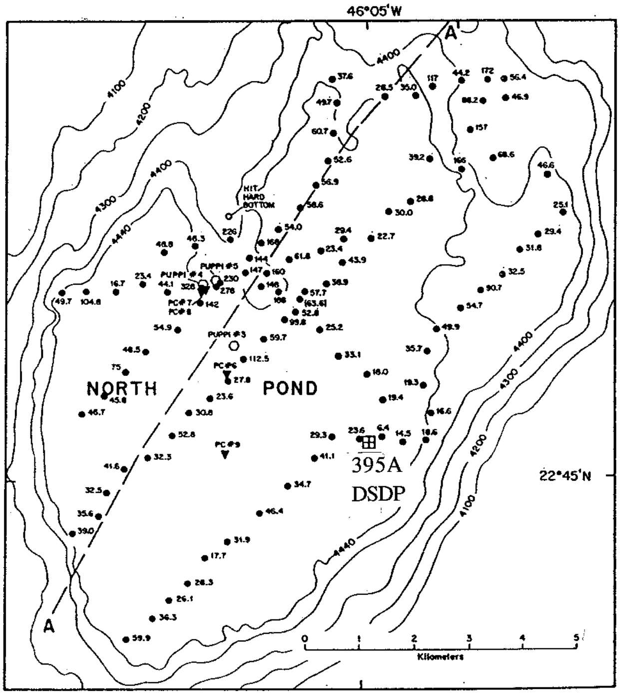


Figure 2. Location of heat flow measurements, PUPPI deployments, and piston cores in North Pond. The heat flow values are given next to the location of each penetration. The box in the lower right hand corner indicates the location of Hole 395A.

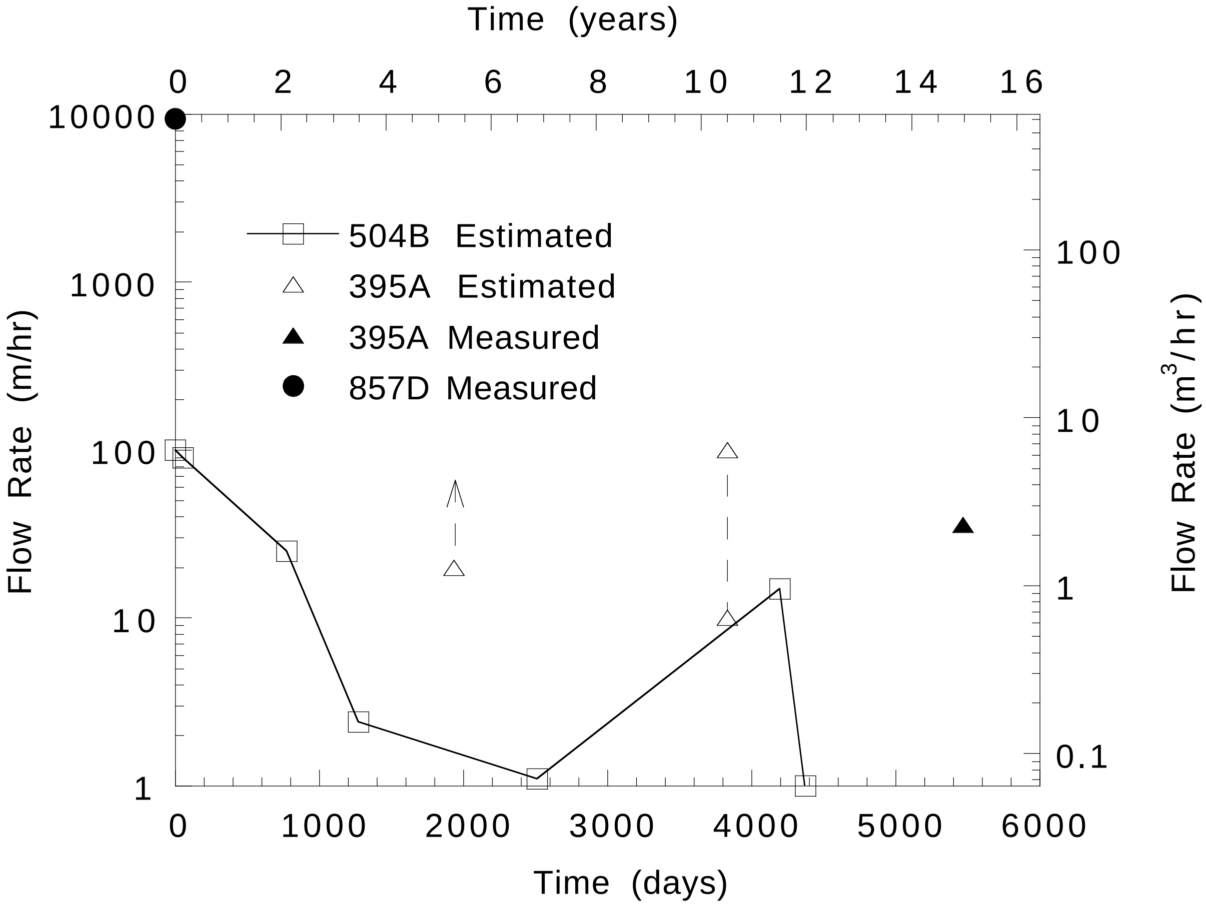


Figure 3. Measured and estimated downhole flow rates in the three best documented cases: Holes 395A, 504B, and 857D. Hole 395A data are from Becker et al. (1984), Kopietz et al. (1990), and Morin et al. (1992).

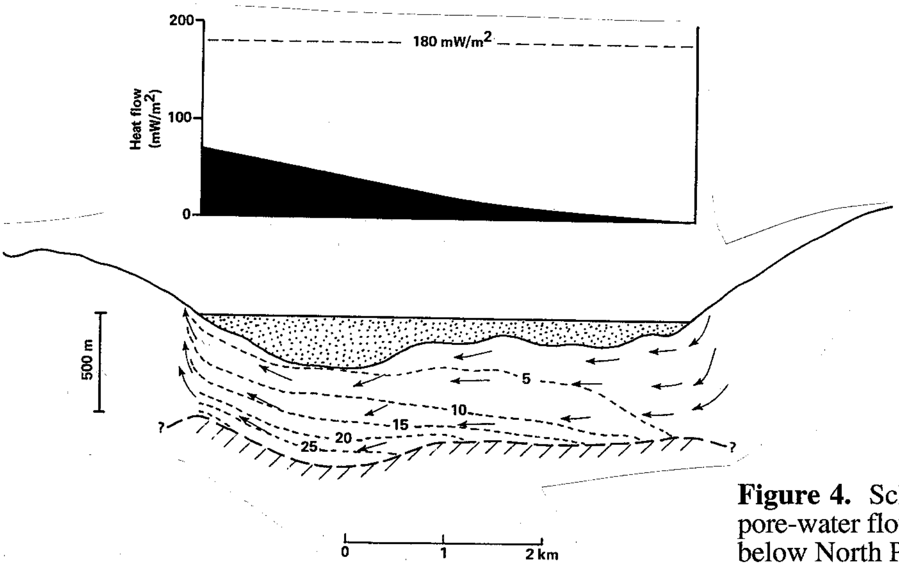


Figure 4. Schematic drawing of pore-water flow and isotherms (°C) below North Pond, assuming laminar flow at a rate of ~1 m/yr. The variation in heat flow across the pond is shown along the top of the figure.

TABLE 1 (CORK 395A)

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: 395A	**PRIORITY**: 1	**POSITION**: 22°45.35'N, 46°04.90'W
WATER DEPTH: 4490.2 m	**SEDIMENT THICKNESS**: 93 m	**TOTAL PENETRATION**: 664 m
SEISMIC COVERAGE: DSDP Leg 45 seismic data; 1989 single channel seismic data; SeaBeam coverage on Site 395 from Conrad Cruise 3001		

Objectives: Perform downhole experiments to acquire detailed permeability and fluid flow information and map fracturing. CORK the hole to monitor how the hydrologic system varies with time as the natural hydrogeological conditions re-establish.

Drilling Program: None

Logging and Downhole Operations: Quad combo with array sonic and DLL, FMS, BHTV, flowmeter, temperature, dipole, sonic, and VSP.

Nature of Rock Anticipated: Basalt

PART II: OFFSET DRILLING ENGINEERING LEG

INTRODUCTION

Experience gained on Ocean Drilling Program (ODP) Legs 147 (Hess Deep) and 153 located at the Mid-Atlantic Ridge at Kane Transform (MARK) indicates the current hard-rock base design is not optimal for establishing boreholes in fractured hard rock environments with moderate slope. This is especially true on thinly sedimented slopes covered with debris or rubble. Therefore, the engineering department has worked on developing new hardware and techniques for establishing a borehole in these environments in order to meet the scientific objectives of hard rock legs. Establishing a borehole refers to actual borehole spudding, emplacement of conductor casing, and establishing reentry capability. This requires some form of seafloor structure, whether it be an independent structure such as a seafloor template, a hard-rock base, or some form of a hard-rock drill-in casing system.

The tool with the most promise of dramatically increasing our ability to establish a borehole in a hard-rock environment is the hammer drill-in casing system. Thorough testing of this tool prior to deployment, at sea in an actual hard-rock environment, will greatly increase the success of future hard-rock legs. Therefore, the engineering portion of Leg 174B will be dedicated solely to testing a hammer drill-in casing system (Fig. 1) in a fractured hard-rock environment.

BACKGROUND

Drilling and coring operations in fractured hard rock must overcome many unique challenges. The boreholes must be spudded on hard, sometimes fractured rock, with little or no overlying sediment cover to help stabilize the bit. The dipping slope generally associated with these areas further compounds the problem. An additional challenge is keeping the borehole open long enough for the emplacement of casing. Rubble and debris from the seafloor continuously sift into the borehole. This rubble, along with the drill cuttings and material dislodged from the borehole wall, must be continuously removed, but the size and density of this in-fill material make it difficult to remove it from the borehole. Because maximum penetration of a borehole is dependent on borehole stabilization, and stabilizing boreholes in fractured hard rock requires emplacement of casing, some form of reentry structure must be installed that is capable of supporting casing.

The hammer drill-in casing system is composed of a hard-rock hammer drill, used to drill the borehole, a casing string with integral reentry funnel, and a casing hammer attached to the top of the casing string. Once the casing string has been drilled into place, the drilling assembly is unlatched and removed, leaving the casing string in place. Reentry capability would be established by means of the integral reentry funnel. The reentry funnel also provides a landing point for additional casing strings if required.

This type of drill-in casing system is currently being used in Iceland to drill-in large diameter casing (18-5/8 in) up to 100 m deep in fractured basalt. Unfortunately, this system is pneumatically driven and thus not suited for use in deep water depths. However, a hydraulically driven version of this hardware is currently under development in Australia; it may be modified for use by ODP.

A viable hammer drill-in casing system would have the following attributes:

1) Eliminate the need for any form of independent seafloor structure such as the hard-rock base or seafloor template.

2) Allow spudding boreholes on much steeper slopes than can be achieved using an independent seafloor structure.

3) Be less sensitive to thin sediment cover, debris, or rubble lying on the spudding surface.

4) Be less dependent on precise site surveys.

ENGINEERING OBJECTIVES

In general, there are three objectives, listed in order of priority, that must be explored to establish a borehole in a hard-rock environment.

1) Determine the viability of the hammer drill by deploying it independently of the drill-in casing system for evaluation. The hammer drill will be thoroughly land tested before it is deployed at sea; however, it is difficult to simulate deployment of such tools from the ship.

2) Determine the viability of the hammer drill-in casing system. Once the hammer drill viability is established, the complete hammer drill-in casing system will be deployed for evaluation. Two or more boreholes will be drilled using the hammer drill-in casing system.

3) Determine the maximum slope that can be spudded with the hammer drill. Once the hammer drill-in casing system viability is established, the maximum slope at which the system can spud will be determined. Multiple boreholes will be spudded on increasing slopes to determine maximum slope spudding capability.

SITE LOCATION

Ideally the Offset Drilling Engineering "Quarter" Leg will be conducted in the Mid-Atlantic Ridge at Kane Transform (MARK) near ODP Site 395 (Fig.1). This would provide for a direct comparison between the performance of a hammer drill-in casing system and that of hardware and techniques already deployed in the same area. Also, pre-site survey requirements would be minimized.

DRILLING PLAN

The proposed drilling plan addresses the minimum requirements to evaluate the potential of a hammer drill-in casing system. No coring is planned during the half leg because the main focus is establishing a borehole using a hammer drill-in casing system. However, it is hoped that several reenterable boreholes will be established that can be used for future scientific exploration.

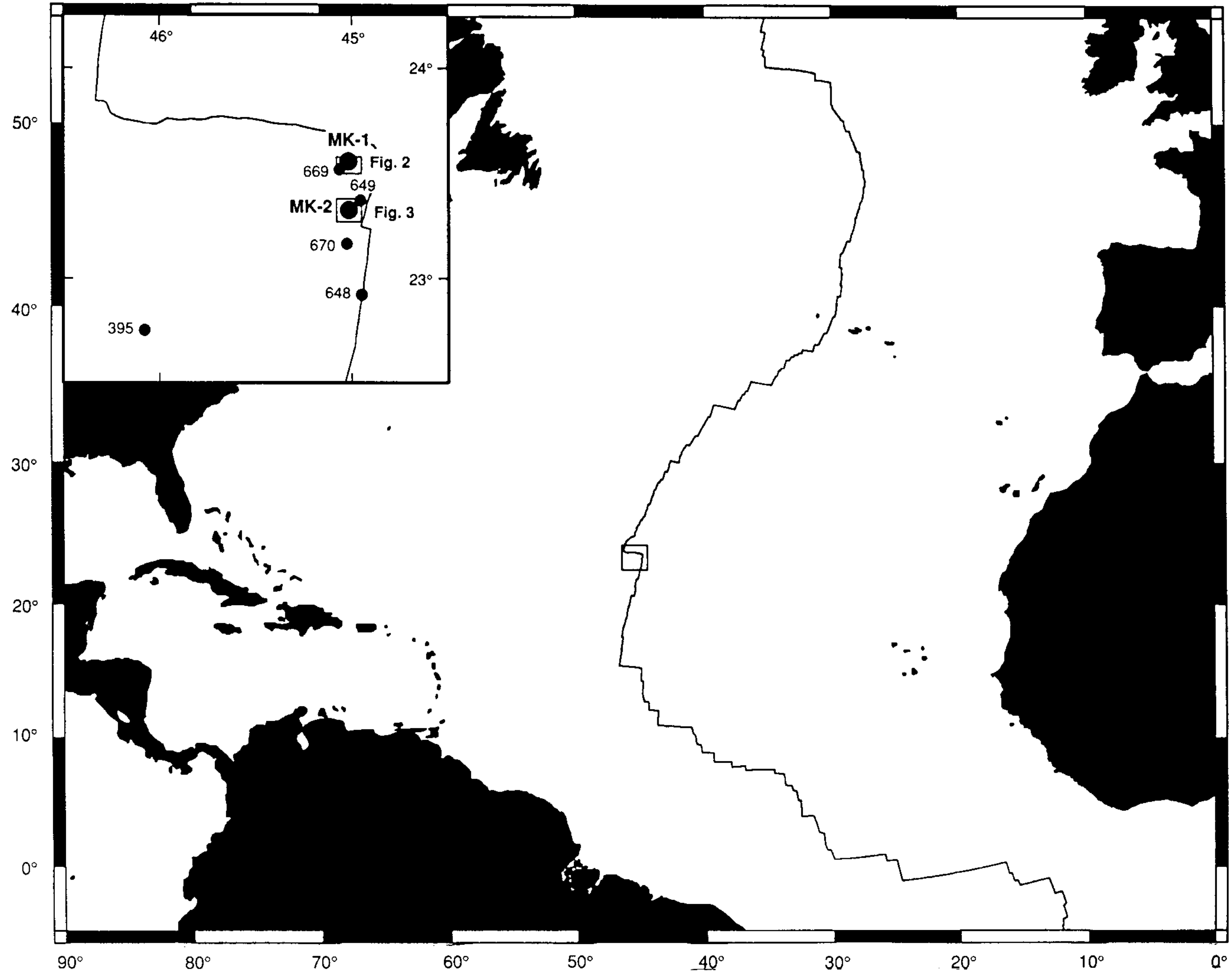
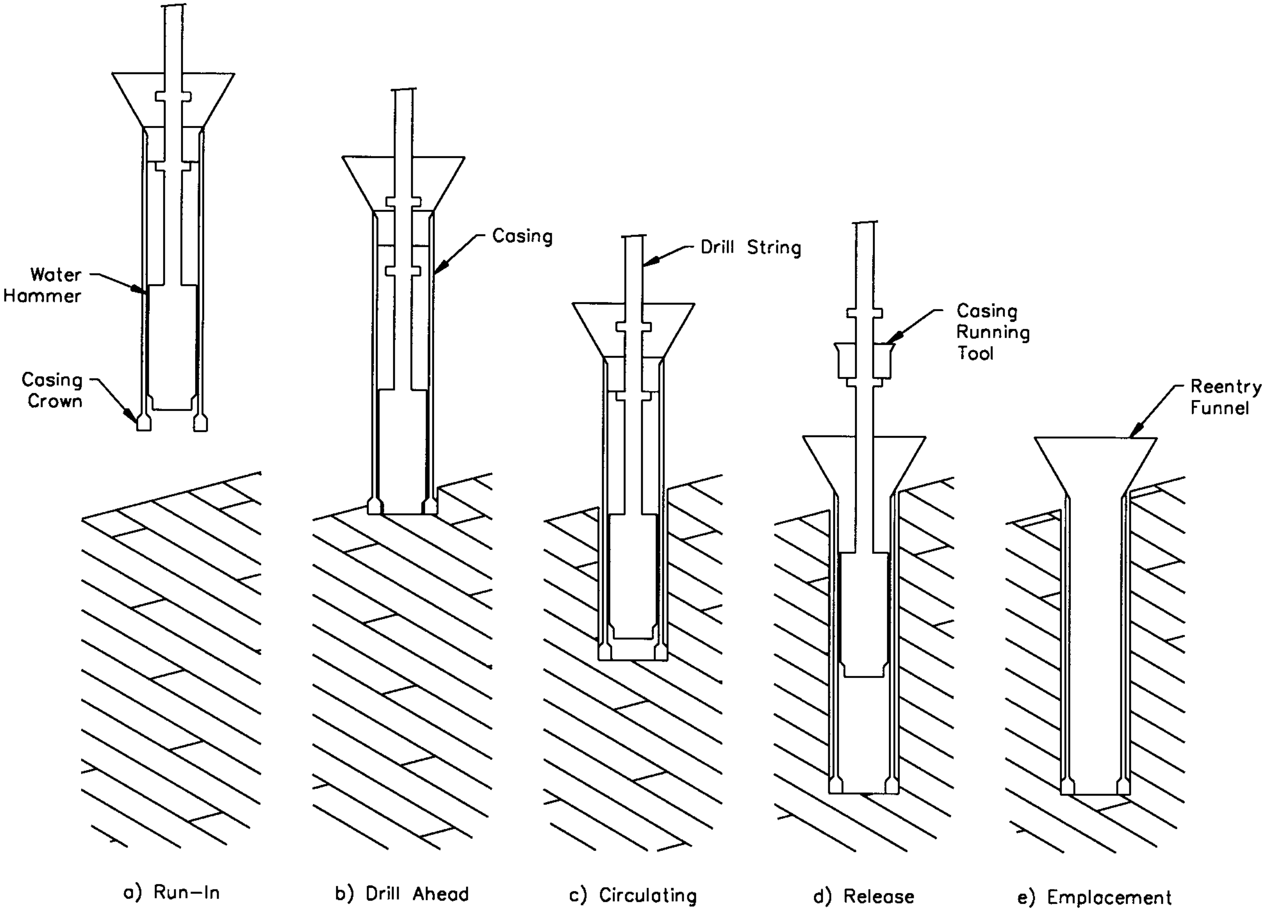


Figure 1. Location of the MARK area on the Mid-Atlantic Ridge. Inset shows Kane Transform, Site 395 (DSDP Legs 45 and 78B, ODP Legs 106 and 109), Sites 648 and 649 (ODP Leg 106), and Sites 669 and 670 (ODP Leg 109).



a) Run–In b) Drill Ahead c) Circulating d) Release e) Emplacement

Figure 2. Schematic diagram of Water Hammer Drill-In Casing System deployment.

LEG 175

BENGUELA CURRENT

Modified from Proposal 354 Submitted By

G. Wefer, V Spieß, U. Bleil, M. Breitzke, K. Gohl, R. Schneider,
G. Uenzelmann-Neben

Staff Scientist: Carl Richter **Co-Chief Scientists:** **Wolfgang Berger**
Gerold Wefer

ABSTRACT

Leg 175 proposes to drill nine APC/XCB sites off Angola and Namibia to reconstruct the Cenozoic history of the Benguela Current and the coastal upwelling off Angola and Namibia between 5°S and 32°S. The Angola/Namibia system is one of the great upwelling regions of the world, and extends over a considerable portion of the western margin of South Africa. Like the Peru system, which was studied during ODP Leg 112, it is characterized by organic-rich sediments that contain an excellent record of productivity history, which can be read on a very fine scale. In addition, this environment provides an excellent setting for natural experiments in diagenesis and in the formation of economically important resources such as petroleum and phosphate.

The individual transects reflect examinations of specific “endmember” upwelling environments, which collectively comprise one of the most concentrated centers of ocean productivity. One of the major aims will be to monitor the evolution of the Benguela Current system and its relationship with the onset of Northern Hemisphere and Antarctic glacial cycles. Many of the proposed sites are expected to have high-sedimentation rates, offering an opportunity to develop very detailed paleoceanographic records, and all proposed sites will expand and refine the partial record of the paleoceanographic and paleoclimatic changes since the early Miocene provided by DSDP Sites 362 and 532. Sediments will be largely diatomaceous and carbonate-rich clays with variable, and occasionally very high, organic-carbon contents.

INTRODUCTION

The ocean's role in climatic change, through heat transport and control of carbon dioxide, increasingly is being recognized. This new awareness, and the urgency that must be accorded the attempt to understand the mechanisms of climatic change, have led to the initiation of large integrated efforts in physical oceanography and chemical oceanography. Likewise, the potential of the ocean record for understanding climatic change has received increased attention in recent years (CLIMAP, 1976; COSOD II, 1987). The Angola/Namibia upwelling system needs to be studied because of its importance in the global ocean-carbon cycle, and to provide a counterpoint to the Peru system, for comparison. Only such comparison will allow us to determine which elements of the systems are peculiar, and which have general validity through time and on a global scale. Leg 175 will drill nine APC/XCB sites (Fig. 1) off the southeastern coast of Africa to study the paleoenvironment of the Benguela Current and Angola/Namibia upwelling system, with emphasis on the late Neogene, to further these goals.

Eastern boundary upwelling is strongly involved in modulation of the carbon cycle and hence in control of the partial pressure of calcium carbonate (pCO_2) ("biological pumping", Berger and Keir, 1984; Sundquist and Broecker, 1985; Boyle and Keigwin, 1987; Sarnthein et al., 1988). It is now generally thought that such pumping is a crucial factor for the explanation of short-term pCO_2 fluctuations, of the type seen in ice cores (Barnola et al., 1987). Along these lines of argument, there is a good correlation between productivity indices in the eastern equatorial Pacific and the ice-core record of pCO_2 (Fig. 2).

On a longer time scale, Vincent and Berger (1985) have postulated that depositional pumping by coastal upwelling is responsible for changing the general level of atmospheric pCO_2. They propose a climatic preconditioning by upwelling-induced carbon extraction from the ocean-atmosphere system for the beginning of the Neogene and, hence, the modern ice-cap dominated world. Their argument is based on the observation that carbon isotopes in deep-sea benthics become ^{13}C enriched just when organic-rich phosphatic sediments begin to accumulate around the Pacific margins (Fig. 3). In this view, eastern boundary upwelling, and therefore upwelling off Angola and Namibia, has global implications for the long-term history

of the carbon cycle and climate, and for the evolution of life and biogeography on land and in the sea.
To be able to predict the effects of changes in productivity on the CO_2 content of the atmosphere, the interrelationships between ocean circulation, nutrient transport, and the sedimentation of organic compounds and carbonate must be established for the important productivity regions. Until now, there is no information on the Neogene upwelling fluctuations off Angola and Namibia, a region that is probably of considerable importance for the global carbon cycle.

The most important period for understanding the workings of the present system is the development since the Miocene. These developments include the evolution of the present orography, the build-up of ice-caps on both poles, the development of modern wind and upwelling regimes, and a stepwise increase of North Atlantic Deep Water (NADW) production, which dominates the style of deep circulation of the ocean. The present system is characterized by a strong 100,000-yr component in the Milankovitch spectrum, throughout Brunhes time. A somewhat similar spectrum, with high amplitudes but with a lesser 100,000 yr component, exists since 2.5 to 2.4 Ma., in the North Atlantic (Shackleton et al., 1984).

BACKGROUND

The Angola/Namibia system is one of the five or six great upwelling regions in the world. It extends over a considerable portion of the western margin of South Africa, with productivity values of 180 gC/m^2yr, and greater (black areas in Fig. 4). Like the Peru system, which was studied during Leg 112, it is characterized by organic-rich sediments, in part deposited under anaerobic conditions. Such sediments contain an excellent record of productivity history, which, in part, can be read on a very fine scale (e.g., Schrader and Baumgartner, 1983). In addition, this environment provides an excellent setting for "natural experiments" in diagenesis, and in the genesis of economically important resources (e.g., petroleum and phosphate).

Upwelling off southwest Africa is at present centered on the inner shelf and at the shelf edge. The Benguela Current flows roughly parallel to the coast and within ~180 km of it south of 25°S, and then turns to the west over the Walvis Ridge between 23° and 20°S (Fig. 1). At about

20°S, warm, tropical-water masses from the north meet the cold Benguela Current water generating eddies. Eddies of cold, upwelled water contain radiolarian and diatom skeletons, which are transported from the upwelling area to the northern part of the Walvis Ridge, where they have been sampled at DSDP Sites 532 (Hay et al., 1984) and 362 (Bolli et al., 1978).

During the last glacial maximum the eddy formation took place farther north and the Benguela Current flowed parallel to the coast and over the Walvis Ridge to reach the Angola Basin, finally bearing to the west at about 17°S. Sediments deposited at Site 532 during the last glacial period confirm the absence of upwelling eddies by containing zero to very few opal skeletons (Hay et al., 1984; Diester-Haass, 1985). Upwelling may have continued to occur on the African shelf, but the Benguela Current did not transport that upwelling signal to the Walvis Ridge. In contrast, from the distribution of foraminiferal assemblages at Site 532 it was suggested that the northeastern Walvis Ridge was characterized by intensified upwelling and a westward expansion of coastal upwelling cells at glacial periods during the last 500,000 years (Oberhänsli, 1991).

The results from Sites 362 and 532 can be used to reconstruct, tentatively, the evolution of the Benguela Current during the past 10 m.y. The 5.2 m.y. transition between the two upwelling regimes marks an important event. At this time, the late Quaternary-Holocene circulation/upwelling pattern became established, perhaps in response to the migration of the polar front to its modern position at the same time.

In addition, the evolution of the climate of the Northern Hemisphere, and particularly that of northern Europe, is linked to the exchange of heat between the South Atlantic and the North Atlantic Oceans (Fig. 5). This energy transport, operating over large distances, is involved in the formation and magnitude of polar ice caps. In today's world, a net heat transfer from the South Atlantic to the North Atlantic exists in currents above the thermocline (Woods, 1981; McIntyre et al., 1989). A part of the heat contribution from the South Atlantic is believed to originate from the Indian Ocean via the Agulhas Current. The Benguela Current is a connection between the waters north of the polar front in the South Atlantic and the Equatorial Currents of the Atlantic. Northward and southward shifts of the Southern Ocean polar front constrict or expand, respectively, the interchange of heat from the Indian Ocean to the South Atlantic (McIntyre et al., 1989). This interchange has drastic impacts on the heat budget of the

Benguela Current and consequently that of the entire Atlantic Ocean. Such variations in heat transfers should appear as changes in the course of the current track and be recorded in the sedimentary accumulations along the southwest African margin.

Paleoceanographic interpretations are derived from the information from a single location off southwest Africa and must be considered preliminary. Given the strong likelihood that the axis and the intensity of the Benguela Current have changed over the past 15 m.y. and that the current has fluctuated with glacial/interglacial cycles, confirmation and refinement of these ideas is needed. Although DSDP Legs 40, 74, and 75 occupied sites in the Cape and Angola Basins and on the Walvis Ridge, these sites are situated too far offshore to provide the needed information. The Benguela Current and its associated upwelling are not recorded well in the sediments of these sites. Even Sites 362 and 532 on the Walvis Ridge are too far offshore to contain a direct record of upwelling. They receive an indirect record of near-coastal upwelling from material transported to their location by the Benguela Current. Furthermore, modern coring technology (APC, XCB) enables high-resolution studies by avoiding much of the drilling disturbance present in the Leg 40 cores. Such high resolution work is crucial if the dynamics of upwelling are to be captured on a scale of glacial-interglacial cycles back to the Miocene. Information from an array of sites situated in the southern and central Cape Basin, on the Walvis Ridge, and in the southern Angola Basin would allow the construction of a coherent picture.

SCIENTIFIC OBJECTIVES

The results from DSDP Sites 362 and 532 suggest that there has been a general northward migration of the Benguela Current upwelling system during at least the last 14 m.y. Because the shape of the South Atlantic has not changed appreciably during this time, the changes in the upwelling system must reflect large-scale, perhaps global, changes in ocean circulation. This leg will focus primarily on the paleoceanographic and paleoclimatic aspects of the area. However there is interest in investigating samples from the upwelling area off Angola and Namibia with regard to early diagenetic processes taking place in this unique environment. Possible work includes the formation of dolomites (Baker and Kastner, 1981), phosphorites (Calvert and Price, 1983), and cherts (see articles in Garrison et al., 1984). We also hope to examine the organic matter type and distribution as a function of time and climatic cycles. Important questions that can be answered with additional drill sites in this region include:

1. Determine the history and early evolution of the Benguela Current.

2. Study the history of productivity of the upwelling off Angola and Namibia and the influence of the Zaire River.

3. Determine what kind of oceanographic changes occur simultaneously in the Atlantic Ocean (Agulhas Current, polar front position, equatorial current, Argentine Current) with the shifting of the Benguela Current. Results from ODP Legs 108 and 114 can help define the equatorial and polar boundaries of the Benguela Current in the past. The final aim is to reconstruct the Oligocene to Quaternary paleocirculation pattern of the South Atlantic Ocean and try to evaluate the glacial-interglacial heat balance between the South and North Atlantic through time.

4. Determine if changes in the surface current/upwelling pattern of the Benguela Current cause, or are related, to changes in climates of western South Africa. For example, is desertification of the Namib related to the initiation of upwelling off Southwest Africa? Sites close to the continent probably contain enough information (clay minerals, grain size of terrigenous material, pollen, phytoliths, fresh water diatoms) to allow reconstruction of continental climatic changes and to determine whether these changes are synchronous with oceanographic changes (i.e., the establishment of upwelling off Southwest Africa).

5. Examine the effect of sea level changes, if any, on the Benguela Current. Published eustatic sea level curves (Haq et al., 1987) can be tested off Southwest Africa not only seismically, but also by sedimentological investigations.

6. Study early diagenetic processes in environments with very high organic carbon and opal contents, which will offer an interesting contrast to the studies undertaken during Leg 112 (Suess, von Huene, et al., 1990) off Peru. The upwelling sediments off the Peruvian active margin are deposited in fore-arc basins in a disturbed tectonic setting, while off Angola/Namibia sedimentation occurs on a steadily sinking passive margin with quite stable

conditions. Therefore, we expect a more continuous and longer record in comparison to the sites drilled off Peru, although the sedimentation rate might not be quite as high. Furthermore, sediments should be higher in organic carbon and opal content (Kulm et al. [1984] for Peru sediments, and Bremner [1983] for Namibia sediments).

DRILLING STRATEGY

Leg 175 will drill nine sites as part of a latitudinal transect between 5°S and 32°S. These sites are located in the Northern Angola Basin (NAB), Mid-Angola Basin (MAB), Southern Angola Basin (SAB), Walvis Ridge (WR), Northern Cape Basin (NCB), and Southern Cape Basin (SCB).

PROPOSED SITES

1. Northern Angola Basin (NAB)

Two NAB sites will sample a complex environment dominated by riverine input, seasonal coastal upwelling, and incursions from the southern equatorial counter current (Fig. 6). While these two sites represent the same depositional environment, they are located at varying distances from the shelf break, in different water depths, and at different positions with respect to the river plume and Congo Canyon.

2. Mid Angola Basin (MAB)

The MAB sites, off the bight of Angola near 12°S, were chosen to provide a section of "most nearly normal" margin sedimentation, being neither influenced by riverine input, or by sustained year-round upwelling. Upwelling, which is predominately related to the Angola Thermal Dome, is seasonal and productivity is relatively weak, compared with adjacent regions to the north and south (Schneider, 1991). This setting allows a maximum participation of a general, pelagic signal, in the regional high productivity record (Figs. 4 and 6). All proposed drill sites are located on seismic line GeoB 93-015, because the southerly profile GeoB 93-017 is significantly influenced by slumping of shelf sediments and turbidity currents. For each of the proposed sites a crossing seismic profile was shot perpendicular to line GeoB 93-015.

3. Southern Angola Basin (SAB)

The Southern Angola Basin sites will sample the northern end of the Angola/Namibia upwelling region. The transect should nicely complement previous results obtained from Walvis Ridge. This transect is important not only for the history of the Benguela Current and coastal upwelling migration, but also for its contribution to the climatic history of southern Africa. The Kunene River, reaching the coast at ~17°S, is at the climatological barrier between an illite zone in arid areas to the south and a kaolinite zone from tropical weathering areas to the north (Bornhold, 1973). The proposed sites are situated on a climatic boundary, and should sensitively reflect changes in the position of continental climatic zones. Suitable drill sites were identified from seismic lines in water depths between 2200 and 3000 meters. The bathymetric survey confirmed the complex nature of the depositional environment. Although the survey was not sufficient to analyze all structures in detail, it is clear from the combined HYDROSWEEP and PARASOUND echosounder data set that few potential drill sites may be found in the area. Seismic line GeoB 93-030 lies across the proposed drill sites (Table 1). Stratigraphic data from two gravity cores (GeoB 1023-5, 17°09.4'5, 11°00.7'E, water depth 1918 m; GeoB 1024-2, 17°09.8'E, water depth 2799 m) show high Pleistocene sedimentation rates (10-50 cm/1000 yr) (Schneider et al., 1992; Wefer et al., 1988).

4. Walvis Ridge (WR)

Site WR 1 together with DSDP Sites 532 and 362 (Legs 75 and 40) in 1300 m water depth form a transect that is central to the reconstruction of the history of the Benguela Current. The DSDP sites are seaward of the upwelling center, but contain an upwelling signal that has been transported to this location by the Benguela Current. At the other end of the transect, proposed site WR 1 will give a better record of the upwelling itself. This transect, situated as it is on the only topographic high over which the Benguela Current passes, is central to the reconstruction of the history of the current. Two cores ~11-m long (GeoB 1705-1, 19°30.3'S, 11°23.9'E, water depth 642 m and GeoB 1706-2, 19°33.7'S, 11°10.5'E, water depth 980 m) taken near proposed site WR 1 show sedimentation rates of 4-7 cm/1000 yr (Schulz et al. 1992).

5. Northern Cape Basin (NCB)

The NCB site will help document the northward migration of the Benguela Current system from the Miocene (perhaps Oligocene) to the Quaternary as well as the shoreward/seaward migration of the upwelling center (Figs. 4 and 5). The site will also provide a record of maximum productivity in the system. Previous work in this area (for a summary see Dingle et al., 1987) has documented anaerobic, in part varved, sedimentation in the upper margin regions. Phosphatic deposits also are abundant (Calvert and Price, 1983).

The results of Emery et al. (1975) and Austin and Uchupi (1982) show a thick hemipelagic wedge sitting on "rifted continental crust." Slumps would not seem to pose a problem. Noteworthy is the confirmation of a thick sequence below the shelf region. A close tie-in between pelagic and terrigenous sedimentation is expected to be present within the slope record. During the SONNE cruise SO-86, vertical profiles were shot over MCS line AM-1 collected by the University of Texas to obtain detailed data for the planned site. A first stratigraphy on an 11-m-long core taken in the high-production upwelling area off Namibia (GeoB 1711-4, 23°18.9'S, 12°22.6'E) from a depth of 1967 m indicated a sedimentation rate of 11 cm/1000 yr (Schulz et al., 1992).

6. Southern Cape Basin (SCB)

This site is located in the southernmost area of the Cape Basin (Fig. 1) to explore the early history of the Benguela Current in the southern Cape Basin and to detect possible Agulhas Current influences. The site is located close to the continent to detect upwelling signals and signals from continental climates (pollen, clay minerals, coarser terrigenous matter) and signals related to sea level changes. South of the proposed transect the margin becomes too steeply sloped to support undisturbed sediments. Site SCB 1 is located along MSC line AM-54 collected by the University of Texas. For an 11-m-long core from about the same water depth (GeoB 1719-7, 28°55.6'S, 14°10.7'E, water depth 1010 m) but about 150 miles to the north, a sedimentation rate of about 5 cm/1000 yr was determined (Schulz et al. 1992).

As recommended by the OHP, we could probably reach the Paleogene at Site SCB 1 with a relatively deep hole. However, drilling through 1300 m of sediment would take 9.5 days instead of 3.5 days (Hole SCB 1, to 600 m). It would not be possible to include the additional 6 days in the one-leg proposal. Another possibility for obtaining a Paleogene core might be Site WR 1 (750 m water depth on the Walvis Ridge).

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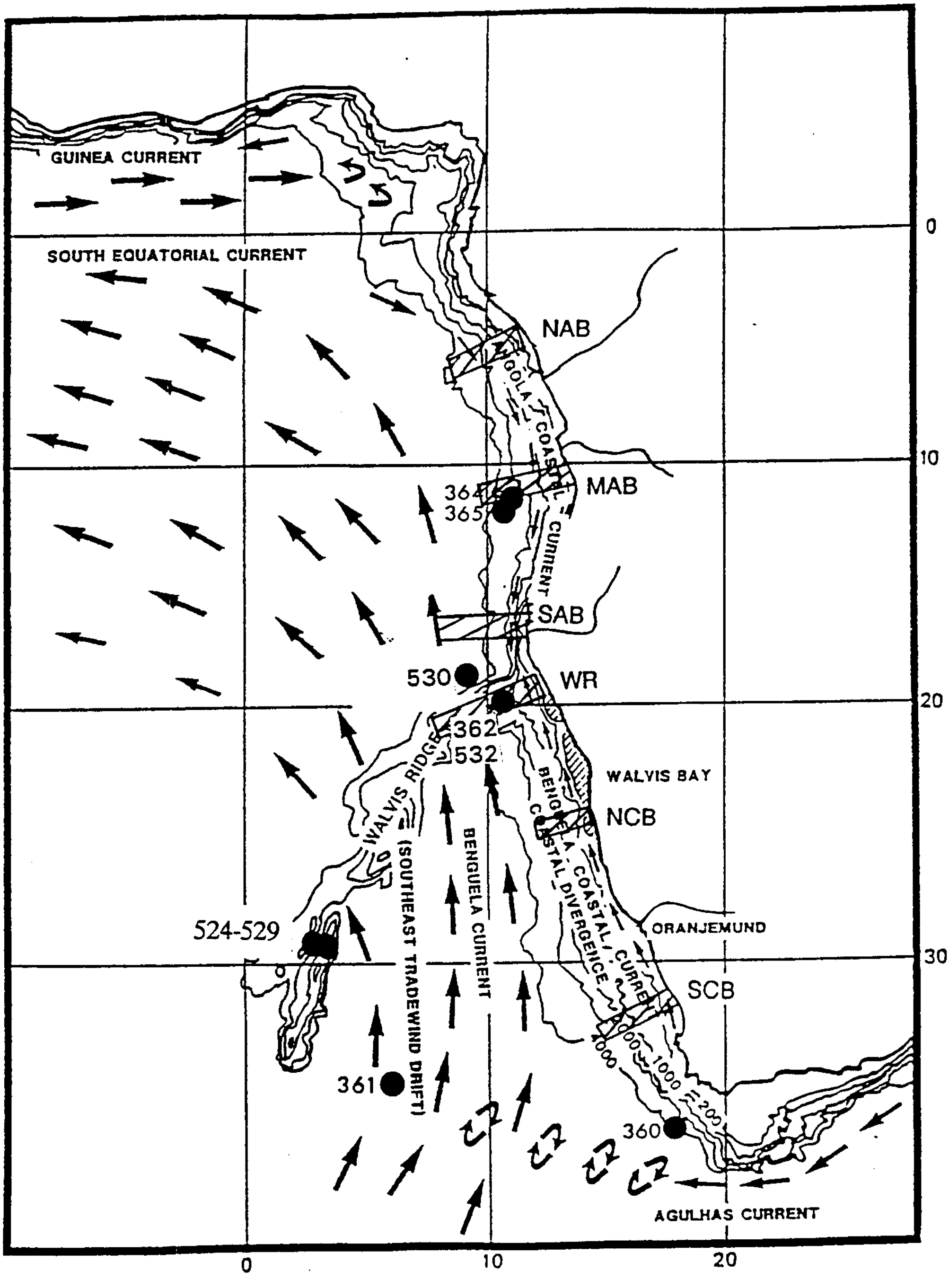

Figure 1. Overview map (from Hay and Brook, 1992) showing planned transects as well as DSDP sites.
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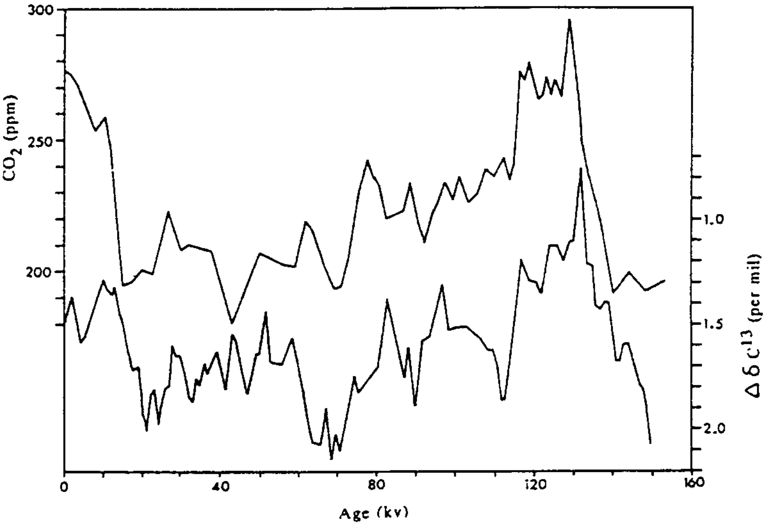


Figure 2. Carbon dioxide concentrations in the Vostok ice core from Antarctica (Barnola et al., 1987), compared with a productivity-related carbon isotope signal from the eastern tropical Pacific (difference between the $\partial^{13}C$ values of planktonic and benthic foraminifera; Shackleton et al., 1983), show that ocean productivity and atmospheric CO_2 tend to vary together. Time scale of Barnola et al. is adjusted to the one of Shackleton et al. by correlation of the deuterium signal in the ice with the oxygen isotope signal in the sediment (from Berger et al., 1989).

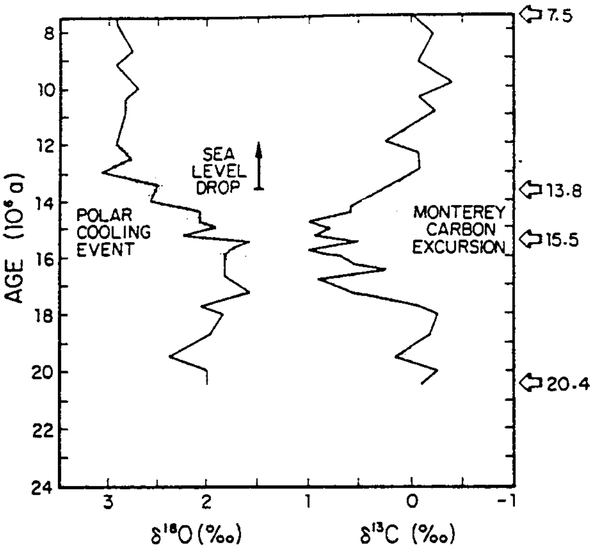


Figure 3. Relationship between $\partial^{18}O$ record and $\partial^{13}C$ record of benthic foraminifera, DSDP Site 216, tropical Indian Ocean. It suggests that extraction of organic carbon in upwelling regions during Monterey time eventually resulted in cooling, from pCO_2 downdraw (from Berger, 1985).

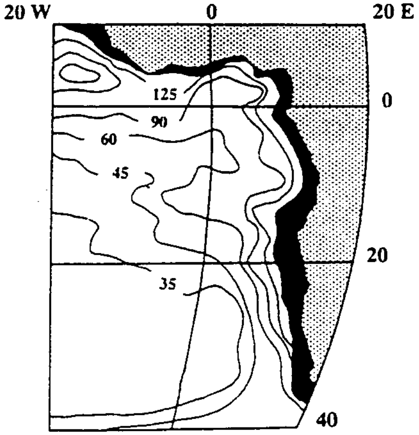


Figure 4. Angola/Namibia upwelling system off southern Africa, as seen in productivity distributions. From Berger (1989, modified). Numbers are primary production in gC/m^{2}yr; black area values are greater than 180 gC/m^{2}yr.

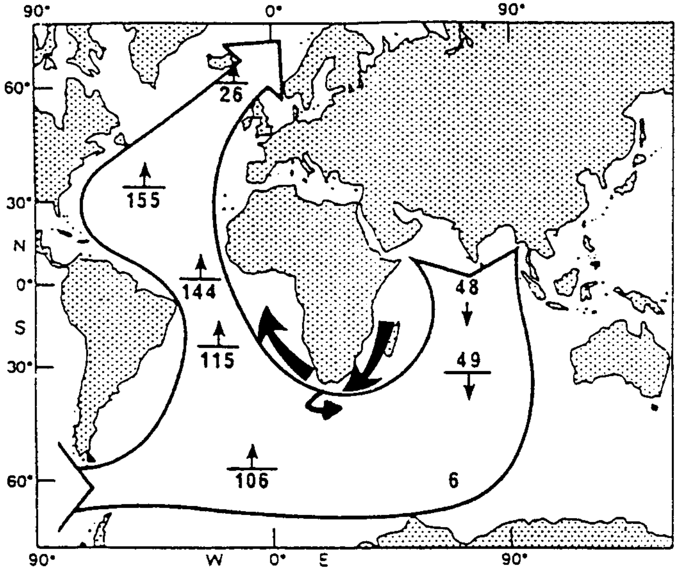
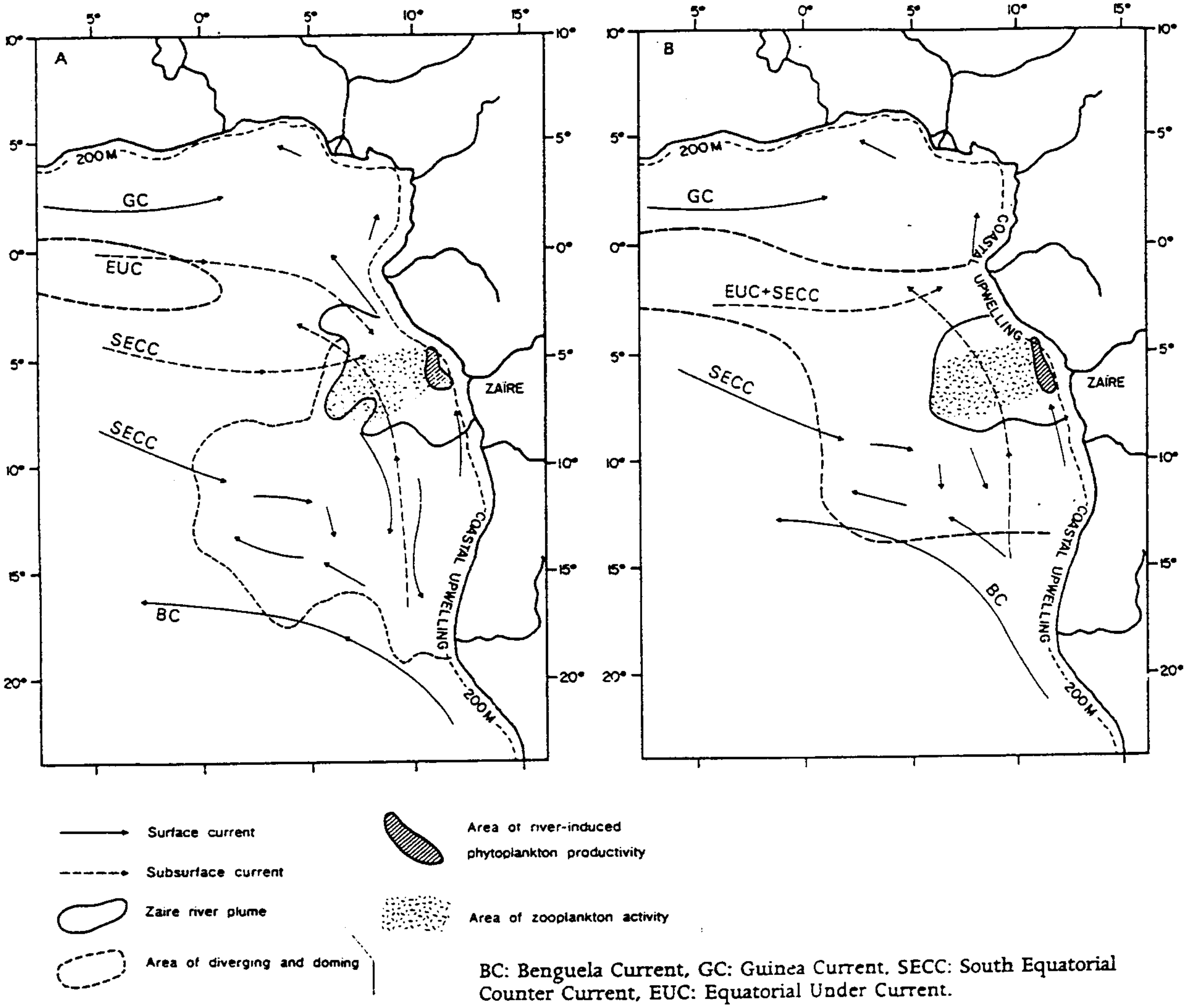


Figure 5. Meridional heat transport in the Indian and Atlantic Oceans (from Woods, 1981, modified). Note the major transfer of heat from the Indian Ocean to the Atlantic, which can be modulated through time.



BC: Benguela Current, GC: Guinea Current, SECC: South Equatorial Counter Current, EUC: Equatorial Under Current.

Figure 6. Regional setting of Angola Transects (from Jansen, 1985). Note that glacial/interglacial contrast, which is reflected in more or less distinct shifts in subsystem boundaries. Perhaps more important are changes in intensity of upwelling and current strength (not shown).

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: NAB-1 **PRIORITY**: **POSITION**: 5˚3.6'S, 11˚6.6'E
WATER DEPTH: 1397 m **SEDIMENT THICKNESS**: >500 m **TOTAL PENETRATION**: 400 m
SEISMIC COVERAGE: GeoB 2301

Objectives: Paleoproductivity/environmental record of fan margin deposits

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Hemipelagic foram and diatom bearing muds

SITE: NAB-4 **PRIORITY**: **POSITION**: 4˚46.8'S, 10˚4.8'E
WATER DEPTH: 3001 m **SEDIMENT THICKNESS**: 600 m **TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: GeoB 93-002

Objectives: Paleoproductivity/environmental record of fan margin deposits; most distal location to Congo Canyon

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Hemipelagic foram and diatom bearing muds

SITE: MAB-1 **PRIORITY**: **POSITION**: 11˚54'S, 13˚21.6'E
WATER DEPTH: 550 m **SEDIMENT THICKNESS**: >500 m **TOTAL PENETRATION**: 400 m
SEISMIC COVERAGE: GeoB 93-015, GeoB 93-018

Objectives: Continental margin sedimentation; paleoproductivity

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Hemipelagic foram and diatom bearing muds

SITE: MAB-3	**PRIORITY**:	**POSITION**: 11˚54'S, 13˚7.2'E
WATER DEPTH: 1178 m	**SEDIMENT THICKNESS**: >500 m	**TOTAL PENETRATION**: 400 m
SEISMIC COVERAGE: GeoB 93-015, GeoB 93-022		

Objectives: Continental margin sedimentation; paleoproductivity

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Hemipelagic foram and diatom bearing muds

SITE: MAB-5A	**PRIORITY**:	**POSITION**: 11˚58.2'S, 12˚53.4'E
WATER DEPTH: 1159 m	**SEDIMENT THICKNESS**: >1000 m	**TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: GeoB 93-015, GeoB 93-028		

Objectives: Continental margin sedimentation; paleoproductivity

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Hemipelagic foram and diatom bearing muds

SITE: SAB-2	**PRIORITY**:	**POSITION**: 11˚33.6'S, 10˚49.2'E
WATER DEPTH: 2770 m	**SEDIMENT THICKNESS**: >1000 m	**TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: GeoB 93-030, GeoB 93-033		

Objectives: Paleoproductivity - upwelling history; relationship to current systems

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT, GHMT, FMS

Nature of Rock Anticipated: Hemipelagic foram and diatom bearing muds

SITE: WR-1	**PRIORITY**:	**POSITION**: 11˚33.6'S, 10˚49.2'E
WATER DEPTH: 750 m	**SEDIMENT THICKNESS**: 1200m	**TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE:		

Objectives: History of Benguela Current

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Nannofossil ooze and chalk

SITE: NCB-2 **PRIORITY**: **POSITION**: 25°30'S, 13°4.8'E
WATER DEPTH: 1850 m **SEDIMENT THICKNESS**: 2000 m **TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: GeoB 93-044, MCS line AM-1

Objectives: History of Benguela Current

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT

Nature of Rock Anticipated: Nannofossil ooze and chalk

SITE: SCB-1 **PRIORITY**: **POSITION**: 31°24'S, 15°16.8'E
WATER DEPTH: 1350 m **SEDIMENT THICKNESS**: 3800 m **TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: MCS line AM-54

Objectives: History of Benguela Current

Drilling Program: APC/XCB

Logging and Downhole Operations: Quad combo, GLT, GHMT, FMS

Nature of Rock Anticipated: Nannofossil ooze and chalk

LEG 176

RETURN TO HOLE 735B

Modified from Proposal 300-Rev Submitted By:

H.J.B. Dick, S. Hart, J.H. Natland, P. Robinson, R. Stephen,
and R.P. von Herzen

Staff Scientist: Jay Miller **Co-Chief Scientists:** **Henry Dick**
James Natland

ABSTRACT

Leg 176 will deepen Hole 735B, originally drilled during ODP Leg 118 on the Southwest Indian Ridge off the southeast coast of Africa, to a nominal depth of 2 km. This endeavor takes advantage of the unique outcrop of the lower oceanic crust exposed along a 15-km-long wave-cut terrace 18 km east of the Atlantis II Transform Fault. At 500 m below seafloor, Hole 735B represents the deepest penetration into plutonic basement in the world's oceans. Further drilling operations will improve our understanding of the nature of the ocean crust. Studies engendered by this project will directly address recent geophysical investigations, placing regional and potentially global constraints on ocean crustal structure and evolution.

The principal objective of Leg 176 is to recover a representative section through the lower ocean crust and potentially into the upper mantle by deepening Hole 735B to at least 2 km, possibly making this the deepest hole ODP has ever drilled. A complete logging suite will complement the downhole data acquired during Leg 118, as well as serve as a singular example of the utility of logging tools in deep basement drilling. Assuming the nearly complete recovery achieved on Leg 118 continues on this project, a representative suite of all lithologies in this section will be sampled. This lithologic suite will be used to develop an internally consistent model of the igneous, metamorphic, and tectonic processes that occurred during the formation and subsequent exhumation of this section through the ocean crust. If drilling conditions prevent deepening Hole 735B, an alternate strategy originally envisioned as the second of a two-leg drilling plan, will be adopted. This alternate strategy will test the lateral and temporal variability in the deep ocean crust by drilling a series of 500-m-deep holes, offset by 100,000-yr increments along a lithospheric flow line.

INTRODUCTION

Despite the success of previous ODP legs, which set out to sample exposures of the lower oceanic crust and upper mantle, many questions regarding the compositional heterogeneity, stratigraphy, and petrogenesis of the ocean crust remain unanswered. Leg 176 will return to Site 735 on the Southwest Indian Ridge to deepen Hole 735B to at least 2 km to in order to characterize the nature of the lower oceanic crust at a slow-spreading ridge. Hole 735B was originally drilled to 500 m below the seafloor (mbsf), into gabbroic rocks exposed on a wave-cut terrace atop the transverse ridge flanking the Atlantis II Fracture Zone (Fig. 1). The primary objective of this leg is to investigate the magmatic, metamorphic, and tectonic processes that attend seafloor spreading in the lower oceanic crust. Based on the phenomenal recovery and superb operational conditions encountered when Hole 735B was cored during Leg 118, we expect that deepening the hole will provide core that will directly address current models of the seismic structure of the oceanic crust. These operations will also provide information on the role of fractures and fluid penetration into the lower oceanic crust and perhaps the sub-oceanic mantle, and define gradients in metamorphic facies, if they exist. From a tectonic perspective, deepening Hole 735B will establish the spacing and morphology of major ductile-shear zones recognized in the recovered core from Leg 118. Layered cumulate gabbros, as might be expected according to the ophiolite model of ocean crust stratigraphy, were not included in the nearly complete section recovered during Leg 118. Only continued drilling will establish if these lithotypes are indeed absent in this environment, discounting the hypothesis of a long-lived magma chamber. Additionally, recognizing that dredging along the fracture zone has recovered mantle lithologies, and that remote sensing studies have established the presence of a seismic transition with potential correlation to the crust/mantle boundary, we have the opportunity to sample, for the first time, the transition between rocks produced by crystallization of magma extracted from the Earth’s mantle and the residues from which these liquids were derived. The overriding goal of this project is to recover sufficient gabbroic rock to ensure representation of all major lithologies to develop a consistent model of the igneous, metamorphic, and tectonic processes that occurred during the formation and subsequent exhumation of this section through the ocean crust.

In the event that drilling conditions preclude deepening Hole 735B, we propose to drill a transect of 500-m-deep holes away from Hole 735B along a lithospheric flow line. Because

800-m spacing of these holes equates to 100,000-yr age increments along the flow line, we will be able to test lateral and temporal variability of processes in the lower oceanic crust. This proposed transect of at least three holes will span an interval of 400,000 years of crustal generation. Owing to basement rotation perpendicular to the flow line, we should sample successively deeper parts of the section, which will reflect multiple magmatic and amagmatic episodes.

BACKGROUND

After an initial debate in the late 1950s and early 1960s, a consensus was achieved for a fairly straightforward layer-cake geologic model for the stratigraphy of the ocean crust. This model was based on the match of density and *P*- and *S*-wave velocities of gabbro, diabase, and tholeiitic basalt dredged from the seafloor and found in ophiolite complexes (fossil sections of ocean crust tectonically emplaced in island arcs and continental margins) to the seismic character of the ocean crust (e.g., Christensen, 1972). An overall stratigraphy was then compiled extrapolating the observed simple-layered seismic structure to the vertical lithologic stratigraphy seen in tectonically disrupted ophiolites.

Based on this information, layer 3 was expected to consist of a uniform layer of magmatic cumulates deposited on the floor and walls of a large continuous magma chamber, overlain by evolved ferrogabbros along its roof. In reality, this internal stratigraphy was more dependent on the documented stratigraphy of the large layered intrusions found on the continents than it was on the internal stratigraphy of gabbros in ophiolites. These large layered intrusions have dominated the thinking of the petrologic community with their systematic progression in chemistry from top to bottom and their historic role in establishing the key role of fractional crystallization in the evolution of magmas. It has been a natural impulse to impose their stratigraphy on that of lower crust in both ophiolites and the present-day ocean basins, thereby, evolving the extremely attractive paradigm of the "infinite onion.” The "infinite onion" example consists of a large continuous magma chamber underlying the global ocean ridge system, disrupted only by the largest of ocean fracture zones, from which layers of ocean crust continuously grow at top, sides, and bottom to form a uniform coarse gabbroic layer comprising two thirds of the ocean crust (Cann, 1970).

Two decades of geophysical testing of this model and study of the stratigraphic structure and chemistry of ophiolites have thrown this simple paradigm into question. Interpretations of seismic structure along ridges have become increasingly complex, while the provenance of ophiolites has become increasingly ambiguous and generally believed to be atypical of ocean crust. Recent work suggests that the ocean crust has a complex, three-dimensional structure that is highly dependent on magma supply and spreading rates without large steady-state magma chambers (e.g., Whitehead et al., 1984; Detrick et al., 1990; Sinton and Detrick, 1992; Barth, 1994; Carbotte and MacDonald, 1994). Compilations of dredge results and seismic data have suggested that a continuous gabbroic layer does not exist at slow-spreading ridges (Mutter et al., 1985; NAT Study Group, 1985; McCarthy et al., 1988; Dick, 1989; Cannat et al., 1992; Tucholke, unpubl. data), and that its internal stratigraphy is governed by dynamic processes of alteration and tectonism as much as by igneous processes. The exceptional abundance of serpentinized peridotite in dredge hauls from the walls of rift valleys in fracture zones and in the rift mountains away from fracture zones (Aumento et al., 1971; Rona et al., 1987; Dick, 1989; Cannat et al., 1992; Tucholke, unpubl. data) is also raising the serious possibility that serpentinite is a major component of seismic layer 3, as originally suggested by Hess (1962).

This re-evaluation of the geometric relationships between lower oceanic crust and the upper mantle has led to the development of three general models for the lithologic architecture of slow-spreading ocean crust (Fig. 2). One model (Fig. 2A) proposes that relatively small gabbroic bodies discordantly cut each other and the upper mantle, with the proportion of gabbroic bodies to mantle lithologies diminishing with depth (see Swift and Stephen, 1992; Cannat, 1993; Sleep and Barth, 1994). This model suggests that the primitive troctolites recovered from the bottom of Hole 735B represent deep level gabbroic rocks, and continued drilling should rapidly intersect upper mantle lithologies. A second interpretation (Fig. 2B) is that the lower crust is made up of an assembly of small discordant gabbroic bodies that transit abruptly into the upper mantle following the concept proposed by Cann (1970) and Nisbet and Fowler (1978) and recently amplified by Smith and Cann (1993). Finally, a third model based on ophiolite studies (Fig. 2C) suggests that the discordant gabbroic bodies occur only in the upper crust, and then grade downward into large layered gabbro intrusions, which overlie and have a sharp magmatic contact with upper mantle peridotite (Pallister and Hopson, 1981; Smewing, 1981). While recent wide-angle seismic profiles over and around the Atlantis II Bank image a distinct Moho with a 4-5 km thick overlying layer (Müller et al., 1995), these data do not unequivocally rule out any of the three models. This seismic boundary may represent a magmatic transition from gabbroic rocks to peridotite; alternatively we could be seeing a transition from hydrous serpentinized peridotite and fresher peridotite. The gabbroic rocks recovered from the 500-m penetration of Hole 735B are invaluable in detailing the compositional heterogeneity of the deep ocean crust; however, they provide insufficient information to determine which model is correct. Consequently, the primary objective of deepening Hole 735B is to penetrate deeply enough into the ocean crust to evaluate which model is most applicable to slow-spreading oceanic crust. An obvious potential highlight of this drilling program is that we may meet one of the longstanding ambitions of several ODP thematic panels and a principal objective of the Mantle/Crust Interactions Working Group at COSOD II—sampling the transition from the oceanic crust to the upper mantle.

Previous Investigations at Site 735

During Leg 118, a large intact 500-m section of gabbros was recovered from Site 735. These gabbros were unroofed and uplifted on the transverse ridge flanking the Atlantis II Fracture Zone. The complex internal structure and stratigraphy of the recovered section provided a first look at the processes of crustal accretion and on-going tectonism, alteration, and ephemeral magmatism at a slow-spreading ocean ridge. The section was not formed in a large steady-state magma chamber, but by continuous intrusion and reintrusion of numerous small, rapidly crystallized bodies of magma. There is little evidence of the process of magmatic sedimentation that is so important in layered intrusions. Instead, new batches of magma are intruded into and initially supercooled by a lower ocean crust that consists of wholly crystalline rock and semisolidified crystal mush. This leads to undercooling and rapid initial crystallization of new magmas to form a highly viscous or rigid crystal mush that prevents the formation of magmatic sediments. Initial crystallization is followed by a longer, and petrologically more important, period of intercumulus melt evolution in a highly viscous crystal mush or rigid melt crystal aggregate.

As a consequence, long-lived magma chambers or melt lenses were virtually absent throughout most of crustal formation beneath the Southwest Indian Ridge. Thus, melts in the highly viscous or rigid intrusions were largely uneruptable throughout most of their crystallization. This explains the near absence of highly evolved magmas such as ferrobasalts along the Southwest Indian Ridge (Dick, 1989), as opposed to fast-spreading ridges where they are common and a long-lived melt lens is believed to underlie the ridge axis (e.g., Sinton and Detrick, 1992).

Wall-rock assimilation occurring while small batches of melt work their way up through the partially solidified lower crust appears to have played a major role in the chemical evolution of the section and, therefore, in the chemistry of the erupted basalt. This process has been largely unevaluated for basalt petrogenesis to date, which has thrown into question the simple models for the formation of mid-ocean-ridge basalt (MORB) drawn from experimental studies. These studies assume equilibrium crystallization and melting processes throughout magma genesis.

An unanticipated major feature of the drilled section is the evidence for deformation and ductile faulting of the still partially molten gabbros. This deformation apparently occurred over a narrow window, late in the cooling history of the gabbros (probably at 70-90% crystallization) when they became sufficiently rigid to support a shear stress. This produced numerous small and large shear zones, creating zones of enhanced permeability into which the late intercumulus melt moved. This synkinematic igneous differentiation of intercumulus melts into the shear zones transformed the gabbro there into oxide-rich ferrogabbros. The net effect of these magmatic and tectonic processes was to produce a complex igneous stratigraphy with undeformed oxide-free olivine gabbros and microgabbros criss-crossed by bands of sheared ferrogabbro. Synkinematic differentiation is probably ubiquitous in lower ocean crust formed at slow-spreading ocean ridges, and should be recorded in ophiolite suites formed in similar tectonic regimes.

At Site 735, ductile deformation and shearing continued into the subsolidus regime, causing recrystallization of the primary igneous assemblage under granulite facies conditions, and the formation of amphibole-rich shear zones (Stakes et al., 1991; Dick et al., 1991a; Cannat et al., 1991). Here again, formation of ductile shear zones localized late fluid flow with the most intense alteration occurring in the ductile faults (Dick et al., 1991a). Undeformed sections of gabbro also underwent enhanced alteration at this time principally by replacement of pyroxene and olivine by amphibole.

A consequence of simultaneous extension and alteration has been far more extensive alteration at high temperatures than found in layered intrusions that were intruded and cooled in a static environment. An abrupt change in alteration conditions of the Hole 735B gabbros, however, occurred in the middle amphibolite facies with the cessation of shearing and ductile deformation. Mineral vein assemblages changed from amphibole-rich to diopside-rich, reflecting different fluid chemistry. Continued alteration and cooling to low temperature occurred under static conditions similar to those found for large layered intrusions. These changes likely occurred due to an inward jump of the master faults defining the rift valley walls, thus transferring the section out of the zone of extension and lithospheric necking beneath the rift valley into a zone of simple block uplift in the adjoining rift mountains. Ongoing hydrothermal circulation, no longer enhanced by stresses related to extension, was greatly reduced, driven only by thermal-dilation cracking as the section cooled to ambient temperature.

The complex section of rock drilled at Site 735 formed beneath the very slow-spreading Southwest Indian Ridge (0.8 cm/yr half rate) and represents the slow end of the spectrum for crust formation at major ocean ridges far from hot spots. Such ridges have the lowest rates of ocean ridge magma supply, and crustal accretion is most heavily influenced by deformation and alteration. At the opposite end of the spreading rate spectrum (7-9 cm/yr), where the majority of the seafloor has formed, the crustal stratigraphy is likely different. Judging from the results of Hole 735B, the critical brittle-ductile transition has migrated up and down through the lower crust due to the waxing and waning of magmatism beneath the Southwest Indian Ridge. In contrast, this transition may be more stable near the sheeted dike gabbro transition at faster spreading ridges such as the East Pacific Rise, reflecting a near steady-state magma chamber or crystal mush zone. This should produce an internal stratigraphy for the lower crust quite different than that described here.

The rather general conclusions drawn to date from Hole 735B, so different from what was anticipated, are based on study of only a small part of what is likely to be a 2- to 4-km-thick section, and thus may represent only part of a more complex overall stratigraphy. By deepening Hole 735B and eventually drilling an offset section of holes along a lithospheric flow line, we will obtain a representative section of the lower ocean crust at one of the two critical ends of the spreading spectrum that, together with seafloor mapping, will permit a true three-dimensional view of the ocean crust. The suite of holes will also provide a natural laboratory for downhole geophysical experiments, where hole-to-hole magnetotelluric and permeability experiments can be conducted, and that will provide a downhole seismic laboratory from which the nature of layer 3 may be directly tested.

Tectonic Setting

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

Over the last 34 m.y., the spreading rate along the Southwest Indian Ridge has been relatively constant, near 0.8 cm/yr, at the very slow end of the spreading-rate spectrum (Fisher and Sclater, 1983). All the characteristic features of slow-spreading ridges, including rough topography, deep rift valleys, and abundant exposures of plutonic and mantle rocks, are present on the Southwest Indian Ridge (Dick, 1989). Significantly, two thirds of the rocks dredged from the walls of the active transform valleys are altered mantle peridotites, whereas most of the remainder are weathered pillow basalts. This exceptional abundance of peridotite, compared to dredge collections of similar size from the North Atlantic, indicates an unusually thin crustal section in the vicinity of Southwest Indian Ridge transforms. Moreover, the paucity of dredged gabbro along the Southwest Indian Ridge suggests that magma chambers were small or absent near fracture zones.

The thin crust adjacent to fracture zones is thought to reflect segmented magmatism along the Southwest Indian Ridge that produces rapid along-strike changes in the structure and stratigraphy of the lower ocean crust (e.g., Whitehead et al., 1984; Francheteau and Ballard, 1983; Crane, 1985; Schouten et al., 1985; MacDonald et al., 1986). This model views the Southwest Indian Ridge as a series of regularly spaced, long-lived shield volcanoes and underlying magmatic centers, which undergo continuous extension to form the ocean crust (Dick, 1989). Site 735 is situated some 18 km from the Atlantis II Transform Fault, and was accordingly situated near the mid-point of a hypothetical magmatic center beneath the Southwest Indian Ridge at 11.5 Ma (Dick et al., 1991b).

Geology of the Atlantis II Fracture Zone

Hole 735B is located on a shallow bank, informally named Atlantis Bank, on the crest of a 5-km-high mountain range constituting the eastern wall of the Atlantis II Transform valley. This transverse ridge is similar to many other flanking fracture zones on the Southwest Indian Ridge (e.g., Engel and Fisher, 1975; Sclater et al., 1978, Fisher et al., 1986; Dick, 1989) where abundant plutonic rocks, particularly peridotite, are uplifted to a shallow level and exposed. The bank consists of a platform, roughly 9 km long in a north-south direction and 4 km wide, which is the shallowest of a series of uplifted blocks and connecting saddles that form a long, linear ridge parallel to the transform. The top of the platform is flat, with only about 100 m relief over 20 km^2. A video survey of a 200 x 200 m area in the vicinity of the hole showed a smooth flat wave-cut platform exposing foliated and massive jointed gabbro locally covered by sediment drift. The platform probably formed by erosion of an island similar to St. Paul's Rocks in the central Atlantic, and then subsided to its present depth from normal lithospheric cooling (Dick et al., 1991b). A similar wave-cut platform occurs on the ridge flanking the DuToit Fracture Zone (Fisher et al., 1986).

The foliation seen in the video survey and at the top of the drill core appears to strike east-west, parallel to the ridge axis and orthogonal to the fracture zone. The orientation of similarly foliated peridotites exposed on St. Paul's Rocks has been measured and is also parallel to the Mid-Atlantic Ridge and orthogonal to St. Paul's Fracture Zone (Melson and Thompson, 1971). This foliation, projected along strike across the Atlantic Bank platform, intersects a long ridge coming up the wall of the fracture zone, which is oriented obliquely west-northwest to the transform. Ridges produced by land-slips and debris flows normally are oriented orthogonal to the fracture zone. The suspicion then is that this oblique ridge and a similar one 2 km to the north represent the trace of the thick zone of foliated gabbros down the wall of the transform. Given the once shallow water depth, the canyon between the two ridges may be erosional and the foliated gneissic amphibolites resistant remnants. A three-point solution for the dip of the shear zone, based on the trend of this ridge, and an east-west strike gives a dip of approximately 40˚, which is close to that observed in the drilled amphibolites.

This shear zone represents a ductile-fault, and thus does not represent a simple stratigraphic discontinuity. The rocks at the top of the shear zone are gabbronorites that pass gradually into a zone of olivine gabbro toward its base. The shear sense determined from drill cores is normal. Thus, it would appear that the rocks to the north of the drill site are down-thrown an unspecified amount. Any offset drill sites to the north would start higher in the stratigraphic section.

The site is located between magnetic anomalies 5 and 5a, approximately 93 km south of the present-day axis of the Southwest Indian Ridge and 18.4 km from the inferred axis of transform faulting on the floor of the Atlantis II Fracture Zone (Dick et al., 1991b). Given the position of the site, the relatively constant spreading direction over the last 11 m.y., and the ridge-parallel strike of the local foliation, the Atlantis Bank gabbros must have crystallized and deformed beneath the median valley of the Southwest Indian Ridge, 15 to 19 km from the ridge-transform intersection, around 11.5 Ma. A single Pb-zircon of 11.3 Ma, as reported by Stakes et al. (1991) for a trondhjemite in amphibolite near the top of the hole, confirms the age determined by plate reconstruction.

The gabbros were subsequently uplifted in a large horst from beneath the rift valley 5 to 6 km up into the transverse ridge (Dick et al., 1991b). The single uniform magnetic inclination throughout the section demonstrates that there has been no late tectonic disruption of the section, although the relatively steep inclination suggests block rotation of up to 18˚ (Pariso et al., 1991). Thus, unlike some rocks dredged from fracture-zone walls, those drilled in Hole 735B formed beneath the rift-valley floor away from the transform fault. Petrologically, these rocks likely represent a typical igneous section of Southwest Indian Ridge ocean crust with an intact metamorphic and tectonic stratigraphy. The rocks, thereby, record brittle-ductile deformation and alteration at high temperatures beneath the rift valley, as well as subsequent unroofing and emplacement on ridge-parallel faults.

The unroofing and exposure of the Hole 735B section relates to the present-day asymmetric distribution of plutonic and volcanic rocks north and south of the ridge axis near the fracture zone, as well as to the striking physiographic contrast between crust spreading in opposite directions at the ridge-transform intersection (Fig. 3) (Dick et al., 1991b). These features suggest that a crustal weld periodically formed between the shallow levels of the ocean crust and the old, cold lithospheric plate at the ridge-transform intersection. This weld caused the shallow levels of the newly formed ocean crust to spread with the older plate away from the active transform, thereby causing the creation of long-lived detachment faults. Beneath the faults, the deep-ocean crust that was spreading parallel to the transform was unroofed and emplaced up into the rift mountains to form a transverse ridge. A similar model was proposed by Dick et al. (1981) to explain the asymmetric physiography and distribution of plutonic and volcanic rocks at the Kane Fracture Zone in the North Atlantic. At the Kane Fracture Zone, the surface of the detachment fault has actually been observed by submersible (Dick et al., 1981; Mevel et al., 1991). Detachment faults similar to the one proposed to explain unroofing of the lower crust at the Atlantic Fracture Zone have been suggested to occur periodically within rift valleys by fault capture during amagmatic periods (Harper, 1985; Karson, 1991). Thus, the structures and fabrics seen in core from Hole 735B are likely to be representative of the kinds of fabrics generally found in lower crustal sections formed at slow-spreading ridges. It is true, however, that due to the proximity to the transform the extent of the ductile shear may be greater than elsewhere beneath the rift valley.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

The principal objective of Leg 176 will be to deepen Hole 735B to a depth of at least 2 km (Fig. 4) to determine the nature of the magmatic, metamorphic, and tectonic processes in the lower oceanic crust. Leg 176 will:

- Investigate the nature of magmatic, hydrothermal, and tectonic processes in the lower ocean crust at a slow-spreading ridge.
- Recover a full representation of the major igneous lithofacies to determine the nature and extent of the igneous processes that occurred during formation of the section.
- Determine the spacing of major ductile shear zones. If the faults associated with the shear zones are listric, then the inclination of the fault plane and the nature of the physical deformation should change with depth as the faults sole into the brittle-ductile transition.

- Determine whether the extensive alteration in the amphibolite facies found in Hole 735B is gradational with depth. The existing section is too short to determine this, particularly given its heterogeneous nature.

Supplementary objectives for the leg if deepening Hole 735B is not achieved:

- Drill a transect of 500-m-deep holes offset in ~100,000-yr increments along a lithospheric flow line.
- Investigate the spatial and temporal heterogeneity in primary and secondary mineralogies.
- Achieve a detailed sampling of the spatial and temporal structural variability of the lower ocean crust by examining the extent of both brittle and ductile deformation shear zones, the spacing, width, and orientation of major and minor fault zones, and the state of internal stress within the borehole.
- Establish a natural laboratory with the potential for future hole-to-hole magnetotelluric and permeability experiments, as well as direct testing of the nature of layer 3.

DRILLING STRATEGY

It is reasonable to assume that drilling conditions will remain roughly constant from the hole's present depth until thermal problems occur, or when serpentinized peridotite is encountered. While the depth at which the latter will occur is difficult to predict, it is reasonable to expect thermal problems at about 2000 m sub-basement, based on experience at Hole 504B, where the present temperature is now close to 190˚C.

Based on the hypothesis that brittle fracture and brecciation decrease with depth in plutonic layer 3 due to the steep geotherm beneath an ocean ridge, and that fine-grained rocks are unlikely to be encountered lower in the section, it is reasonable to suspect that the overall penetration rate would remain close to that for Leg 118. Five hundred meters were drilled at Hole 735B in 19 days, including setting a guide base and starting with the mud motor rather than the top drive, and using minimum bit weight and extreme operational conservatism. Improved bit design subsequent to Leg 118 and the observed lack of bit wear during Leg 118, suggests that operations during Leg 176 should extend bit life, which should make up for increased trip time as the hole is deepened.

The priorities for 735B drilling defined by PCOM are as follows:

1) Deepen Hole 735B to at least 2 km below the seafloor
2) Log the deepened hole
3) Conduct both Packer and VSP experiments in the deepened hole
4) In the event difficulties are encountered while drilling, the following priorities should be maintained:
    - offset HRGB in present 200 m survey box.
    - bare rock spud-in at 800 m intervals on lithospheric flow line.
    - video survey and distal HRGB deployment.
5) Efforts should focus on the wave-cut terrace on which Hole 735B is located.

LOGGING PLAN

Establishing the depth/seismic tie by means of a VSP and synthetic seismograms is essential to identifying deep crustal reflectors. During the first phase of drilling Hole 735B during Leg 118, geochemical data from the geochemical logging tool (GLT), compressional- and shear-wave velocity and amplitude logs, the borehole televiewer (BHTV), and magnetic susceptibility logs were especially useful in delineating structural and stratigraphic features of magmatic layering and fractures. In anisotropic formations such as those at Site 735, the shear-wave velocity and amplitude measured at different azimuths in the borehole may indicate fracture orientation and the regional paleostress direction. The Formation MicroScanner (FMS) high-resolution images will also vastly improve the determination of the fracture and alteration zone distribution in the crust and should be given high priority. FMS logs will also be useful in re-orientation of the structural markers in the cone. Magnetic susceptibility was useful in identifying metallic oxides that are quite abundant in the upper 500 m of the hole. Log resistivities were as high as 40,000 ohm-m in the upper 500 m of the hole, and the dual laterolog (DLL) is recommended in such high-resistivity environments. In summary, the Quad, GLT (providing low core recovery necessitates it), dipole sonic, DLL, FMS, and BHTV tool strings, should be run. In addition, a vertical-incidence VSP and a high-temperature magnetometer are recommended.

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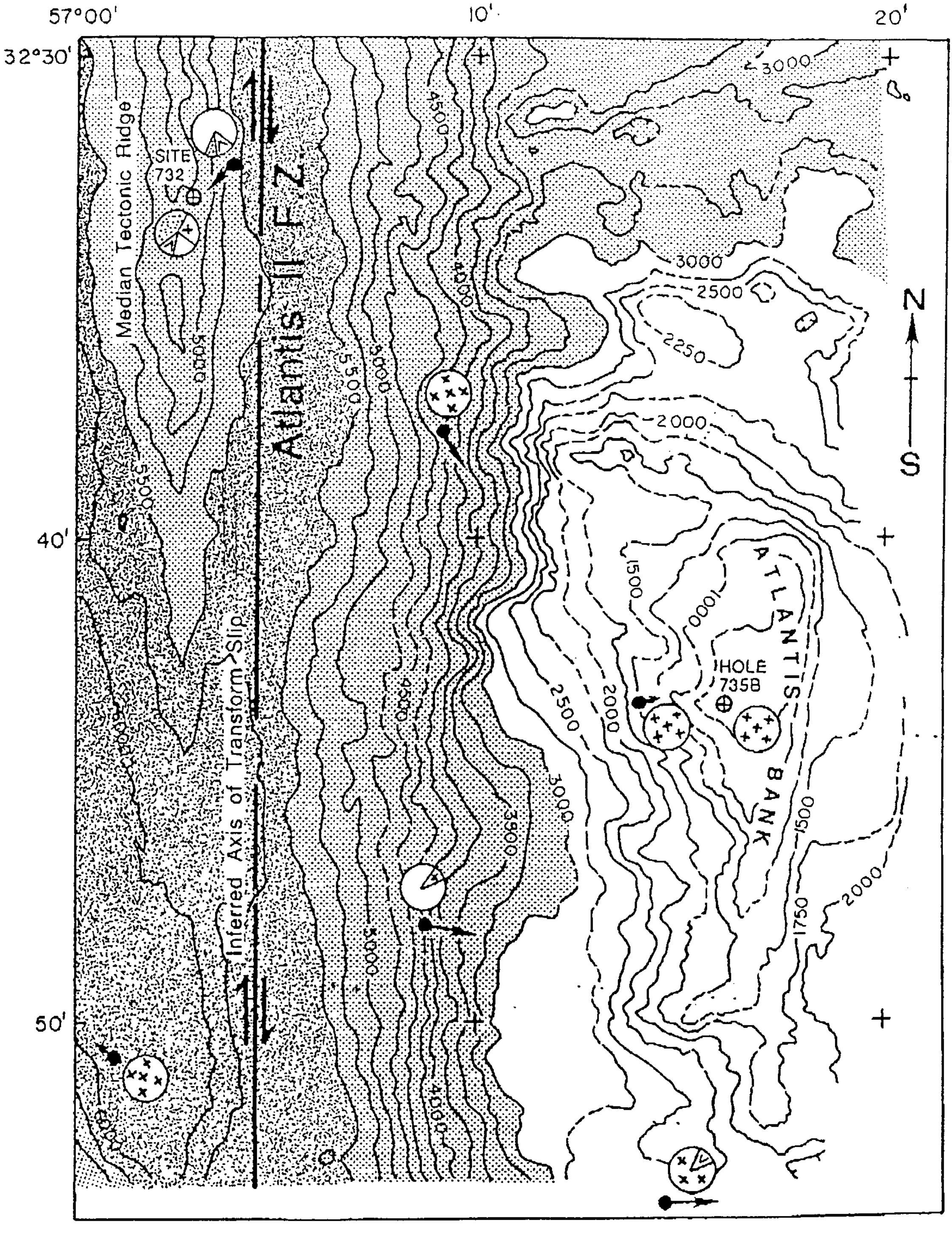

Figure 1. Hand-contoured bathymetric map of the eastern transverse ridge, showing the location of Site 732 and Hole 735B. SeaBeam tracks hand-shifted by eye to eliminate conflicts in the data. Solid lines indicate actual data, while hatched lines show inferred contours. Contour interval is 250 m. Solid dots and arrows indicate the starting point and approximate track of dredge hauls. Filled circles indicate the approximate proportions of rock types recovered in each dredge - white = altered gabbro; + = gabbro; V = basalt and diabase, stippled = greenstone.

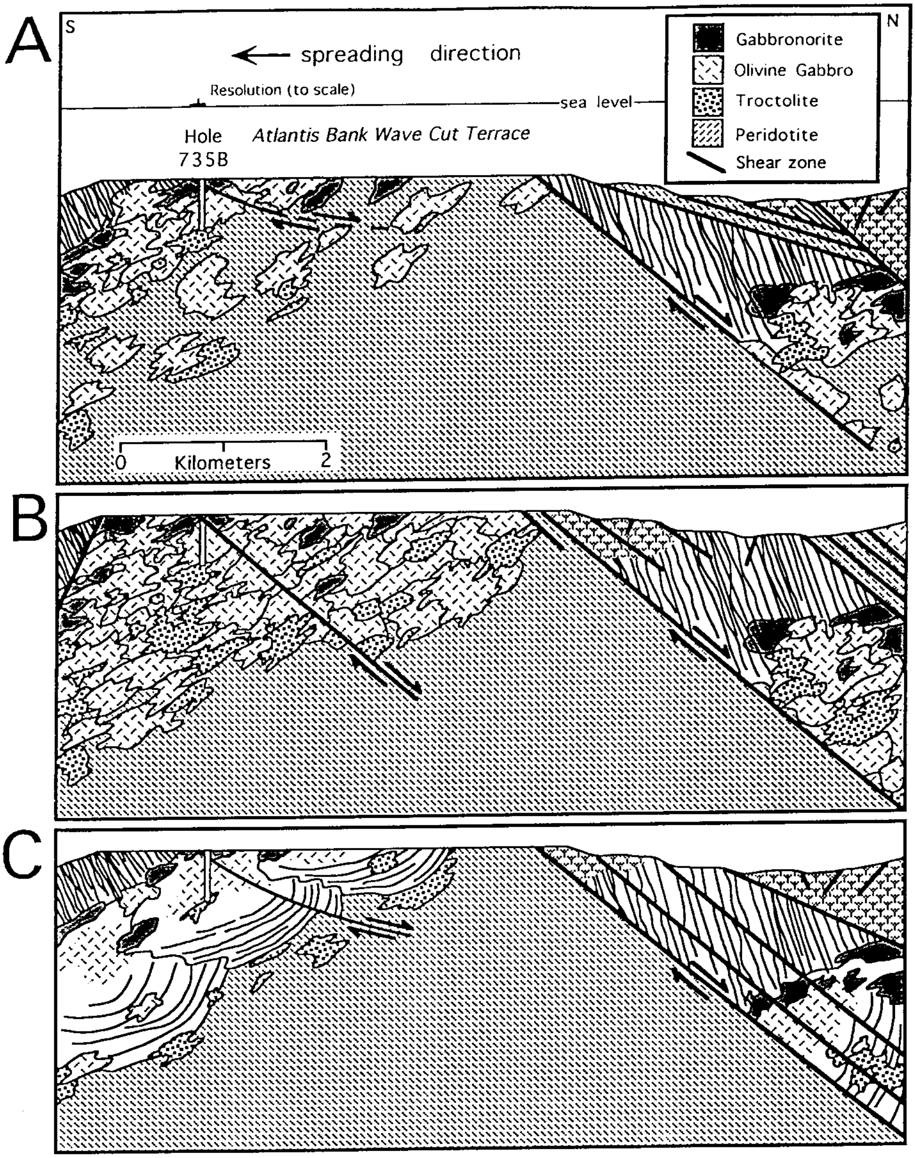

Figure 2. Possible N-S geologic cross sections of the Atlantis II Bank through Hole 735B, consistent with existing geological and geophysical data, gravity, and magnetics. Except at Hole 735B, fault locations and geometries are uncertain. The presence of a dike-gabbro transition as shown on the right of all the models is also hypothetical. A) Crustal stratigraphy around Hole 735B as suggested by Cannat (1993) and Swift and Stephen (1992), consistent with earlier inferences of Hess (1962). B) Crustal stratigraphy assuming Hole 735B is representative of the lower crust down to the mantle (Dick et al., 1991b). C) Crustal stratigraphy based on the layered intrusion model for ophiolites as proposed for Oman (After Pallister and Hopson, 1981; Smewing, 1981).

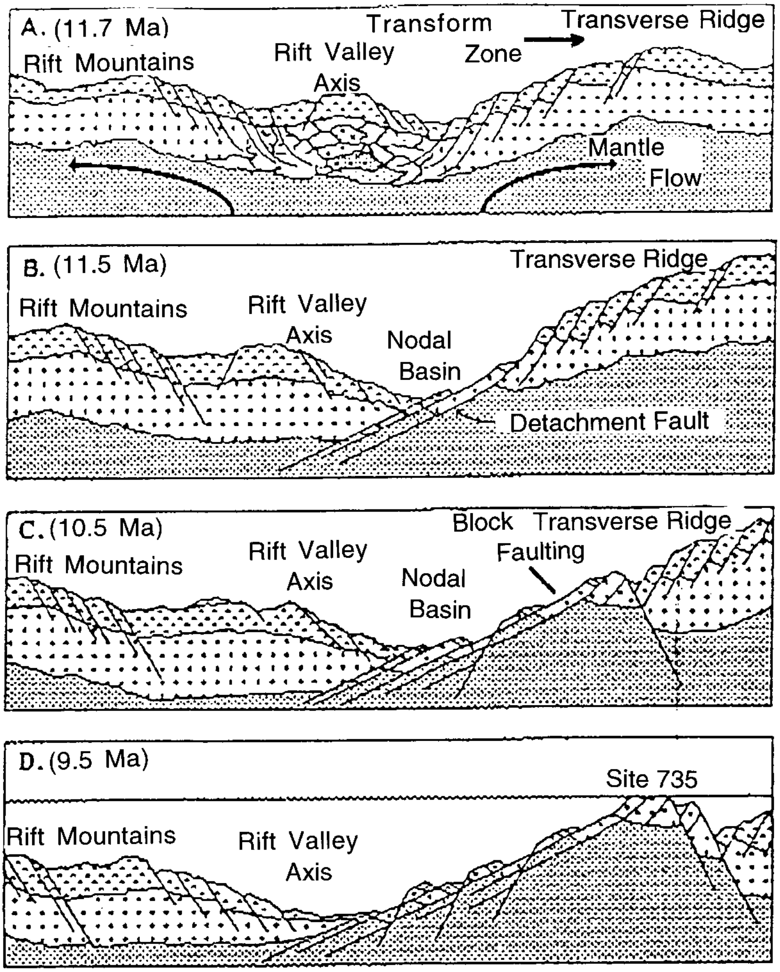

Figure 3. Temporal cross sections across the Southwest Indian Ridge rift valley drawn parallel to the spreading direction (not across the fracture zone, but parallel to it), showing the postulated tectonic evolution of the transverse ridge and Hole 735B (Dick et al., 1991). The sequential sections are drawn at about 18 km from the transform fault. Crust spreading to the right passes into the transverse ridge and spreads parallel to the transform valley. Crust spreading to the left spreads into the rift mountains of the Southwest Indian Ridge parallel to the inactive extension of the Atlantis II Fracture Zone.

A. Initial symmetric spreading, possibly at the end of a magmatic pulse. Late magmatic brittle-ductile deformation occurs because of lithospheric necking above (and in the vicinity of whatever passes for a magma chamber at these spreading rates). Hydrothermal alteration at high temperatures accompanies necking and ductile flow in subsolidus regions.

B. At some point, the shallow crust is welded to the old, cold lithosphere to which the ridge axis abuts, causing formation of a detachment fault, and nodal basin, initiation of low-angle faulting, continued brittle-ductile faulting, and amphibolite-facies alteration of rocks drilled at Hole 735B.

C and D. Block uplift of the rift mountains at the ridge-transform corner forms a transverse ridge enhanced by regional isostatic compensation of the local negative mass anomaly at the nodal basin. Initiation of the block uplift terminates the extension driving cracking, and drastically reduces permeability in the Hole 735B rocks, effectively terminating most circulation of seawater and alteration. Greenschist-facies retrograde alteration continues along the faults on which the block is uplifted to account for the greenschist-facies alteration that predominates in dredged gabbros.

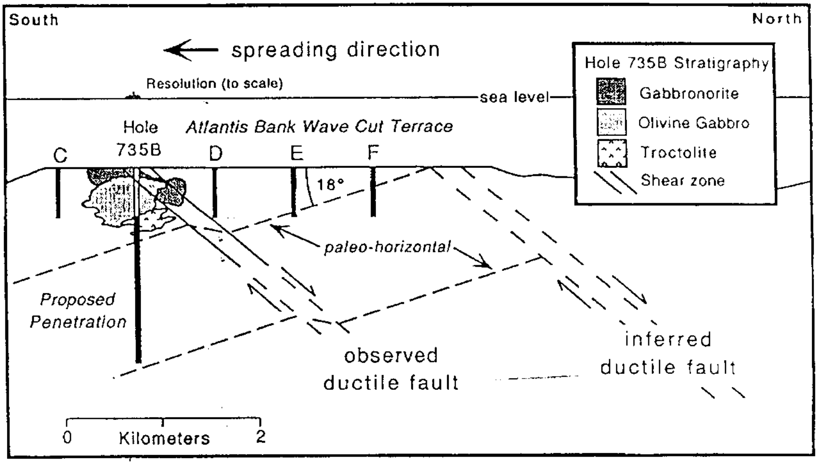

Figure 4. Cross section along a lithospheric flow line over the wave-cut platform at Hole 735B, showing the proposed Leg 176 deepening of the hole and drilling transect (no vertical exaggeration). At the observed spreading rate of 0.8 cm/yr, the proposed 800 m offset of the holes equates to 100,000 year spreading increments. Simplified stratigraphy based on Leg 118 lithostratigraphy (Dick et al., 1991). The inferred ductile fault is based on the bathymetry which suggests the presence of such a structure. The paleo-horizontal is inferred on the basis of the rock rotation needed to explain the deviation of the observed magnetic inclination of 70° from the predicted 52° (Pariso et al., 1991).

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: 735B	**PRIORITY**: 1	**POSITION**: 32°43.395´S, 57°15.959´E
WATER DEPTH: 740 m	**SEDIMENT THICKNESS**: 0 m	**TOTAL PENETRATION**: 2000 m
SEISMIC COVERAGE: Single channel seismic RC-27-09		

Objectives: Deepen Hole 735B to at least 2 km to drill oceanic mantle/crust transition

Drilling Program: RCB

Logging and Downhole Operations: Quad combo, GLT, DLL, FMS, BHTV, VSP dipole sonic, magnetometer

Nature of Rock Anticipated: Gabbro and peridotite

ALTERNATE-STRATEGY SITES

SITE: Alt-1, -2, & -3	**PRIORITY**: 2	**POSITION**: Near 735B
WATER DEPTH: 740 m	**SEDIMENT THICKNESS**: 0 m	**TOTAL PENETRATION**: 500 m
SEISMIC COVERAGE:		

Objectives: Offset in 800 m intervals along a lithospheric flow line to sample lateral and temperal variability

Drilling Program: RCB

Logging and Downhole Operations: Quad combo, GLT, DLL, FMS, BHTV, VSP dipole sonic, magnetometer

Nature of Rock Anticipated: Gabbro